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Integrating renewables in biomethane production plants: an economic and environmental assessment

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Abstract

This thesis presents an evaluation of the feasibility of using heat pumps to heat feedstock within anaerobic digesters for biomethane production. Given the increasing production of biogas and biomethane in both advanced and developing countries, incorporating alternative forms of renewable energy for this purpose not only enhances production capabilities but also contributes to environmental improvement. Thus, utilizing a heat pump to cover the heat demand of the anaerobic digestion process in biomethane production will amplify environmental benefits.

In the introductory section of the thesis, an overview of the anaerobic digestion process will be provided, along with an exploration of various technologies employed for upgrading biogas into purer biomethane and a concise summary of trends in biogas and biomethane production will be presented. In this case study, an anaerobic digestion plant located close to Turin (NW Italy) is used to produce biomethane. The facility operates for 31 days each month and mesophilic temperature conditions (37°C) are utilized for the anaerobic digestion processes. In the following section, the selection of feedstocks, determination of digester size, and estimation of biogas and biomethane production quantities will be detailed.

Five scenarios are analysed to address the energy consumption needs of the project, encompassing both heat and electricity requirements, namely 1) heat demand covered with a ground-source heat pump, electricity demand is fulfilled through a combination of PV panels and sourcing from the national grid.; 2) the entire electricity demand is covered only by the PV panels; 3) a combined heat and power (CHP) unit is employed to fully meet both the heat and electricity demand and any surplus electricity demand is fulfilled through the Italian national grid network; 4) the heat demand is satisfied using a ground-source heat pump, while the electricity demand is fulfilled by the Italian national grid network; 5) the heat demand is met by the wood chips boiler, while the electricity demand by the PV panels. A comprehensive cost analysis was undertaken considering capital and operational costs, and revenues. The impact of the cost of electricity from the grid was assessed as well. Finally, the environmental impact of biomethane production was assessed estimating greenhouse gas (GHG) emissions.

Acknowledgements

I would like to express my deepest gratitude to my supervisor, Prof. Alessandro Casasso, for their unwavering support and guidance throughout the course of this research. His patience and understanding provided me with the confidence to overcome challenges encountered along the way.
I am also truly grateful to my co-supervisor, Ms. Maria Adele Taramasso, whose expertise and perspectives have significantly contributed to the refinement of this work.

Special thanks are owed to my parents, Mohammad and Mahnaz, for their unconditional love and support throughout my life. Their sacrifices and belief in my abilities have been the foundation of my resilience and determination. The encouragement and unwavering faith they have shown in me fueled my ambition and sustained me through times of doubt. This thesis is not only a testament to my academic endeavors but also a reflection of their enduring dedication and hard work.

1 Introduction

1.1 Anaerobic Digestion

Anaerobic digestion (AD) is a naturally occurring bacterial fermentation process that takes place in an oxygen-free environment, resulting in a biogas primarily composed of methane and carbon dioxide. This biological phenomenon is commonly observed in anaerobic habitats, including marshes, sediments, and wetlands, as well as within the digestive tracts of ruminants and specific insect species.

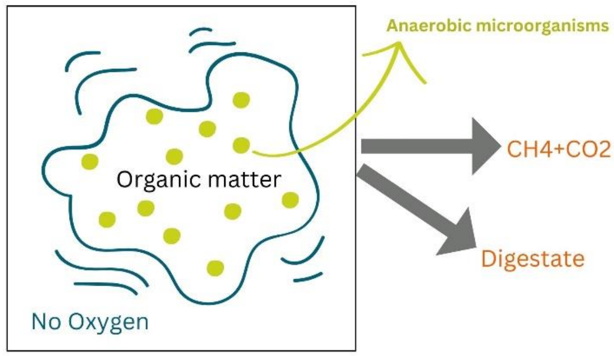

Figure 1. Simplified scheme of AD process

AD systems play a crucial role in various wastewater treatment facilities, contributing to the degradation and stabilization of sludge. These systems are additionally utilized in engineered anaerobic digesters to treat high-strength industrial and food processing wastewater before their discharge. Furthermore, AD finds application in animal feeding operations and dairies, where it is employed to address the environmental impacts of manure. This includes limiting the emissions of uncontrolled greenhouse gases such as methane (CH_4) and nitrous oxide (NO), while also serving as a mean of energy production. In Figure 2, stages of the overall process of AD are mentioned.

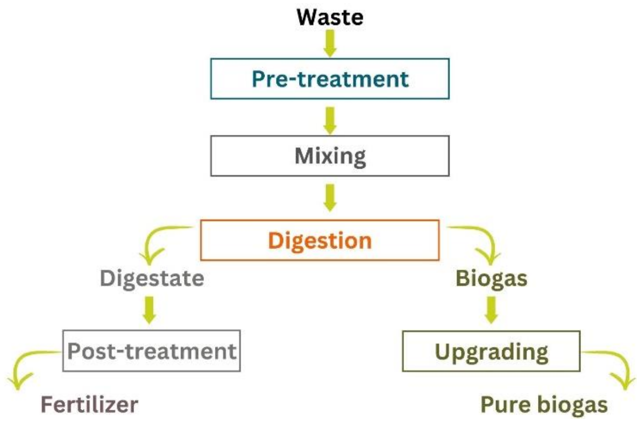

Figure 2. Stages of the overall process of AD.

The anaerobic digestion process typically consists of four distinct phases, each facilitated by specific groups of microorganisms which are visualized in Figure 3 .

The key phases are:

1. Hydrolysis: large organic molecules (complex organic matter such as carbohydrates, fats, and proteins) are broken down into simpler compounds.
2. Acidogenesis (fermentation): the simpler compounds from hydrolysis are further broken down into volatile fatty acids, alcohols, and other intermediate products.
3. Acetogenesis: the intermediate products from acidogenesis are converted into acetic acid, hydrogen, and carbon dioxide.
4. Methanogenesis: methane is produced from acetic acid, hydrogen, and carbon dioxide in a series of biochemical reactions.

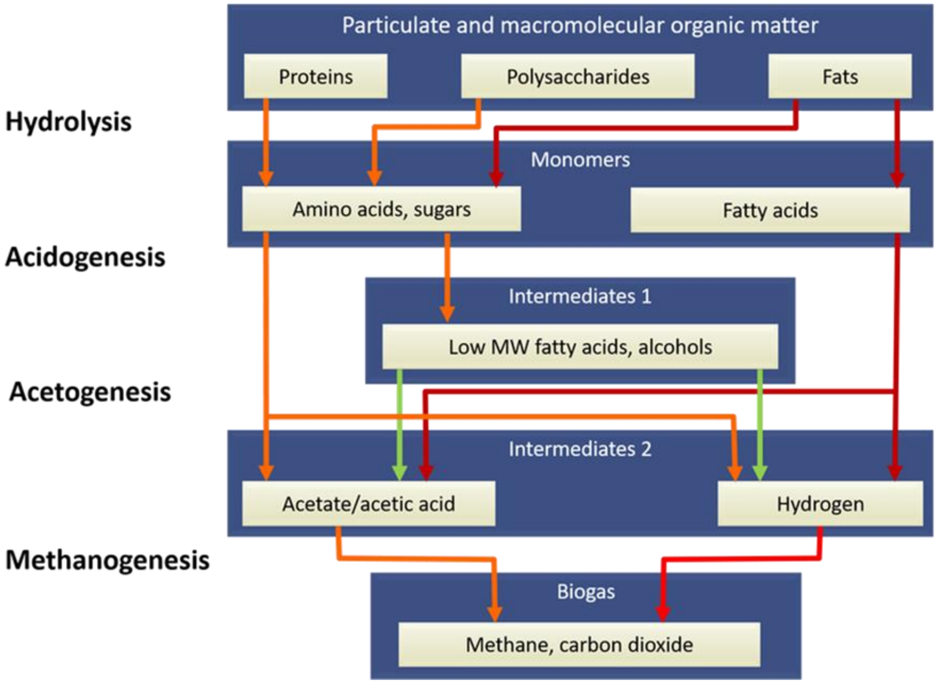

Figure 3. The four phases of anaerobic digestion: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (1).

Some factors that influence AD process, which is mentioned in Figure 4.

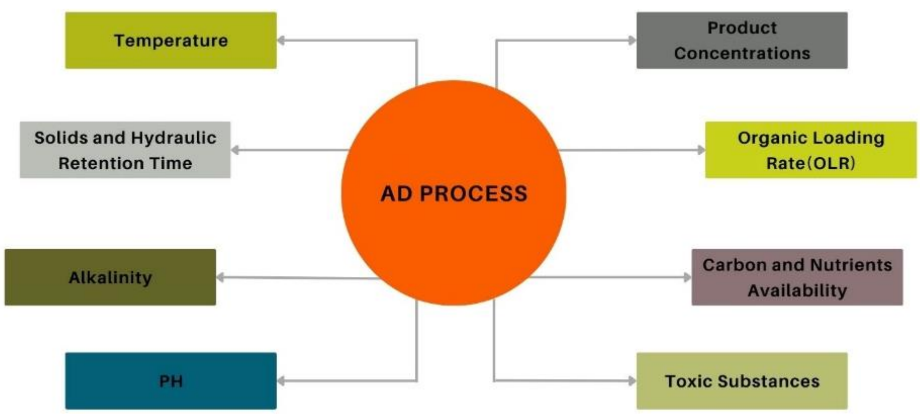

Figure 4. Factors affecting an AD process.

It is essential to balance the moisture content to create an environment that supports the microbial community responsible for anaerobic digestion while avoiding potential challenges like excessive water content or dryness. Dry, semi-dry, and wet fermentation are terms used to describe variations in the moisture content of the feedstock or substrate in AD systems. These terms refer to the amount of water present in the organic material undergoing digestion. Here's a brief explanation of each:

1. Dry fermentation: the moisture content of the substrate is typically low, usually less than 70%. The solid nature of the feedstock allows for better control of the digestion process. Dry fermentation is often associated with higher solids content, which can result in a more efficient production of biogas.
2. Semi-dry fermentation: between dry and wet fermentation in terms of moisture content, it combines some of the benefits of both. The substrate usually has a moisture content ranging from 20% to 60%.
3. Wet fermentation: the substrate has a high moisture content, typically exceeding 90%. The feedstock is in a slurry or liquid form. Wet fermentation is suitable for materials with high moisture content, ensuring better mixing and contact between microorganisms and organic matter.

The selection of temperature conditions is crucial in biological processes because it influences the activity and efficiency of microorganisms. The choice between thermophilic, mesophilic, or psychrophilic conditions depends on the specific requirements of the process, the nature of the feedstock, and the desired outcomes.

1. Thermophilic (55-60 °C): thermophilic microorganisms thrive in elevated temperatures. They are well-suited for processes that require high temperatures, such as thermophilic composting and certain types of anaerobic digestion. Thermophilic digestion is known for its faster reaction rates and increased pathogen reduction compared to mesophilic digestion.
2. Mesophilic (30-40 °C): mesophilic microorganisms operate at moderate temperatures. They are commonly involved in various biological processes, including conventional anaerobic digestion and wastewater treatment. Mesophilic digestion is often considered more stable and less sensitive to temperature fluctuations than thermophilic digestion.
3. Psychrophilic (10-30 °C): psychrophilic microorganisms thrive in cold temperatures. While less commonly used in anaerobic digestion and similar processes, psychrophilic microorganisms can still play a role in the breakdown of organic matter in colder environments. Certain psychrophilic bacteria adapted to function at low temperatures and can be found in cold-climate ecosystems.

1.2 Biomethane production through Biogas Upgrading

The process of biogas upgrading involves the separation or conversion of carbon dioxide (CO_2) from methane (CH_4) in biogas. Various physical, chemical, and biological technologies are employed for biogas upgrading.

1. Physical and Chemical Technologies:

In the absorption process, solvents are employed to selectively absorb CO_2 from the biogas, leading to the purification of methane, like the water scrubbing system mentioned in Figure 5.

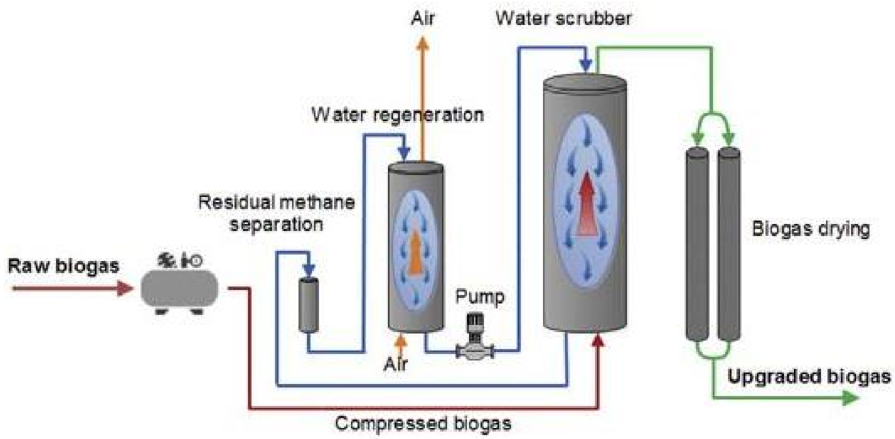

Figure 5. Flow chart of physicochemical processes for biogas upgrade - water scrubbing system (2).

Adsorbent materials selectively capture CO_2 from the biogas, allowing purified methane to pass through. This process, illustrated in Figure 6, often involves technologies like pressure swing adsorption.

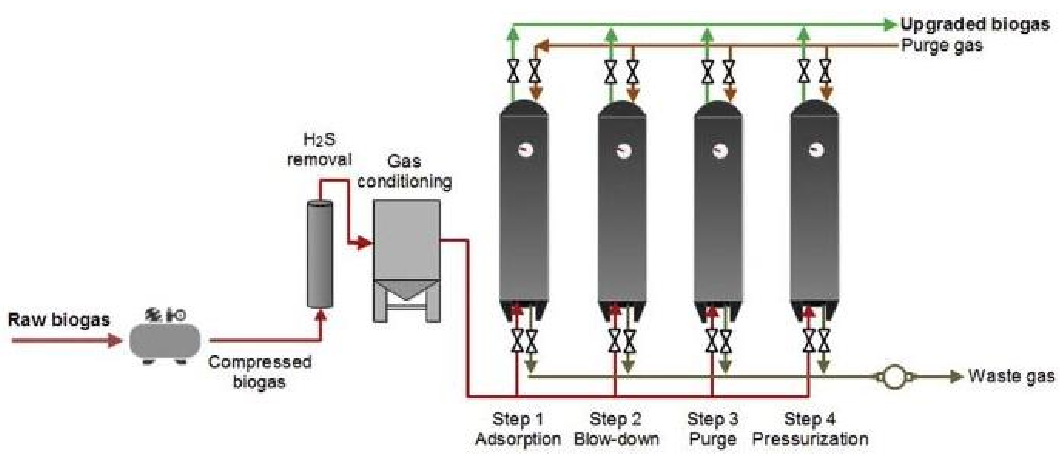

Figure 6. Flow chart of physicochemical processes for biogas upgrade - pressure swing adsorption technology (2).

Membrane separation employs specialized membranes with selective permeability to separate biogas components based on their permeation rates. This process, exemplified by the membrane cascade separation system in Figure 7, helps remove CO_2.

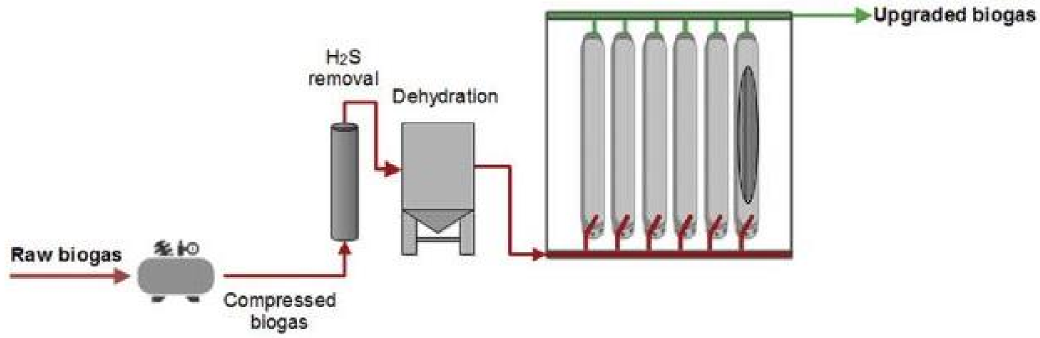

Figure 7. Flow chart of physicochemical processes for biogas upgrade - membrane cascade separation system (2).

2. Biological Technologies:

Chemoautotrophic Methods employ hydrogenotrophic methanogens, utilizing H_2 to convert CO_2 to CH_4 under mild operational conditions. Photosynthetic methods, on the other hand, involve photosynthetic microorganisms converting CO_2 into energy-containing or high-value products. The biological biogas upgrading technologies possess the advantage of transforming CO_2 into other products under mild operational conditions, thereby contributing to a sustainable bio-based and circular economy.

The challenges linked with biogas upgrading encompass the existence of trace gases in the biogas, a shortage of elements for crafting efficient catalysts, the requirement for pure gases, and the high energy costs associated with maintaining operational conditions. Overall, the biogas upgrading process plays a critical role in purifying biogas to elevate its quality, enabling diverse applications like energy generation and utilization as a transport fuel (2).

The transition from combined heat and power (CHP) to biomethane production carries significant implications for meeting electricity and heating needs. Biomethane production presents an opportunity to disconnect bioenergy production from biomass availability, creating a more sustainable and adaptable energy source. Moreover, the consistent generation of heat and power from biomethane replaces wind or solar power and biomass, promoting a more dependable and diverse energy supply. Additionally, stored biomethane enables replacing fossil-based transport fuels and fossil electricity during periods with low wind, resulting in substantial environmental benefits compared to direct heat/power production. Overall, replacing CHP with biomethane production holds the potential to improve energy security, diminish dependence on fossil fuels, and contribute to a more sustainable energy system (2).

1.3 Trends in the biogas and biomethane production

1.3.1 Global Growth

The global production of biogas has experienced a significant increase since the start of the 21st century, that has prompted heightened global attention towards the utilization of biogas as a prominent form of renewable energy. In 2020, the total energy content of global biogas production reached 1.46 exajoules, showcasing a substantial increase from the 0.29 exajoules recorded in the year 2000, as shown in Figure 8. The major biogas markets are in Europe and the Asia-Pacific region, while Europe in 2022 accounted for more than 40% of the global biogas market value, with Germany at the forefront; the Asian-Pacific biogas market is expected to increase by over 10 billion U.S. dollars from 2022 to 2030, as shown in Figure 9.

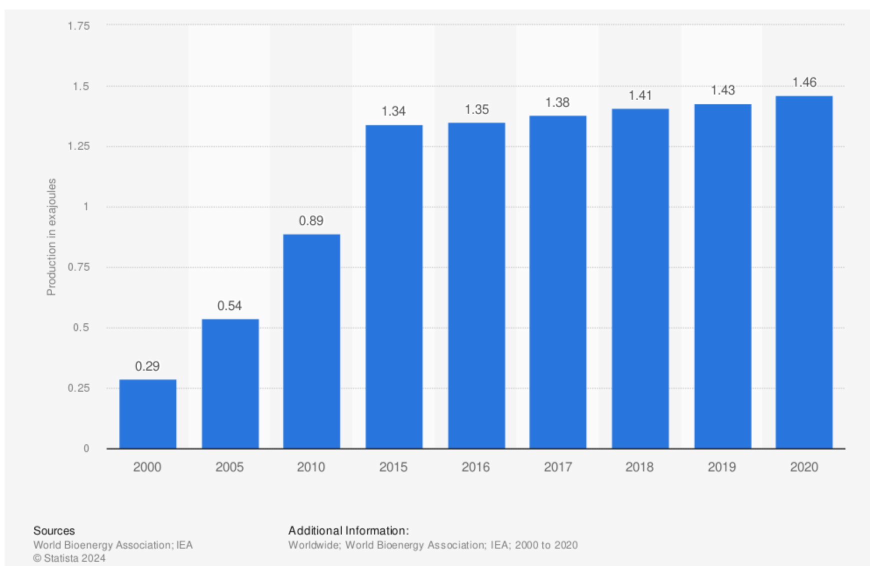

Figure 8. Production of biogas worldwide from 2000 to 2020 (3)

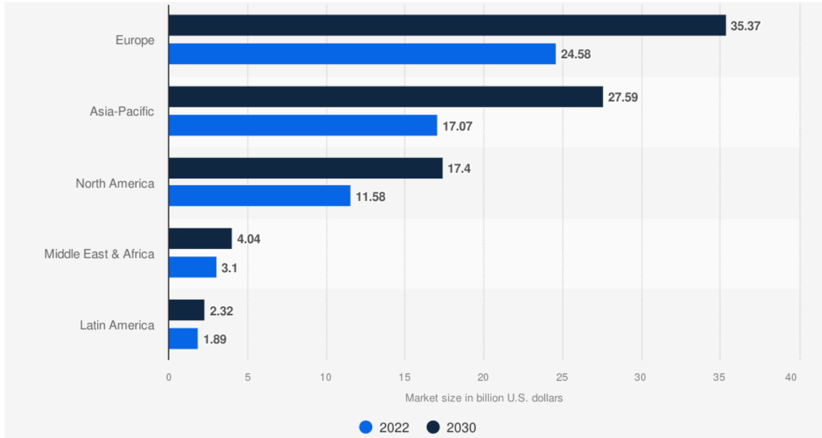

Figure 9. Size of the biogas market worldwide in 2022 with a forecast for 2030, by region (in billion U.S. dollars) (4)

Europe currently holds a leading position in the biogas market. Within the European Union (EU-27), comprising 27 member countries, the production of biomethane stands at 3 billion cubic meters (bcm), alongside 15 bcm of biogas. Furthermore, there is a projected potential of 38 billion cubic meters (bcm) for anaerobic digestion in the EU-27 by the year 2030, with an anticipated increase to 91 bcm by 2050, focusing on advancements in anaerobic digestion technology (5).

In both the years 2030 and 2050, the top five countries contributing significantly to biogas production consistently comprise France, Germany, Italy, Poland, and Spain. Notably, key feedstocks in 2030 include manure (33%), agricultural residues (25%), and sequential cropping (21%). A significant shift is observed in 2050, where sequential cropping takes the lead, constituting 47% of the total, accompanied by substantial contributions from manure (19%) and agricultural residues (17%). Additionally, industrial wastewater maintains a consistent contribution, exceeding 10% of the potential in both 2030 and 2050, as illustrated in Figure 10 and Figure 11.

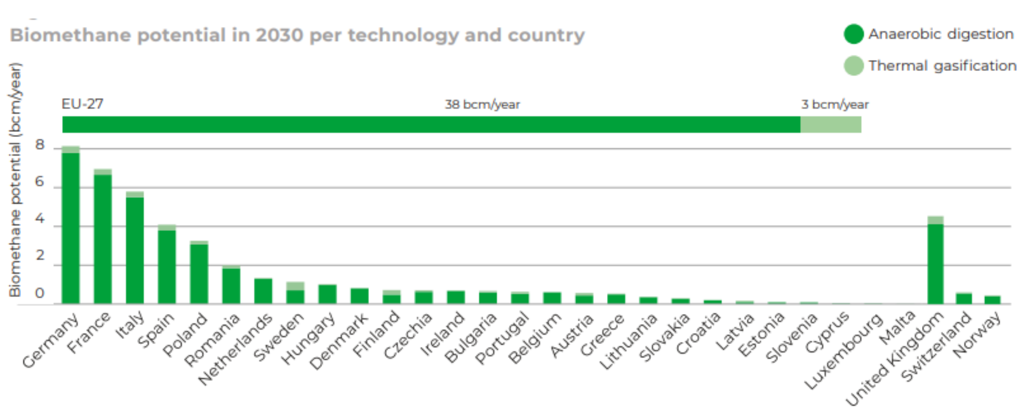

Figure 10 Biomethane potential in 2030 per technology and country (5).

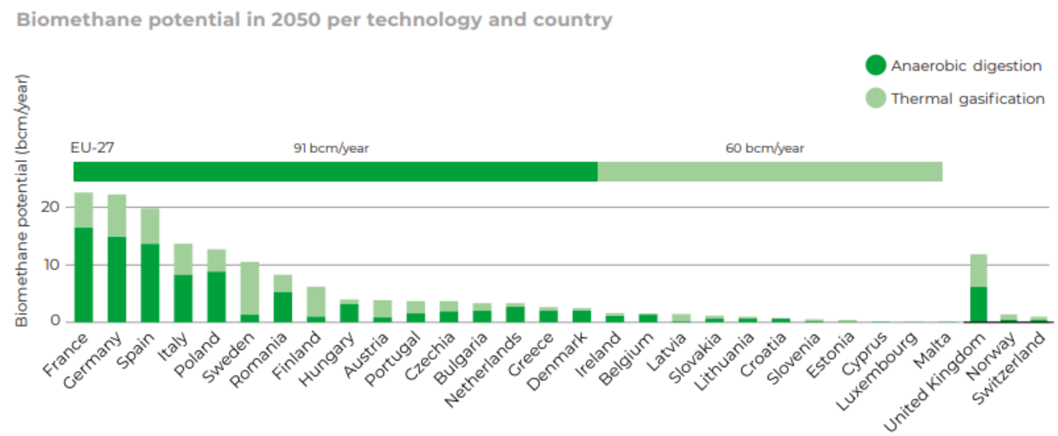

Figure 11 Biomethane potential in 2050 per technology and country (5).

1.3.2 Feedstock Diversity

A diverse range of materials, including crop residues, animal manure, the organic fraction of municipal solid waste (MSW), industrial waste and wastewater sludge, can serve as feedstocks for biogas production. This is visually represented in Figure 12.

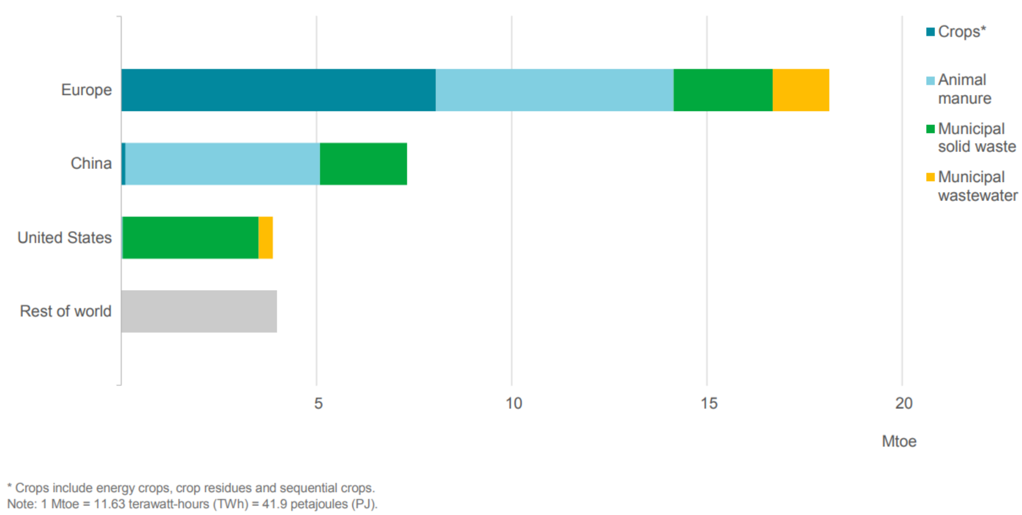

Figure 12. Biogas production by feedstock type, 2018 (6)

As Europe mentioned as the leading position in the biogas market, the chart highlights that the principal contributors to biogas production there are crops and animal manure, with the term "crops" including energy crops, crop residues, and sequential crops. This case study specifically utilizes crop residues as the chosen feedstock, and additional details regarding this selection will be elucidated in the following sections.

1.3.3 Investment Interest

Among the leading nations contributing substantially to biogas production, Italy has experienced increasing investments in converting waste into biogas since 2008. Currently, there is a comprehensive plan to further invest in the production of biogas from waste, with an anticipated expenditure of approximately 3,544 million euros by 2030.

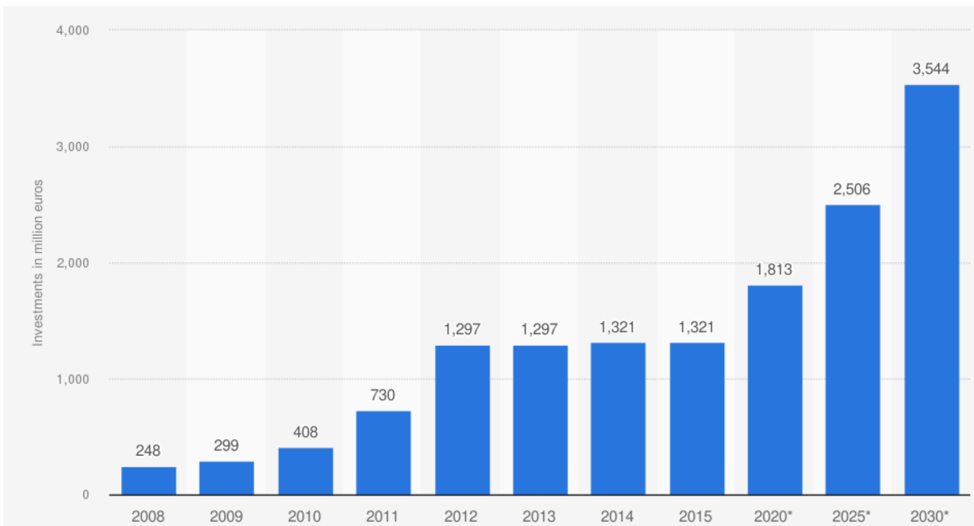

Figure 13. Planned investment in biogas produced from waste in Italy in selected years between 2008 and 2030 (in million euros) (7)

2 Methodology

2.1 Description of the case study

This case study focuses on an AD facility centred on biogas production located in Turin, Italy. The facility operates 31 days a month, using mesophilic temperature conditions (37 °C) for the AD processes. Biogas is produced through anaerobic digestion of organic waste in an oxygen-limited setting, resulting in a mixture primarily composed of methane (CH_4), carbon dioxide (CO_2), and small amounts of other gases. The composition of biogas may vary based on the feedstock's characteristics, such as onion waste, fish waste, bread trash, and water, chosen for its high volatile solids content for this study.

Biomethane, also known as "renewable natural gas," is a purified form of methane produced through biogas upgrading, where carbon dioxide (CO_2) and impurities are removed. Alternatively, it can be generated by gasifying solid biomass and purifying the resulting gas. The calculation shows a daily biogas production of 6,219 $\frac{Nm^3{}_{BG}}{day}$, and the total volume of biomethane produced is 3,732.9 $\frac{Nm^3{}_{CH_4}}{day}$, considering methane loss related to digester and membrane technology.

The AD plant thermal balance is influenced by two factors, as a constant temperature of 37°C is required: the preheating of feedstocks and the compensation for biodigester dispersions due to external temperature variations in both hot and cold seasons. This study examines two seasons, summer, and winter, characterized by a temperature difference to be compensated of around 20 and 25 °C, respectively.

Within the scope of this case study, the AD facility is designed with the objective of generating biogas and subsequently producing pure biomethane. The thermal and electrical energy needs for the entire processes are satisfied through the implementation of five distinct scenarios. Cost analysis serves as a crucial tool for businesses and organizations, offering a systematic method to examine and comprehend the financial aspects of their operations. This process involves a thorough evaluation of investment and operational costs, and resource distribution, aiming to gain insights into the financial stability and efficiency of the organization's activities. Through the cost analysis, businesses can make informed decisions, enhance profitability, and optimize expenditure, contributing to overall financial sustainability. This methodology is crucial for evaluating project viability, setting suitable prices for products and services, identifying areas where costs can be minimized, and enhancing financial administration, all of which are currently being examined within this context.

In the cost analysis section, the focus is on expected membrane upgrading system, heat pump and wells, PV panels, combined heat and power (CHP) unit and boiler capital and operational costs, and on the cost of purchasing electricity from the grid. Additionally, the plant generates a saving through power generation from biogas and disposal tariff for organic waste.

Incorporating biogas as an alternative to fossil fuels presents numerous environmental and economic benefits, which these environmental advantages are also taken into account in this study. As previously noted, biogas, produced via the anaerobic digestion of organic substances, is classified as a renewable energy source owing to the continual replenishment of these materials. Notably, it is derived from organic waste, mitigating the release of methane, a potent greenhouse gas, into the atmosphere. By capturing and utilizing this methane, overall greenhouse gas emissions are reduced. Biomethane production significantly contributes to reducing greenhouse gas emissions by incorporating more environmentally sustainable gases into our overall energy use.

The assessment of the carbon footprint associated with producing and using biogas depends on various factors, including emissions from devices, methane losses during the digestion process, and the greenhouse gas impact of energy production or consumption. In this case study, major greenhouse gas emissions associated with biogas production also come from methane losses during the digestion process and upgrading.

2.1.1 Feedstocks

Utilizing organic waste in AD and biomethane production offers several specific benefits. Beyond energy generation, it contributes to waste reduction, it reduces greenhouse gas (GHG) emissions, and it exemplifies a sustainable use of resources. This process closes the loop on waste by transforming it into a valuable energy resource, promoting a more sustainable and resource-efficient approach. Additionally, the solid byproduct of anaerobic digestion, referred to as digestate, is nutrient rich. With proper treatment, digestate can serve as a valuable fertilizer, replenishing nutrients in the soil and supporting sustainable agricultural practices.

In this case study the plant situated in Turin, Northwestern Italy, the AD plant incorporates onion waste, fish waste, bread waste and water as key feedstocks.

Onion waste, with its blend of organic matter and fibers, stands as a biodegradable material suitable for processes like anaerobic digestion or composting. Its moisture content, which varies with freshness, renders it moderately moist. Fish waste, characterized by a high moisture level owing to inherent water content in fish tissues, emerges as a rich source of proteins and essential nutrient, and it significantly contributes to the generation of nutrient-rich digestate. Moreover, bread waste comprising leftover or expired bakery products, possesses a mix of carbohydrates, proteins, fats, and fibers. The moisture content fluctuates, generally leaning towards the higher side based on freshness and specific products included. While onion and bread waste tend to exhibit neutral to slightly acidic pH levels, fish waste may slightly lean towards alkalinity due to protein presence. All three waste types play a crucial role in fostering microbial activity during anaerobic digestion, thereby facilitating biogas production. This choice is by the thermal needs associated with the selected feedstock, as detailed in Table 1.

Table 1. Properties of the feedstocks.

Feedstock	Amount inlet wet weight $\left(\frac{ton}{day}\right)$	Total Solid (TS) $\left(\frac{kg_{TS}}{kg}\right)$	Volatile Solid (VS) $\left(\frac{kg_{VS}}{kg}\right)$	BMP $\left(\frac{Nm^3}{t_{VS}}\right)$
Onions	3	7.48%	79.90%	435.9
Bread waste	10	77%	74.30%	378
Fish waste	60	24.70%	21.50%	485.9
Water	40	0%	0%	0

The total combined inlet wet weight of onion waste, bread waste, fish waste, and water amounts to 113 $\frac{ton}{\text{day}}$. Moreover, in the context of AD, the duration for which feedstock must stay within the reactor, allowing microorganisms to complete the decomposition of organic materials and produce biogas, is referred to as "retention time." In this study, a retention period of 30 days has been applied (8).

2.1.2 Digester

The term "digester volume" explains the capacity or size of a biogas digester, a specialized system or container employed for the storage of organic waste and the facilitation of the anaerobic digestion process, resulting in the generation of digestate and biogas. The volume of a digester represents a pivotal design parameter that profoundly influences its overall efficiency and performance. The mass of the digestate is measured and the overall volume of the digester for our digestate can be determined employing the Equation 1 provided below.

$$V = \frac{M}{\rho} \cdot SRT$$ Equation 1

Where $V(m^3)$ is the volume of the reactor, $M\ (kg)$ is the mass of digestate, and $\rho\ \left(\frac{kg}{m^3}\right)$ is the density of digestate. The total volume of the digester was measured as the optimum volume of the reactor and 10% of the overall digester volume that is conventionally reserved for gas storage purposes, as visually illustrated in Figure 14 (9).

Figure 14. Scheme of the biodigester

By using Equation 1, the optimal volume of the cylindrical tank has been computed to be 3,905.6 m^3, with an estimated headspace volume of 390.6 m^3. Consequently, the total volume of the digester was determined to be 4,296.1 m^3. A commercial digester with a diameter of 27 m and a height of 8 m, resulting in a total capacity of 4,335 m^3(10), is chosen to accommodate the mentioned volume.

2.1.3 Biogas Production

The initial step involves the computation of the mass of solid and mass of volatile solid (ton_{VS}) by these formulas:

$$m_s = W_w * TS$$ Equation 2

$$m_{vs} = VS * m_s$$ Equation 3

Where $m_s\left(\frac{kg_{TS}}{day}\right)$ is the mass of solid, $W_w\left(\frac{kg}{day}\right)$ is the wet weight, $TS\left(\frac{kg_{TS}}{kg}\right)$ is the total solid, $m_{vs}(ton\ VS)$ is the mass of volatile solid and $VS\left(\frac{kg_{VS}}{kg}\right)$ is the volatile solid content. Subsequently, by having the biomethane potential (BMP), gives the overall quantity of biomethane $\left(\frac{Nm^3}{day}\right)$ generated through the AD process.

$$Produced\ biogas = m_s * BMP \qquad \text{Equation 4}$$

In scenarios 1, 2, 4 and 5, the entire volume of biogas produced is directed to an upgrading unit, where it undergoes a purification procedure to obtain pure biomethane. In the case of scenario 3, where a Combined Heat and Power (CHP) system is utilized, only 80.15% of the biogas is allocated for the upgrading process. Moreover, loss fraction of methane from digester and upgrading, which is acknowledged to stand at 0.3% (11) and 1.18% (12) respectively, should be taken into consideration.

2.2 Description of scenarios

In the context of this case study, the AD facility aims at the production of biogas and then pure biomethane. The thermal and electrical energy requirements for the whole processes are met through the five possible scenarios listed below.

2.2.1 Scenario 1: heat pump + PV panels and grid

The fully biomethane production plant is equipped with a ground source heat pump and a photovoltaic (PV) plant to supply the thermal and electrical demand, respectively, while extra electricity requirements are fulfilled by the national grid.

In this scenario, the feedstocks undergo the pretreatment and AD processes under mesophilic conditions at 37 °C. A ground-source heat pump is considered to cover the heat demand of the process, which offer various advantages, including high energy efficiency, year-round heating and cooling capabilities, reduced environmental impact, potential cost savings, safety due to the absence of combustion processes, long lifespan, independence from fossil fuels, zoning capabilities, and availability of incentives or rebates for installation.

The efficiency of the system, assessed by the Coefficient of Performance (COP) of the heat pump, indicates its ability to produce heat or cooling relative to the energy input. For this analysis, a

Mitsubishi EW- HT0182 heat pump, with a COP of 4.07, is selected, and it operates continuously for $22\left(\frac{hours}{day}\right)$ to cover the heat demand of the system. Conversely, the electricity demand of the system, encompassing the needs of the heat pump and the upgrading plant, is fulfilled by the PV panels and national network grid. Solar photovoltaic panels offer benefits such as clean and renewable energy generation, reduced electricity bills, low operating costs, minimal environmental impact, energy independence, grid support, and off-grid functionality. PV panels offer an appealing and sustainable energy solution due to their scalability, extended lifespan, ongoing technological improvements and government incentives. For meeting 33% of the electricity requirements, SunPower-SPR-MAX6 PV panels are selected. These panels have a nominal power rating of 445 Watts and an efficiency of 23.0% and the remaining portion of the electricity demand is covered by the grid network. The diagram in Figure 15 gives a big-picture view of the process of first scenario.

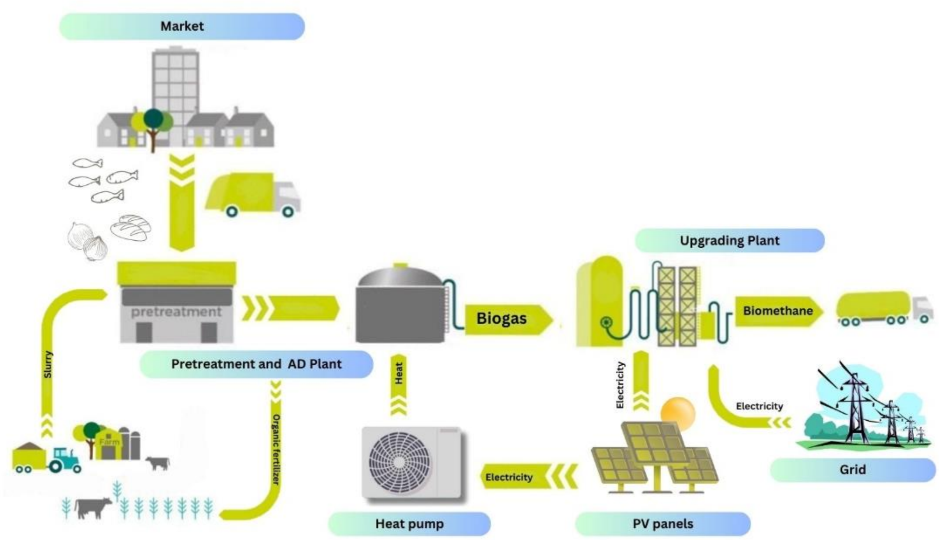

Figure 15. Scenario 1: electricity and heating needs fully covered by GSHP, PV panels and grid network.

2.2.2 Scenario 2: heat pump + PV panels

This scenario operates similarly to scenario 1, where a fully biomethane production plant is utilized, with heat provided by the ground source heat pump. In this scenario, the entire electricity demand is exclusively met by PV panels, rather than just a portion of it. The heat pump utilized is the Mitsubishi EW-HT0182, while the PV panels employed are the SunPower-SPR-MAX6. Figure 16 provides an overview of the process followed in the first scenario.

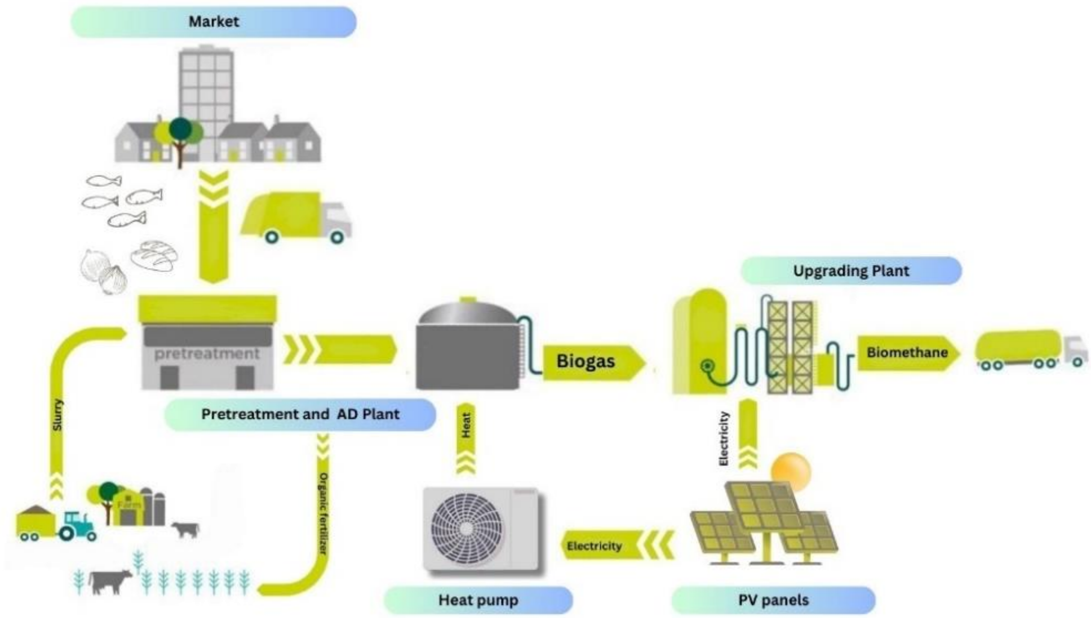

Figure 16. Scenario 2: electricity and heating need fully covered by PV panels and GSHP, respectively.

2.2.3 Scenario 3: combined heat and power (CHP) + electricity from the grid

In this scenario, biomethane production is achieved by utilizing a Combined Heat and Power (CHP) unit to fulfil the heat requirements of the process and the electricity demand of the upgrading plant. Additionally, any expected surplus electricity demand is met through the Italian national grid network. CHP demonstrates the potential to significantly reduce greenhouse gas emissions and air pollutants by more than 40% compared to the separate generation of heat and grid power. The adaptability, eco-friendliness and applicability of CHP across diverse industries are enhanced by waste heat utilization, distributed generation, and financial incentives. In this context, 80.15% of the generated biogas is designated for the biomethane conversion process in the upgrading plant, with the remaining 19.85% is directed to the Combined Heat and Power (CHP) system. Figure 17 provides an overview of the second scenario process.

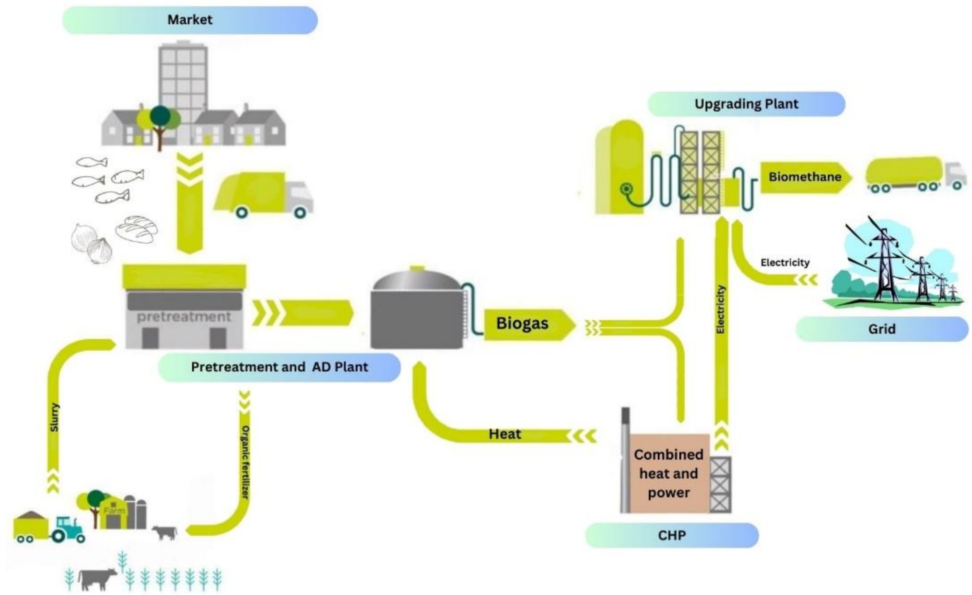

Figure 17. Scenario 3: electricity and heating needs covered using CHP unit and grid.

As depicted in Figure 17, a portion of the biogas produced is designated for the biomethane conversion in the upgrading plant, with the remainder is directed to the Combined Heat and Power (CHP) system. This allocation led to a resizing of the upgrading plant, consequently modifying the electricity demand. The detailed daily biogas needs for the CHP system and upgrading plant can be found in Table 2.

Table 2. Daily biogas dedicated to CHP unit and upgrading plant.

Feedstock	Biogas to the CHP unit ($\frac{Nm^3}{day}$)	Biogas to the upgrading unit ($\frac{Nm^3}{day}$)
Onion waste	15.47	62.45
Bread waste	428.08	1,728.01
Fish waste	306.44	1,237.02
Total	749.99	3,027.48

2.2.4 Scenario 4: heat pump supplied from the grid

In this scenario, which involves the comprehensive setup of a fully biomethane production plant, the heat needs are fulfilled by a designated heat pump, while the electricity demand for both the heat pump and the upgrading plant are totally satisfied by the national Italian grid. This configuration signifies an integrated approach to biomethane production. Figure 18 illustrates an overview of the fourth scenario's process.

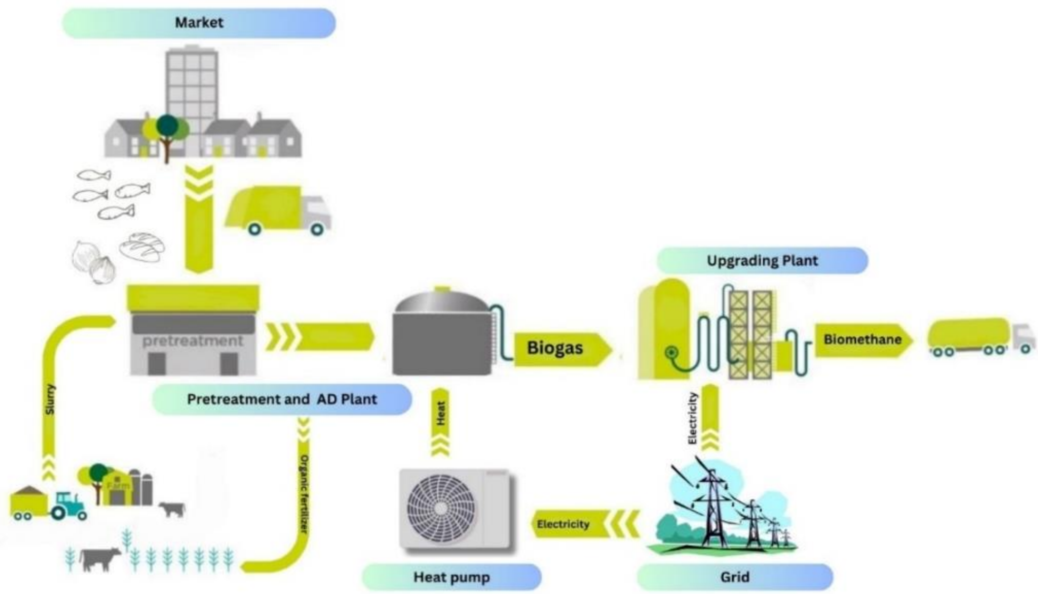

Figure 18. Scenario 4: electricity and heating needs covered by grid and GSHP.

2.2.5 Scenario 5: wood chips boiler + electricity by PV

In this scenario, biomethane production is achieved by employing a wood chips boiler to fulfill the heat requirements of the process, while PV panels are utilized to meet the electricity demand of both the upgrading plant and the boiler. The utilization of wood chips offers several benefits, including their accessibility and potential for local sourcing. They are more cost-effective compared to other forms of biomass fuels, contributing to waste reduction. Additionally, their use can result in decreased carbon dioxide emissions, supporting the use of renewable resources and aiding in the achievement of carbon-neutral energy objectives (13). Figure 19 provides an overview of the process in this scenario.

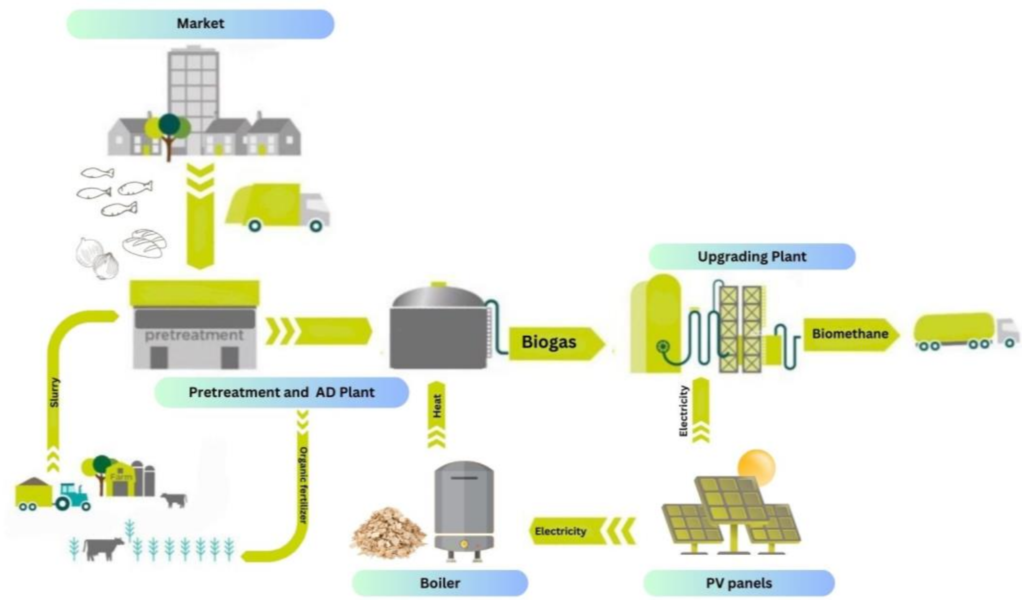

Figure 19 Scenario 5: heating needs covered using boiler and electricity covered by PV panels.

2.3 Energy Consumption

2.3.1 Heat

Initially, the calculation of heat requirements for preheating and for compensating the thermal losses, and heat supply from the heat pump and the CHP will be undertaken.

2.3.1.1 Heat demand for AD Plant

The thermal balance of the AD plant, as the operating temperature of 37 °C must be maintained, is influenced by two key factors: the preheating of feedstocks and the compensation of biodigester dispersions towards the outside due to variations of the external temperatures experienced during both hot and cold seasons. These two variables collectively contribute to the overall heating demand for the AD plant.

To account for these thermal dynamics, two distinct seasons are considered, the hot and the cold seasons. The hot season, referred to as the summer season, lasts from March to August. During this period, the feedstock is encountered at 17 °C, while the average external temperature reaches 18 °C. Conversely, the cold season, designated as the winter season, extends from September to February and is characterized by a feedstock temperature of 12°C and an average external temperature of 13 °C.

The total heat demand, expressed in MWh/y, is a cumulative summation of two contributing components: the heat demand arising from preheating (Q_{ph}), and the heat loss towards the outside (Q_{loss}).

2.3.1.1.1 Heat demand for feedstocks preheating

The heat demand required for preheating the feedstocks within the AD plant to attain operational temperature is computed using the following formula:

$$Q_{ph} = M * C * \Delta \mathrm{T_{tot}} * t_{hp} \qquad \text{Equation 5}$$

In this equation, $M(kg)$ represents the total weight of inlet wet feedstocks, $C\ \left(\frac{J}{kg \cdot °\mathrm{C}}\right)$ is the specific heat capacity, and $\Delta \mathrm{T_{tot}}(°\mathrm{C})$ refers to the previously mentioned temperature differential between the digester mesophilic operating temperature and the feedstock temperature during summer and winter seasons. The variable $t_{hp}(h)$ corresponds to the number of operating hours for the heat pump, calculated over the course of a day, with a specific consideration of 22 $\frac{h}{day}$.

2.3.1.1.2 Heat losses through digester

To ensure the consistent maintenance of digesters at the requisite operational temperatures, a thorough assessment of heat loss is essential. The following Equation 6 (11) is employed to ascertain this parameter.

$$Q_{loss} = \left[\pi \mathrm{r}^2 \cdot U_{floor} + 2\pi \mathrm{r} h_1 \cdot U_{walls} + \pi(r^2 + h_2^2\,) \cdot U_{dome}\right] \cdot \Delta T_{tot} \qquad \text{Equation 6}$$

In this equation, the parameters encompass the digester radius ($r = 6\ m$), the transmittance values for the floor ($U_{floor} = 0.465\ \frac{W}{m^2K}$), the transmittance values for the lateral walls ($U_{walls} = 0.32\ \frac{W}{m^2K}$), the transmittance values for the dome ($U_{dome} = 1\ \frac{W}{m^2K}$), the active depth of the digester $(h_1 = 6\ m)$ and the height of the dome-shaped gasometer section $(h_2 = 7\ m)$ (11). The variable ΔT_{tot} represents the temperature differential between the digester mesophilic operating temperature and the outside temperature during summer and winter seasons.

2.3.1.1.3 Total heat demand

In conclusion, the comprehensive inventory of the aggregate heating requirements is quantified in $\left(\frac{MWh}{y}\right)$, within the AD plant. The heat demand value remains consistent across all stages of biogas utilization, remaining the same for all scenarios. However, the installed thermal power varies depending on the technology employed to fulfil the heat demand.

2.3.1.2 Heat supply:

2.3.1.2.1 Heat supply by the heat pump (Scenarios 1, 2 and 4)

In the pursuit of an optimal solution for meeting heat demands associated with the biomethane production segment, the incorporation of a heat pump is considered. Geothermal energy harnesses the Earth's inherent heat, offering a renewable and environmentally benign energy source. Its merits extend to a notably low carbon footprint and minimal environmental impact. However, it is imperative to acknowledge the geographical constraints, primarily favouring regions provided with abundant geothermal resources.

The production of heat pump encompasses several critical factors, including the temperature differentials between the heat source and the heat sink, the required heat load, and the overall efficiency of the heat pump system.

In these scenarios mentioned that the heat pump operates for 22 hours per day. A calculation method is employed to determine the energy needed to cover the actual heat demand of the digesters, stemming from preheating and heat loss. Therefore, power required for the heat pump is calculated, and a Mitsubishi ground-source heat pump (GSHP) model EW-HT0182 (14) is considered for this purpose.

2.3.1.2.2 Heat supply by the CHP unit (Scenario 3)

Combined heat and power (CHP), also known as cogeneration, is a technology that uses a single fuel source to simultaneously produce mechanical power, electricity, and/or useful thermal energy for heating and/or cooling, being able to use a variety of fuels, both fossil and renewable-based (15). The main advantages of CHP are its high efficiency (over 80%) and the ability to reduce greenhouse gas emissions and other air pollutants by 40% or more compared to separate heat and grid power generation (16). To calculate the annual heat produced by CHP by Equation 7.

$$Q_{produced\ by\ CHP} = HPE \cdot LHV \cdot BM \quad \text{Equation 7}$$

Where BM $\left(\frac{Nm^3}{y}\right)$ is the biomethane used for the CHP unit, HPE $(\%)$ is the heat production efficiency, as it is a measure of how effectively a CHP system generates and utilizes thermal energy (heat) as part of its energy production process, which is considered 50% (11).

Additionally, the study necessitates the consideration of the low heating value (LHV), expressed in $\left(\frac{kWh}{m^3}\right)$, a critical metric denoting the amount of heat energy produced when a unit volume of biogas undergoes complete combustion, a parameter typically evaluated under standardized conditions. It is important to note that the LHV of biogas can vary based on the feedstock materials and the specific digester employed in its production. In the present context, the LHV of the biogas is derived from the LHV of the biomethane, which are 4.55 $\frac{kWh}{m^3}$ and 9.94 $\frac{kWh}{m^3}$, respectively.

2.3.1.2.3 Heat supply by the wood chips boiler (Scenario 5)

In this scenario, the heat demand is fulfilled by a wood chips boiler operating for 22 hours per day. The optimum operation of heating systems heavily depends on the quality of wood chips used. For optimal performance, wood chips should have a moisture content around 20-30% and be derived from natural, untreated wood. The heating value of wood chips is influenced by factors such as their moisture content, particle size, and the type of wood – hardwood or softwood. Wood chips that contain a higher level of moisture exhibit a reduced heating value, which in turn diminishes the efficiency of boilers (17). Thus, the power required for the boiler is calculated, and a Hargassner boiler model Eco-HK 90 is selected for this purpose (18).

2.3.2 Electricity

The calculation of electricity demand initiates with the determination of the required amount, followed by an evaluation of how this demand is covered in each scenario. In scenario 1, the electricity demand is fulfilled by PV panels and national grid while in scenario 2 it is totally covered by the PV panels. In scenario 3, coverage is provided by the CHP unit, supplemented by any excess obtained from the national grid. In scenario 4, the entire electricity demand is exclusively met by the national grid. Furthermore, in scenario 5, the entire electricity demand is covered by the PV panels.

2.3.2.1 Electricity demand

2.3.2.1.1 Electricity demand of the heat pump (scenario 1, 2 and 4):

An essential factor influencing the overall efficiency of a heat pump is the Coefficient of Performance (COP). This metric serves as an indicator of the system capacity to generate heat or cooling output with respect to the energy input applied, as higher COP values signify heightened efficiency. Heat pumps are known for their impressive coefficient of performance (COP) ratings, and there is vast selection of heat pump models that satisfy to different customer needs and requirements. In scenarios 1, 2 and 4, the utilization of a Mitsubishi heat pump (GSHP) model EW-HT0182 is described by a Coefficient of Performance (COP) value of 4.07 and a total heating capacity of 79.5 (kW) (14).

The quantification of the electricity consumption of the heat pump $E_{GSHP}\left(\frac{MWh_{el}}{y}\right)$ can be achieved dividing the thermal energy production of the heat pump $Q_{GSHP}\left(\frac{MWh_{th}}{y}\right)$ by the COP, as expressed by the following formula:

$$E_{GSHP} = \frac{Q_{GSHP}}{COP}$$ Equation 8

2.3.2.1.2 Electricity demand of the Upgrading plant:

The electricity requirements for the upgrading and compression stages were assessed at 0.3 $\frac{kWh}{Nm^3}$ and 0.4 $\frac{kWh}{Nm^3}$ respectively (11), across all scenarios with designated fractions.

2.3.2.2 Electricity supply

2.3.2.2.1 Electricity supply by PV panels and national grid (Scenario 1)

In scenario 1, the overall electricity requirements of the plant, including the heat pump, upgrading, and compression segments, are covered using PV panels and national grid. The solar panels are responsible for delivering the requisite electrical energy to support the operation of the biomethane production unit. Solar energy technologies encompass a spectrum of applications designed to harness solar radiation for diverse purposes, including but not limited to heating, desalination, and electricity generation. The solar energy technologies fall into two categories: photovoltaics (PV) and concentrating solar-thermal power (CSP). Photovoltaic systems employ solar cells, electronic devices that directly convert sunlight into electricity. As these solar energy technologies continue to advance and enhance their efficiency, they are poised to assume an increasingly substantial role in the global transition to sustainable and clean energy sources, contributing to the realization of a future characterized by environmentally friendly and renewable energy resources (19,20). Several parameters can affect the electric energy generation of PV panels, like geographical location, temperature, materials, intensity of solar radiation, obstacles, shadow, clouds .etc (21).

The SunPower-SPR-MAX6 solar panels, boasting a nominal power rating of 445 (W) with an efficiency of 23.0%, are selected. Each solar panel possesses dimensions of 1.032 (m) and 1.87 (m), effectively occupying a collective area of 1.93 m^2 (22).

Based on using PVGIS tools, installed peak PV power are calculated by Equation 9 (23).

$$P_p = 1\frac{kW}{m^2} \cdot A \cdot (EFF/100) \qquad \text{Equation 9}$$

Where P_p (kW_p) is the peak power, A (m^2) is the area occupied by each panel, and EFF $(-)$ is the efficiency of the panel. Following this, the peak power is determined, and PVGIS is employed to estimate the PV energy output, with July selected as the reference month. Solar photovoltaic (PV) panels are utilized to address 33% of the total electricity demand for this scenario, and 67% are covered by grid networks.

2.3.2.2.2 Electricity supply by just PV panels (Scenario 2):

Like scenario 1, the electricity demand remains the same, encompassing the requirements of both the heat pump and upgrading plant with the same configuration. To estimate the PV energy output, PVGIS also is utilized, with July selected as the reference month. PV panels are employed to meet 100% of the total electricity demand for this scenario.

2.3.2.2.3 Electricity supply by CHP unit (Scenario 3):

The calculation of electrical consumption with the new fraction for the upgrading and compression segment, as noted before, is performed. Moreover, the electricity production by the CHP unit is derived by Equation 10.

$$E_{CHP} = LPE \cdot LHV \cdot BM \qquad \text{Equation 10}$$

Where BM $\left(\frac{Nm^3}{y}\right)$ is the biomethane used for the CHP unit, LPE is the electricity production efficiency set at 40% (9), and the LHV of the biogas to be 4.55 $\frac{kWh}{m^3}$. In this scenario, any additional electricity demand will be met by the Italian national grid.

2.3.2.2.4 Electricity supply by Italian national grid (Scenario 4):

In this scenario, the entirety of the electricity demand for the plant, including the pump, compression, and upgrading processes, are fulfilled by the Italian national grid. This scenario highlights a reliance on the national grid to meet all electrical requirements within the system.

2.3.2.2.5 Electricity supply by PV panels (Scenario 5):

The utilization of wood chips as boiler fuel can result in fluctuations in electricity consumption, attributed to their moisture content and combustion efficiency. Specifically, wood chips with greater moisture content possess a diminished heating value, potentially reducing the efficiency of boilers (17). Consequently, boilers might require an increased amount of electricity to reach the intended heating output when operating with wood chips that have a high moisture content. The variance in wood chip quality can affect their combustion efficiency and overall performance(13). Furthermore, as it was mentioned, the Hargassner wood chips boiler, model Eco-HK 90, considered for the system shows an electrical consumption equal to 300 W (18). The yearly electricity demand of the boiler and the upgrading plant is calculated, and the total electricity demand is met entirely by the PV panels, according to the same model as in the previous scenarios.

2.4 Economic Analysis

2.4.1 Capital Costs

Businesses and organizations use cost analysis as a critical method to assess and comprehend the financial aspects of their operations. It involves the systematic analysis and evaluation of costs, investments, and the distribution of resources. Understanding the financial stability and effectiveness of an organization's operations is the main objective of cost analysis. Businesses are then able to make well-informed decisions, maximize profits, and optimize their spending. Cost analysis assists in evaluating project viability, establishing prices for goods and services, pinpointing areas where cost-cutting strategies can be applied, and improving overall financial sustainability.

The cost analysis in this study focuses on both the capital and operational costs associated with the various involved devices. This examination includes the cost of digester, upgrading plant, heat pump, PV panels, CHP unit, boiler, and electricity covered by the national grid. By study these costs over 20 years, which is lifetime of the plant, we aim to provide a comprehensive understanding of the financial aspects related to each device involved in the energy production process.

2.4.1.1 Digester

In this context, the average capital cost for each digester, encompassing expenses related to its construction, associated equipment, and installation, is set at 24€ per unit of digester volume (11).

2.4.1.2 Upgrading plant

The expected price was set based on reference values by TUW for membrane upgrading systems is 4800 $\frac{€}{m^3/h}$ (11).

2.4.1.3 Heat pump

The correlation represented by Equation 11 has been used to establish the relationship between thermal power and the cost of ground-source heat pumps (24).

$$C_{GSHP} = 2485 \cdot P^{0.6094} \qquad P < 1.7MW \qquad \text{Equation 11}$$

Where P (kW) is the thermal power and C_{GSHP} (€) is the cost of the heat pump. Also, a 20% inflation rate is considered for the heat pump.

2.4.1.4 PV panels

Regarding the purchasing and installation expenses of the photovoltaic (PV) facility, the cost of PV panels is estimated at 750 $\frac{€}{kW}$, and the price of a single-phase inverter (5 kW) is 980 €. The estimated price of installation was 148.58 $\frac{€}{m^2}$, derived from regional pricing lists (24).

2.4.1.5 CHP unit

The cost of CHP systems, also known as cogeneration systems, varies depending on factors such as system size, technology, and application. Therefore, the investment cost of CHP unit is regarded as 1800 $\frac{€}{kW}$ (25).

2.4.1.6 Wood Chips boiler

The cost for implementing a heating solution involving a 150 kW wood chip boiler is estimated at 50,000 € (26), and this expense is allocated for the scenario involving the boiler.

2.4.2 Operational Costs

2.4.2.1 Cost of electricity from grid

The cost of electricity obtained from the Italian national grid has been approximated to be 210 $\frac{€}{MWh}$.

2.4.2.2 Maintenance costs

2.4.2.2.1 Digester

Operational costs for digesters include routine maintenance, monitoring, control, labour, and utilities, including energy expenses for operating pumps, agitators, and other equipment within the digester system. The operational cost for each digester is determined as 3% of the corresponding capital cost (11).

2.4.2.2.2 Upgrading

Upgrading plant operational costs conclude the costs associated with the operation and maintenance of upgrading equipment for refining biogas (e.g., removal of impurities like hydrogen sulphide and carbon dioxide), utilities, labour, and maintenance. The total operational cost for the upgrading plant is considered to be 2% of the capital cost (11).

2.4.2.2.3 Heat Pump

Heat pump operational costs consist of the maintenance, monitoring and controls and costs for any replacement parts or components over the system lifespan. Therefore, a 1% maintenance cost are applied to the cost of the heat pump (27).

2.4.2.2.4 PV panels

Operational costs associated with PV panels include expenses for low maintenance requirements, monitoring, inverter maintenance, and land lease or installation costs. It is important to note that the operational cost of PV panels in this case study typically accounts for 20% of the initial capital cost (24).

2.4.2.2.5 CHP

Operational costs for Combined Heat and Power (CHP) encompass expenses related to maintenance, monitoring and controls, and labour, which is estimated to be 18 $\frac{€}{MWh_{el}}$ (11).

2.4.2.2.6 Wood chips boiler

The operational cost of the wood chips boiler is estimated at 24 $\frac{€}{MWh_{th}}$ (26), which includes the expense of purchasing the wood chips from the market.

2.4.3 Revenues

2.4.3.1 Biomethane sale

The annual revenues are derived from the incentivized feed-in tariff, set at a specific rate of 0.70 $\frac{€}{Nm^3}$ of biomethane production (11).

2.4.3.2 Disposal tariff for organic waste

In costs analysis, a focus will be on the expenditure associated with the procurement of the three feedstocks, namely onion, bread and fish waste. The cost assigned to vegetable waste was assumed to be uniform at a rate of 30 $\frac{€}{ton}$, which counted as the revenue to the system.

2.5 Greenhouse gas (GHG) Analysis

Using biogas instead of fossil fuel offers several environmental and economic benefits. Biogas is produced from the anaerobic digestion of organic materials and can be considered a renewable energy source because these materials can be continually refilled. Also, it is produced from organic waste that would otherwise decompose releasing methane into the atmosphere. By capturing and utilizing this methane, the overall greenhouse gas emissions are reduced.

The complex GHG budget associated with producing biogas and using it to produce power or biomethane depends on several factors. The carbon footprint assessment is conducted, based on the energy needs of the plant, which are the emissions produced by the devices and energy produced and/or taken from the grid, and on the methane losses.

2.5.1 Energy needs of the plant

2.5.1.1 PV plant

In general, any technology of solar PV is able to provide energy with emissions of 35 $\frac{g_{CO_{2eq}}}{kWh}$, except some regional locations.(28)

2.5.1.2 Heat Pump

In terms of heat production, a heat pump can reduce greenhouse gas emissions by 54-66% (11). GHG emission of heat pump powered with electricity from the Italian grid are equal to 63.318 $\frac{g_{CO_{2eq}}}{kWh}$ (26).

2.5.1.3 CHP

CHP was deemed environmentally neutral as the organic materials utilized in the anaerobic digester absorbed CO_2 during their growth. The conversion of this feedstock into biogas through anaerobic digestion includes accounting for methane emissions in the greenhouse gas budget. Consequently, when the biogas is burned for energy production, the emitted CO_2 is regarded as integral to the natural carbon cycle and not an extra emissions source (11).

2.5.1.4 Wood chips boiler

The carbon footprint of wood and its derivatives is contingent upon transport distances and the energy consumed during transformation operations, such as sawing, chipping, and palletization. However, CO_2 emissions from wood combustion are typically regarded as being perfectly compensated by the CO_2 absorbed by trees during their life cycle. Hence, the GHG emission factor for CO_2 from the wood chip boiler is 19 $\frac{g}{kWh}$, or, equivalently, 31.237 $\frac{gCO2eq}{kWh}$.

2.5.1.5 GHG emission from energy produced and/or taken from the grid

In calculating the GHG budget, supplying energy to the grid (in the form of biomethane and electricity) is regarded as a negative contribution, while taking energy from the grid is considered a positive contribution (11). Default emission factors of electricity from the national Italian grid is 337.1 $\frac{g_{CO_{2eq}}}{kWh}$ (29).

2.5.2 GHG emission from methane loss

The operation of the anaerobic digester has climate implications, mainly due to methane losses during the digestion process and emissions from biogas upgrading. Methane losses were transformed into CO_2 equivalent using the global warming power value (GWP = 28, i.e., 1 kg CH_4 = 28 kg $CO_{2,eq}$) (11).

3 Results and Discussion

3.1 Biogas and biomethane Production

As previously mentioned, the cumulative daily inlet wet weight of the mixture feedstock stands at 113 $\frac{ton}{day}$. The calculation derived from employing Equation 2 to Equation 4 gives a daily biogas production of 6,219 $\frac{Nm^3{}_{BG}}{day}$. In scenarios 1, 2, 4 and 5, the total estimated biomethane production, accounting for the methane percentage (%CH4), is 3,789 $\frac{Nm^3{}_{CH_4}}{day}$. Considering methane losses from the digester and from the membrane technology for the upgrading, the actual volume of biomethane produced is determined to be 3,732.9 $\frac{Nm^3}{day}$.

However, in scenario 3, where a portion of the biogas is directed to the upgrading plant (amounting 3,027.48 $\frac{Nm^3}{day}$, the achievable biomethane, factoring in losses from the digester and upgrading, is equivalent to 2,991.76 $\frac{Nm^3}{day}$.

3.2 Energy Consumption

3.2.1 Heat Demand

3.2.1.1 Heat demand for feedstock preheating

By employing Equation 5, the resulting heat demand necessary for preheating the feedstocks within the anaerobic digestion (AD) is presented in Table 3.

Table 3. Heat demand for feedstocks preheating

	Winter	Summer
Seasonal energy for preheating $\left(\frac{MWh}{season}\right)$	217.10	173.68
Yearly energy for preheating $\left(\frac{MWh}{y}\right)$	390.78	

3.2.1.2 Heat losses

By employing Equation 6, the outcome of this calculation supplies the final heat loss values, as presented in Table 4.

Table 4. Heat losses from the digesters

	Winter	Summer
Seasonal energy for heat loss $\left(\frac{MWh}{season}\right)$	153.25	79.02
Yearly energy for heat loss $\left(\frac{MWh}{y}\right)$	232.27	

3.2.1.3 Total heat demand

Table 5 presents an annual summary of the total heat demands, including both the heat needed for preheating and heat loss.

Table 5. Total annual heat demand for feedstocks preheating and heat loss compensation

	Winter	Summer
Seasonal energy demand $\left(\frac{MWh}{season}\right)$	370.35	252.69
Yearly energy demand $\left(\frac{MWh}{y}\right)$	623.05	

The analysis reveals a consistent heat demand of 623.05 $\frac{MWh}{y}$ for the plant across all scenarios. The following sections will elaborate on the available options to fulfil this heat requirement.

3.2.2 Heat Supply Options

3.2.2.1.1 Heat pump

In scenarios 1, 2 and 4, as previously highlighted, the heat pump operates for 22 h/day. A calculation method is employed to determine the energy needed to cover the actual heat demand of the digesters, stemming from preheating and heat loss. Therefore, the power required for the Mitsubishi ground-source heat pump (GSHP) model EW-HT0182 (14) is calculated, with the relevant specifications provided in Table 6.

Table 6. Heat production of heat pump

Power of HP (kW_{th})	77.59
Actual heat production by HP $\left(\frac{MWh_{th}}{y}\right)$	623.05

3.2.2.1.2 CHP unit

Based on the calculation and analysis, 80.15% of the biogas production is allocated for the conversion of biomethane in the upgrading plant, while the remaining 19.85% is directed towards the CHP system. By using Equation 7, the computed heat generated by the CHP system, as well as the plant heat requirements mentioned earlier, are detailed in Table 7.

Table 7. Annual heat balance

Heat demand $\left(\frac{MWh}{y}\right)$	Heat produced by CHP $\left(\frac{MWh}{y}\right)$	Heat balance $\left(\frac{MWh}{y}\right)$
623.05	623.05	0

Through the heat balance between production of CHP and consumption of plant, it was observed that all the heat demand of the plant was effectively met by the heat generated from the CHP system.

3.2.2.1.3 Wood chips boiler

As mentioned before, the yearly heat demand for the plant is calculated at 623.05 ($\frac{MWh}{y}$) and the boiler operates for 22 hours per day, resulting in a required power of 77.6 kW for the boiler. Consequently, a Hargassner wood chips boiler model Eco-HK-90 (18) is selected to meet this installed power requirement of the boiler.

3.2.3 Electricity Demand

3.2.3.1 Heat Pump

As per Equation 8, the calculated annual electrical energy demand for heat pumps in scenarios 1, 2 and 4 remains consistent when utilizing the ground-source heat pump with the specified configuration, as detailed in Table 8.

Table 8. Electricity demand of the heat pump

Heat pump COP (-)	4.07
Annual electricity demand for HP $\left(\frac{MWh_{el}}{y}\right)$	153.08

3.2.3.2 Upgrading plant

Table 9 details the electricity requirements for the upgrading and compression segments for all the scenarios. It's important to note that the heat demand remains constant across all three scenarios, as it is independent of the produced biogas subsequent use, but there is a variation in the electricity demand. Specifically, electricity demand remains the same in scenarios 1, 2, 4 and 5, while in scenario 3, the adjustment in the size of the upgrading plant leads to a corresponding modification in electricity requirements.

Table 9. Electricity demand for upgrading and compression for all scenarios.

	Scenarios 1, 2, 4 and 5	Scenario 3
Electricity demand for upgrading and compression $\left(\frac{MWh_{el}}{y}\right)$	965.1	764.39

3.2.3.3 Wood chips boiler

Electricity demand of the upgrading plant calculated before and electricity required for the boiler according to the catalog of the Hargassner with the mentioned model is 300 W, which makes the annual electricity of the boiler 2.4 $\frac{MWh_{el}}{y}$. The total electricity demand for upgrading and the boiler results in 967.6 $\frac{MWh_{el}}{y}$.

3.2.4 Electricity Supply Options

3.2.4.1 PV plant and grid (scenario 1)

By using Equation 9, the single panel peak power is calculated to be 0.85 kW_p. Subsequently, employing the geographical coordinates of Turin (latitude: 45.188, longitude: 7.646) in the PVGIS tool, the electricity generation from PV panels in July is estimated to be 124.5 $\frac{kWh}{month}$ (23). The assumption is made that the average operating time amounts to six hours per day based on the application. Additionally, only 33% of the required electricity demand is supplied by PV production, with the remainder sourced from the national grid. Consequently, a total of 250 panels are considered necessary to cover this portion of electricity, equating to 373.05 $\frac{MWh}{y}$. Furthermore, each panel has a total area of 1.93 m^2, requiring a total installation area of 482.50 m^2 to accommodate the specified number of PV panels. Furthermore, the surplus electricity amounting to 745.18 $\frac{MWh}{y}$ is supplied by the national Italian grid network to cover the total electricity requirement of the upgrading plant and the heat pump, which totals 1118.23 $\frac{MWh}{y}$.

3.2.4.2 PV plant to cover HP (scenario 2)

To fulfil the total electricity demand of the upgrading plant and the heat pump, amounting to 1118.23 $\frac{MWh}{y}$, a total of 749 panels with the same configuration are employed. Each panel occupies an area of 1.93 m^2, requiring a total installation area of 1445.57 m^2 to accommodate the specified number of PV panels in this case.

3.2.4.3 CHP (scenario 3)

The calculation of electrical demand for the upgrading and compression segment, considering the revised fraction of biogas directed to the CHP (scenario 3), is detailed in Table 10.

Table 10. Annual electricity demand in scenario 3

$E_{upgrading}\ \left(\frac{MWh_{el}}{y}\right)$	327.6
$E_{compression}\ \left(\frac{MWh_{el}}{y}\right)$	436.8
$E_{uprading+compression}\ \left(\frac{MWh_{el}}{y}\right)$	764.39

The electricity output generated by the CHP unit, quantified at 498.44 $\frac{MWh}{y}$, is a crucial outcome derived from the computations outlined in Equation 10, as this electrical energy is responsible for powering various components of the system, ensuring the system functionality. The electricity balance, comparing what the CHP unit produces with what the system needs, is detailed in Table 11. It highlights a shortage of 265.96 $\frac{MWh}{y}$ requiring additional power from the grid network.

Table 11. Electricity balance by production and consumption

$E_{produced\ by\ CHP}\ \left(\frac{MWh_{el}}{y}\right)$	$E_{demand\ used\ for\ plant}\ \left(\frac{MWh_{el}}{y}\right)$	$E_{balance(produced-demand)}\ \left(\frac{MWh_{el}}{y}\right)$
498.44	764.39	-265.96

3.2.4.4 Italian National grid (scenario 4)

In the third scenario, the Italian national grid provides the entire 1118.23 $\frac{MWh}{y}$ needed to cover the electricity demands of both the upgrading plant and the heat pump.

3.2.4.5 PV plant to cover boiler (scenario 5)

The total electricity demand for the upgrading system and the boiler mentioned 967.6 $\frac{MWh}{y}$, which is fully covered by the PV panels. According to the PVGIS tool, the electricity generation from PV panels in July is considered as references, which leads to the 648 panels to cover the demand. Also, in this case each panel occupies an area of 1.93 m^2, requiring a total installation area of 1250.64 m^2 in this scenario.

3.2.5 Comparison and Discussion

When comparing the heat demand analysis, which considers the necessity of feedstock preheating and heat loss compensation, a stable requirement of 623.05 $\frac{MWh_{th}}{y}$ for the plant is evident across all scenarios. This constancy is crucial, indicating no observed variation throughout the different scenarios. In scenarios 1, 2 and 4, the allocation of power requirement remains consistent, with the heat pump handling the power needs, while in Scenario 3 there is the CHP unit, and in Scenario 5 there is the wood chip boiler.

When comparing the electricity demand coverage in different scenarios, notable distinctions are observed. In scenario 1, 33% of the plant electricity demand is met by PV panels, with any excess electricity being supplied by the national grid. In scenarios 2 and 5, 100% of the plant electricity demand is met by PV panels. In scenario 3, although part of the electricity demand being covered by a CHP unit, there is an excess electricity requirement that necessitates direct supplementation from the grid. This contrasts with Scenario 4, where the grid assumes the responsibility for covering the entire electricity demand.

3.3 Economic Analysis

3.3.1 Capital Costs

3.3.1.1 Digester

As previously mentioned regarding the cost of the digester per unit of digester volume, the capital cost for each digester was estimated at 103,107.43 €. This cost remains consistent across all five scenarios due to the digesters identical size.

3.3.1.2 Upgrading plant:

The expected price for the upgrading system with membrane technology is consistent in scenarios 1, 2, 4 and 5, while it slightly differs in Scenario 3, as indicated in Table 12.

Table 12. Capital cost of upgrading plant.

	Scenarios 1, 2, 4, 5	Scenario 3
Cost of membrane upgrading system (€)	746,580.07	598,351.98

3.3.1.3 Heat pump:

The cost of a GSHP determined through Equation 11, and the costs for well construction and inflation are presented in Table 13, which is the same for both scenarios with the heat pump.

Table 13. Heat pump costs

	Scenario 1, 2 and 4
Cost of heat pump (€)	35,234.91
Inflation for HP (€)	7,046.98
Cost of well (€)	100,000

3.3.1.4 PV plant

The comprehensive capital cost of PV panels is detailed in Table 14, providing a comprehensive overview of the financial aspects associated with this component.

Table 14. Capital cost of PV plant and inverter, including the installation

	Scenario 1	Scenario 2	Scenario 5
Cost of PV panels (€)	83,437.50	249,978.75	216,270
Cost of installation of PV panels (€)	71,689.85	214,782.79	185,820.09
Cost of single-phase (5 kW) inverter (€)	980	980	980

3.3.1.5 CHP unit

The capital cost for the Combined Heat and Power (CHP) unit is determined to be 111,729.28 €, specifically applicable only to Scenario 3, which is equipped with the CHP unit.

3.3.2 Operational Costs

3.3.2.1 Cost of electricity from network grid

There is an excess electricity requirement that needs to be covered by the grid in scenarios 1, 3, and 4. In scenario 1, the amount of electricity needed from the grid is 745.18 $\frac{MWh}{y}$, resulting in a cost of 156,486.91 $\frac{€}{y}$. In Scenario 3, there is an excess electricity demand of 265.96 $\frac{MWh}{y}$, resulting in a cost of 55,851.16 $\frac{€}{y}$. Finally, all the electricity needed in scenario 4 is absorbed by the grid, resulting in a total cost of 234,827.72 $\frac{€}{y}$.

3.3.2.2 Maintenance costs

3.3.2.2.1 Digester

The operational cost for each digester in all scenarios is calculated at 3% of the capital cost, resulting in a total of 2,062.15 $\frac{€}{y}$.

3.3.2.2.2 Upgrading plant:

The operational cost of the upgrading plant is calculated as a percentage of the capital cost, as detailed in Table 15.

Table 15. Operational cost of upgrading plant.

	Scenario 1, 2, 4, 5	Scenario 3
Operational cost of upgrading system (€/y)	14,931.60	11,967.04

3.3.2.2.3 Heat pump:

The operational cost for the heat pump remains consistent in Scenarios with the heat pump, scenarios 1, 2, and 4, including inflation and maintenance expenses, totalling 422.82 $\frac{€}{y}$.

3.3.2.2.4 PV plant

The operational cost for the PV panels is determined as 20% of the capital cost. For scenario 1, this translates to 31,221.47 $\frac{€}{y}$, while for scenario 2, it reaches 93,148.31 $\frac{€}{y}$. In scenario 5, the operational cost amounts to 80,614.02 $\frac{€}{y}$.

3.3.2.2.5 CHP unit

The operational cost for the CHP unit, as mentioned earlier, is designated as 8,971.86 $\frac{€}{y}$.

3.3.2.2.6 Wood chips boiler

Given that the operational cost of the wood chips boiler is specified at 24 $\frac{€}{MWh_{th}}$, the total operational cost in this case amounts to 14,953.10 $\frac{€}{y}$.

3.3.3 Revenues

3.3.3.1 Biomethane sale

Based on the prevailing incentives for electricity generation from biogas, the associated costs of electricity, acquired through selling to the grid, are delineated in Table 16.

Table 16. Biomethane sells to the market.

	Scenario 1, 2, 4 and 5	Scenario 3
Cost of biomethane sells to the market (€/y)	953,756.05	764,394.65

3.3.3.2 Disposal tariff for organic waste

The expected cost for the feedstocks was recorded as 30 $\frac{€}{ton}$. The facility utilizes 113 $\frac{\text{ton}}{day}$ of feedstocks, resulting in a total cost for the organic waste equal to1,237,350 $\frac{€}{y}$, which is the same for all scenarios.

Total revenues are derived from each scenario, accounting for disposal tariffs on organic waste and sales of biomethane throughout the plant operational lifespan. Scenarios 1, 2, 4 and 5 generate an equal amount of revenue, totalling 43,822,120.91 € over 20 years, while scenario 3 yields lower revenue due to reduced biomethane sales in the market, accounting for 40,034,892.99 €. This decrease can be attributed to the utilization of the CHP unit, which consumes a portion of the produced biogas.

3.3.4 Comparison and Discussion

Figure 20 provides a summary of each device considered in the project for all three scenarios, facilitating the calculation of the Capital and Operating (C&O) costs.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Digester	✓	✓	✓	✓	✓
Upgrading plant	✓	✓	✓	✓	✓
Heat pump	✓	✗	✗	✓	✗
PV panel	✓	✓	✗	✗	✓
CHP	✗	✗	✓	✗	✗
Boiler	✗	✗	✗	✗	✓
Electricity from the grid	✓	✗	✗	✓	✗

Figure 20. Components in the five scenarios.

Figure 21 illustrates the comparison of capital costs across the five different scenarios. It is notable that scenario 2 exhibits the highest capital cost primarily due to the number of panels, followed by scenario 5. Conversely, scenario 3 demonstrates the lowest capital cost, attributed to the relatively lower expense of the CHP unit compared to the others. Notably, the highest share of the capital cost is attributable to expenses related to the upgrading plant in all scenarios.

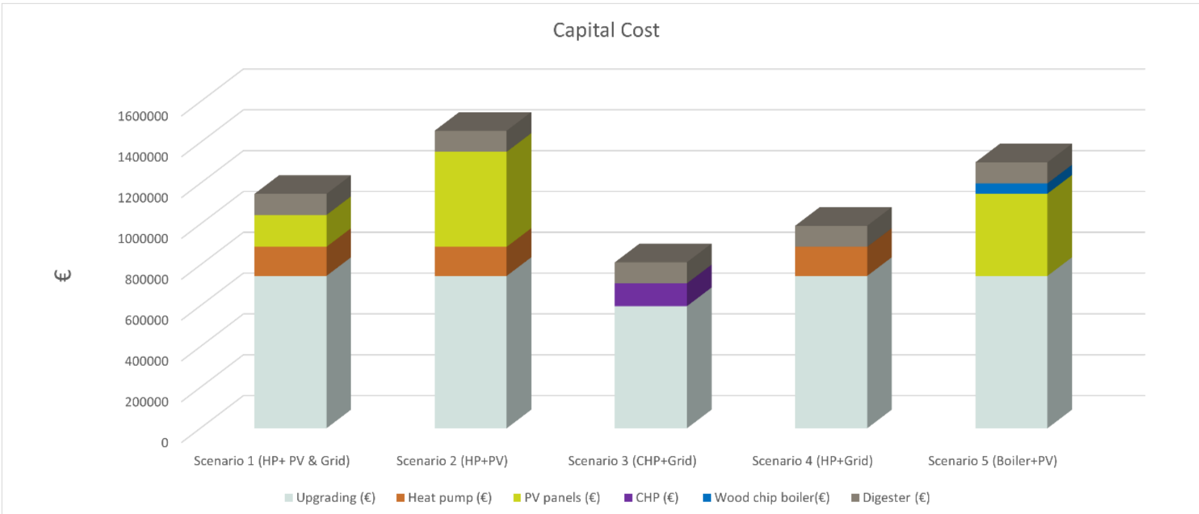

Figure 21. Capital costs for the five scenarios.

Figure 22 presents a comparison of the operational costs among the five different scenarios over the 20-year lifetime of the plant. It is evident that scenario 4 has the highest operational cost, due to the fact that the total electricity demand of the system is covered by the grid, which results in the highest cost. In scenario 1, the operational cost ranks second, attributed to the utilization of PV panels instead of directly sourcing electricity from the grid. In contrast, scenario 3 mainly relies on the CHP to fulfil the electricity demand, with only surplus electricity being sourced from the national grid, resulting in the lowest overall cost among the scenarios.

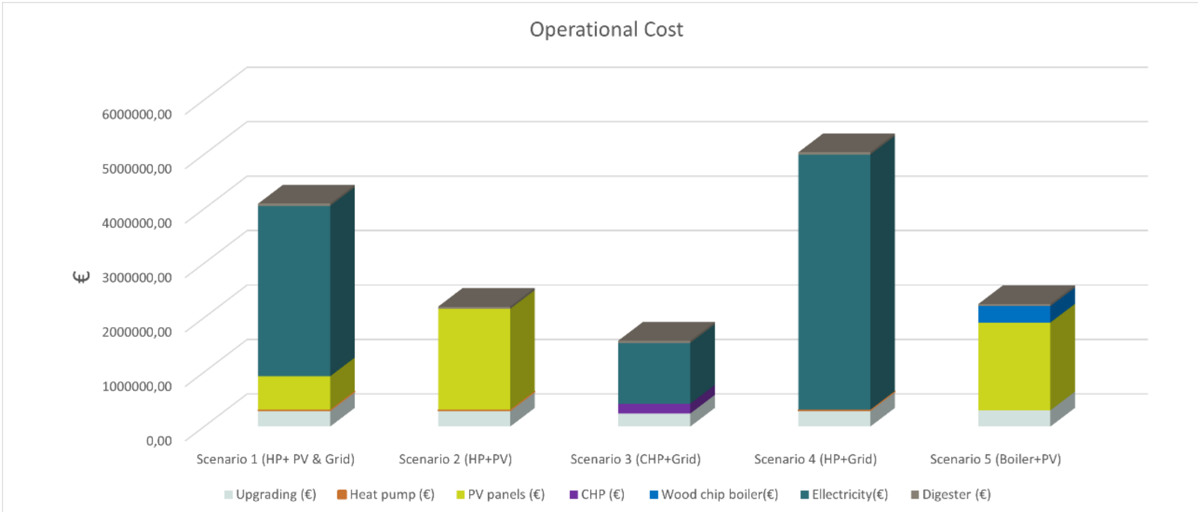

Figure 22. Operational cost of all scenarios.

Over the 20-year lifetime of the plant, calculations were conducted to assess the financial implications, which are mentioned in Figure 23. The study found that biomethane sales generate high income, but there are also considerable costs to consider.

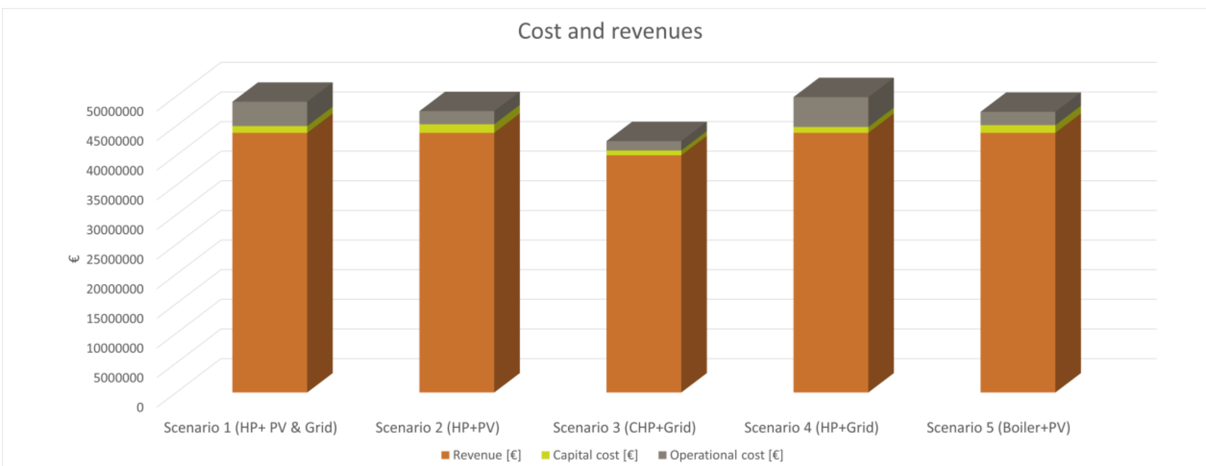

Figure 23. Capital cost, Operational cost, and Revenue for all scenarios.

In this section, a sensitivity analysis was conducted to assess the cost of biomethane by varying the cost of electricity from the grid across all scenarios. Sensitivity analysis plays a crucial role in discerning the inputs that notably impact the output, thereby offering insights into the model's robustness and informing decision-making processes. Its objectives encompass assessing the model resilience to uncertainty, enhancing comprehension of input-output relationships, minimizing output uncertainty by pinpointing key inputs, and guiding decision-making by identifying areas where additional precision or information could be advantageous.

The assumption in this study was that all elements remained fixed except for the cost of electricity from the grid. This includes the operational cost, which were calculated over a 20-year period for all five scenarios and were considered constant except for the electricity. The range of the cost of electricity was considered from 110 to 310 (€/MWh) with intervals of 20. Then, the ratio of the total cost of electricity from the grid over 20 years (€) to the Biomethane production over 20 years (Nm3) was calculated, and the results are presented in Figure 24.

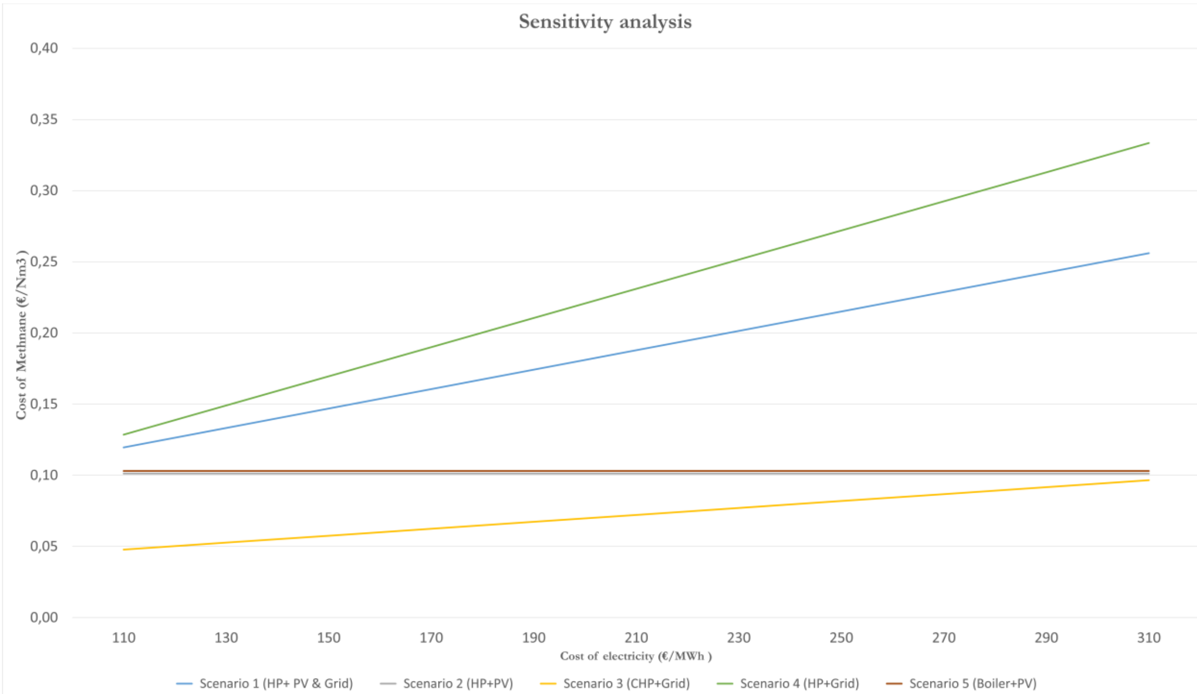

Figure 24 Sensitivity analysis focused on the cost of electricity across all scenarios.

The graph indicates that Scenario 3 is the most favourable, it utilizes the CHP unit with a lower cost itself. However, a small portion of the electricity demand in scenario 3 is still dependent on the cost of the grid network.

In Scenarios 2 and 5, there is no dependency on the grid at all, as evidenced by the straight line. Scenarios 1 and 4 are the most resilient to changes in the cost of electricity. In Scenario 1, 67% of the electricity demand is covered by the grid, while in Scenario 4, 100% of the electricity is sourced from the national grid.

To conclude, scenario 3 emerges as the most cost-effective option with some grid dependence, while Scenarios 1 and 4 demonstrate high resilience to electricity cost changes, differing in their grid reliance (67% and 100%, respectively).

3.4 Greenhouse gas (GHG) Analysis

3.4.1 Scenario 1

In this scenario, greenhouse gas (GHG) emissions arise from PV panels, the heat pump, electricity from the grid and, notably, methane loss from the digester and upgrading plant, which is mentioned in Table 17.

Table 17 GHG emissions of the scenario 1

	Scenario 1 (HP +PV & Grid)
GHG emission from PV panels ($\frac{t_{CO_{2eq}}}{y}$)	13.05
GHG emission from heat pump ($\frac{t_{CO_{2eq}}}{y}$)	39.45
GHG emission from methane losses of digester and upgrading ($\frac{t_{CO_{2eq}}}{y}$)	375.62
GHG emission from buying electricity from the grid ($\frac{t_{CO_{2eq}}}{y}$)	251.20

The total greenhouse gas (GHG) emissions for scenario 1 comprise all previously mentioned factors, totaling 679.32 ($\frac{t_{CO_{2eq}}}{y}$).

3.4.2 Scenario 2

In this scenario, greenhouse gas (GHG) emissions are equivalent to those in scenario 1, except for the emissions related to the PV panels, which are higher due to the installation of additional panels in this section. Additionally, there is no electricity coverage from the grid in this scenario, which is mentioned in Table 18.

Table 18 GHG emissions of the scenario 2

	Scenario 2 (HP + PV)
GHG emission from PV panels ($\frac{t_{CO_{2eq}}}{y}$)	39.13
GHG emission from heat pump ($\frac{t_{CO_{2eq}}}{y}$)	39.45
GHG emission from methane losses of digester and upgrading ($\frac{t_{CO_{2eq}}}{y}$)	375.62

The total greenhouse gas (GHG) emissions for scenario 2, considering methane loss, 749 panels, and a heat pump, amount to 454.20 ($\frac{t_{CO_{2eq}}}{y}$).

3.4.3 Scenario 3

GHG emissions in the second scenario originate from the CHP unit, methane loss from the digester and upgrading plant (a significant portion), and the purchase of electricity from the grid, which is mentioned in Table 19.

Table 19 GHG emissions of the Scenario 3

	Scenario 3 (CHP+GRID)
GHG emission from CHP ($\frac{t_{CO_{2eq}}}{y}$)	0
GHG emission from buying electricity from the grid ($\frac{t_{CO_{2eq}}}{y}$)	89.65
GHG emission from methane losses of digester and upgrading ($\frac{t_{CO_{2eq}}}{y}$)	316.19

The total greenhouse gas (GHG) emissions for Scenario 3, considering all mentioned factors, amount to 405.85 ($\frac{t_{CO_{2eq}}}{y}$).

3.4.4 Scenario 4

The GHG emissions in this scenario arise from the heat pump, digester and upgrading plant's methane loss, and the acquisition of electricity from the grid, which is shown in Table 20.

Table 20 GHG emissions of the Scenario 4

	Scenario 4 (HP + GRID)
GHG emission from heat pump ($\frac{t_{CO_{2eq}}}{y}$)	39.45
GHG emission from buying electricity from the grid ($\frac{t_{CO_{2eq}}}{y}$)	376.95
GHG emission from methane losses of digester and upgrading ($\frac{t_{CO_{2eq}}}{y}$)	375.62

The cumulative greenhouse gas (GHG) emissions for Scenario 4, considering all specified elements, total 792.02 ($\frac{t_{CO_{2eq}}}{y}$).

3.4.5 Scenario 5

The GHG emissions in this scenario arise from the wood chips boiler and the methane loss from upgrading and digester, which is mentioned in Table 21.

Table 21. GHG emissions in scenario 5

	Scenario (Boiler + PV)
GHG emission from PV panels ($\frac{t_{CO_{2eq}}}{y}$)	33.86
GHG emission from wood chips boiler ($\frac{t_{CO_{2eq}}}{y}$)	19.46
GHG emission from methane losses of digester and upgrading ($\frac{t_{CO_{2eq}}}{y}$)	375.62

The cumulative greenhouse gas (GHG) emissions for this Scenario amount to 428.94 ($\frac{t_{CO_{2eq}}}{y}$).

3.4.6 Comparison and Discussion

Understanding the environmental impact of the anaerobic digester operation is crucial, particularly concerning methane losses during digestion and upgrading, as well as electricity sourced from the grid. This analysis provides insights into its climate implications. The analysis aimed to explain the environmental impact associated with different energy utilization strategies, providing insights on the potential contributions to reducing GHG emissions through the integration of renewable energy technologies.

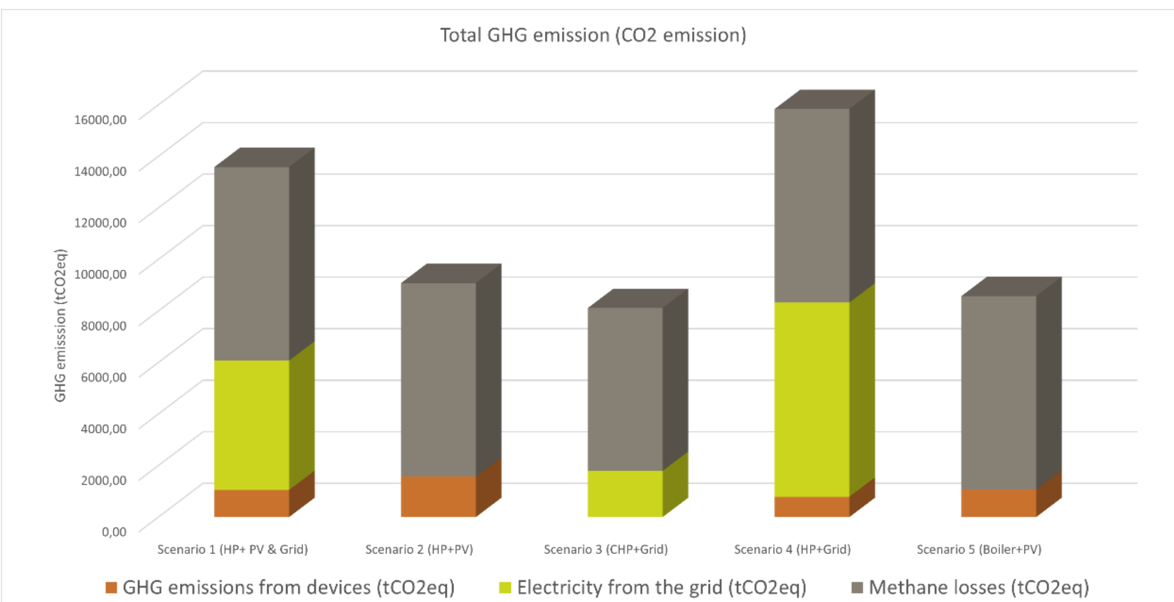

Figure 25 Comparative of GHG Emissions for all scenarios [tCO2eq]

In Figure 25, assessing greenhouse gas (GHG) emissions over 20 years across different scenarios reveals that Scenario 4 stands out with the highest emissions. This outcome can be attributed to its heavy dependence on grid electricity and the consequential methane loss.

Moreover, Scenarios 3 and 5 exhibit lower emissions compared to other scenarios. This is attributed to the efficient utilization of the combined heat and power (CHP) unit in Scenario 3, resulting in reduced methane loss and grid electricity consumption. Additionally, the utilization of a wood chips boiler and PV panels in Scenario 5 contributes to decreased total GHG emissions. Notably, PV panels play a crucial role in mitigating emissions, thereby facilitating the reduction outlined in scenarios featuring PV panel equipment. Overall, the comparison indicates that Scenarios 3 and 5 have the lowest GHG emissions, while Scenario 4 exhibits the highest emissions.

A sensitivity analysis was also conducted to evaluate the greenhouse gas (GHG) emissions resulting from the volume of produced biomethane by altering the GHG emissions associated with electricity from the grid.

The assumption made in this section involves varying the CO2 emissions from the electricity sourced from the grid to observe the resulting output. In this case, the factors affecting emissions include emissions from the devices, methane loss, and electricity from the grid. CO2 emissions from the devices and methane loss over 20 years are calculated and treated as fixed elements. The emissions due to electricity are then calculated within a range from 50 to 600 (gCO2/kWh) with intervals of 50. Subsequently, the ratio of the total emissions produced from the electricity from the grid over 20 years (gCO2) to the Biomethane production over 20 years (Nm3) is computed, and the results are depicted in Figure 26.

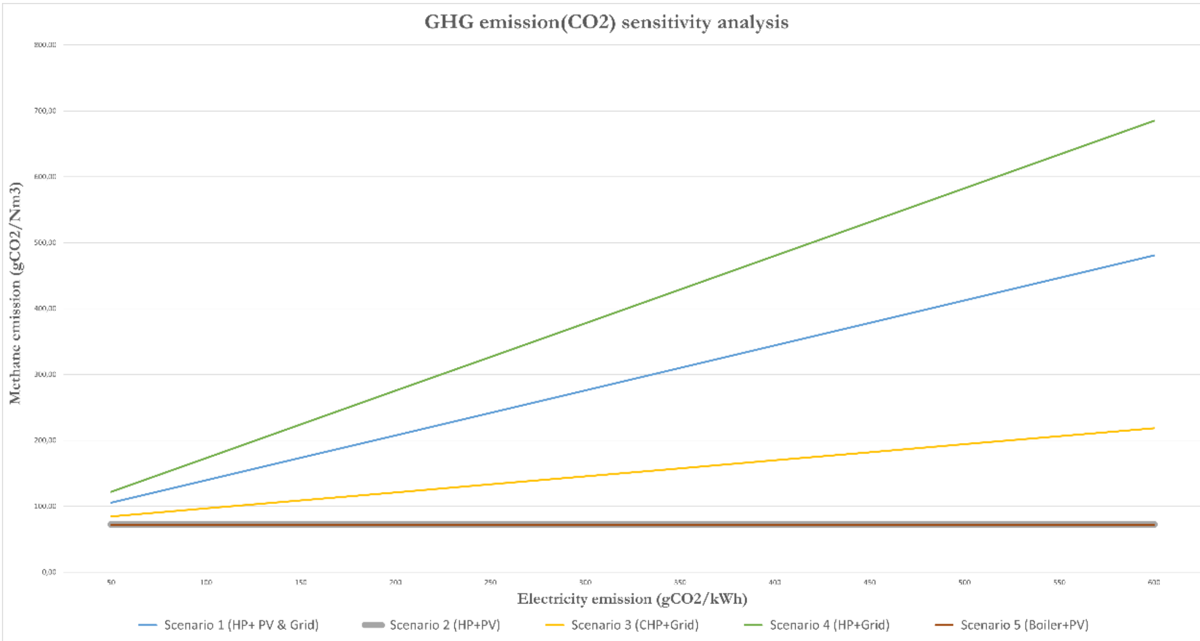

Figure 26 Sensitivity analysis considering the CO2 emissions attributed to electricity sourced from the grid across all scenarios.

The graph illustrates that scenarios 5 and 2 demonstrate no reliance on the grid network as their electricity needs are entirely met by PV panels, resulting in lower CO2 emissions from both devices and methane loss. On the other hand, scenarios 3 and 1 indicate a reduced impact of emissions from the electricity grid owing to their decreased reliance on it. Conversely, scenario 4 heavily relies on the Italian national grid, resulting in the highest impact on grid emissions as it is fully dependent on it.

4 Conclusions

In conclusion, this thesis has systematically explored the integration of renewable energy technologies in biomethane production, emphasizing both economic viability and environmental sustainability. Through the examination of five distinct scenarios, it has become evident that renewable integration not only enhances the operational efficiency of biomethane plants but also significantly contributes to the reduction of greenhouse gas emissions, aligning with global sustainability targets.

The economic analysis revealed that scenarios incorporating photovoltaic (PV) panels, particularly when fully satisfying the plant's electricity demand, present a promising pathway towards financial viability, despite the higher initial capital costs. These scenarios underscore the potential for renewables to lower operational expenses, mainly due to reduced reliance on grid electricity and the utilization of solar energy, which is abundant and free.

Environmental assessment outcomes demonstrated the substantial benefits of integrating renewable energy sources in mitigating greenhouse gas emissions. Specifically, scenarios using the combined heat and power (CHP) unit and wood chips boiler, alongside PV panels, exhibited the lowest GHG emissions. These findings highlight the critical role of renewable energy technologies in achieving a more sustainable biomethane production process, significantly contributing to climate change mitigation efforts.

However, it is crucial to acknowledge the limitations encountered in this study, including the variability in renewable energy production and its impact on the plant's operational stability. Future research should, therefore, focus on exploring innovative solutions to enhance the resilience and reliability of renewable energy integration in biomethane production. This could include the development of advanced energy storage systems, the implementation of smart grid technologies, and the investigation of hybrid renewable energy systems to ensure a consistent and reliable energy supply.

Moreover, further studies could explore the potential for integrating emerging renewable energy technologies and assessing their economic and environmental impacts in biomethane production. This would not only broaden the scope of renewable energy applications but also contribute to the continuous improvement of sustainability standards in the energy sector.

Abbreviations

AD	Anaerobic Digestion
HP	Heat Pump
GSHP	Ground Source Heat Pump
CHP	Combined Heat and Power
PV	Photovoltaic
COP	Coefficient Of Performance
GHG	Green House Gas
CSP	Concentrating Solar-thermal Power
GWP	Global Warming Power value
BG	Biogas
EU	European Union
CO2	Carbon Dioxide
CH4	Methane

References

1. Sludge Processing [Internet]. 2020 [cited 2024 Jan 29]. Sludge treatment − how does anaerobic digestion work? Available from: https://www.sludgeprocessing.com/anaerobic-digestion/how-does-anaerobic-digestion-work/

2. Angelidaki I, Treu L, Tsapekos P, Luo G, Campanaro S, Wenzel H, et al. Biogas upgrading and utilization: Current status and perspectives. Biotechnology Advances. 2018 Mar;36(2):452–66.

3. Statista [Internet]. [cited 2024 Feb 2]. Global production of biogas. Available from: https://www.statista.com/statistics/481791/biogas-production-worldwide/

4. Statista [Internet]. [cited 2024 Feb 2]. Global biogas market value by region 2022-2030. Available from: https://www.statista.com/statistics/1405237/biogas-market-value-worldwide-forecast-by-region/

5. GfC_national-biomethane-potentials_070722.pdf [Internet]. [cited 2024 Feb 2]. Available from: https://www.europeanbiogas.eu/wp-content/uploads/2022/07/GfC_national-biomethane-potentials_070722.pdf

6. Outlook_for_biogas_and_biomethane.pdf [Internet]. [cited 2024 Jan 30]. Available from: https://iea.blob.core.windows.net/assets/03aeb10c-c38c-4d10-bcec-de92e9ab815f/Outlook_for_biogas_and_biomethane.pdf

7. Statista [Internet]. [cited 2024 Feb 2]. Planned investments in biogas from waste in Italy in 2008-2030. Available from: https://www.statista.com/statistics/804902/planned-investments-in-biogas-from-waste-in-italy/

8. Schnaars K. What every operator should know about anaerobic digestion.

9. Engineering LibreTexts [Internet]. 2021 [cited 2023 Oct 21]. 1.2: Biogas Energy from Organic Wastes. Available from: https://eng.libretexts.org/Bookshelves/Biological_Engineering/Introduction_to_Biosystems_Engineering_(Holden_et_al.)/01%3A_Energy_Systems/1.02%3A_Biogas_Energy_from_Organic_Wastes

10. xedig,+Krou_etal_2021_1.pdf.

11. Casasso A, Puleo M, Panepinto D, Zanetti M. Economic Viability and Greenhouse Gas (GHG) Budget of the Biomethane Retrofit of Manure-Operated Biogas Plants: A Case Study from Piedmont, Italy. Sustainability. 2021 Jul 16;13(14):7979.

12. Sun Q, Li H, Yan J, Liu L, Yu Z, Yu X. Selection of appropriate biogas upgrading technology-a review of biogas cleaning, upgrading and utilisation. Renewable and Sustainable Energy Reviews. 2015 Nov;51:521–32.

13. The Pros and Cons of Wood Chips or Wood Pellets for Biomass Boilers [Internet]. [cited 2024 Feb 18]. Available from: https://www.jlphillips.co.uk/wood-chips-vs-wood-pellets-biomass/

14. data-book_ew-ht-0152-0612.pdf [Internet]. [cited 2023 Oct 27]. Available from: https://confort.mitsubishielectric.fr/entreprise/sites/default/files/2022-03/data-book_ew-ht-0152-0612.pdf

15. Energy.gov [Internet]. [cited 2023 Oct 22]. Combined Heat and Power Basics. Available from: https://www.energy.gov/eere/iedo/combined-heat-and-power-basics

16. US EPA O. What Is CHP? [Internet]. 2015 [cited 2023 Oct 22]. Available from: https://www.epa.gov/chp/what-chp

17. Bošnjaković M, Soldan C, Veljić N. INFLUENCE OF MOISTURE CONTENT IN WOOD CHIPS ON THE BOILER OPERATION. In 2020.

18. HargassnerBoilerBrochure.pdf [Internet]. [cited 2024 Feb 16]. Available from: https://irp.cdn-website.com/91bc4263/files/uploaded/HargassnerBoilerBrochure.pdf

19. Solar energy [Internet]. [cited 2023 Oct 22]. Available from: https://www.irena.org/Energy-Transition/Technology/Solar-energy

20. Energy.gov [Internet]. [cited 2023 Oct 22]. How Does Solar Work? Available from: https://www.energy.gov/eere/solar/how-does-solar-work

21. Rahman MM, Hasanuzzaman M, Rahim NA. Effects of various parameters on PV-module power and efficiency. Energy Conversion and Management. 2015 Oct;103:348–58.

22. sp_max6_66c_res_e4_ac_ds_en_a4_546816.pdf [Internet]. [cited 2024 Feb 6]. Available from: https://sunpower.maxeon.com/int/sites/default/files/2023-03/sp_max6_66c_res_e4_ac_ds_en_a4_546816.pdf

23. JRC Photovoltaic Geographical Information System (PVGIS) - European Commission [Internet]. [cited 2024 Feb 6]. Available from: https://re.jrc.ec.europa.eu/pvg_tools/en/

24. Ruffino E, Piga B, Casasso A, Sethi R. Heat Pumps, Wood Biomass and Fossil Fuel Solutions in the Renovation of Buildings: A Techno-Economic Analysis Applied to Piedmont Region (NW Italy). Energies. 2022 Mar 24;15(7):2375.

25. Campanari S. La cogenerazione : tecnologie, mercato, incentivi.

26. Casasso A, Capodaglio P, Simonetto F, Sethi R. Environmental and Economic Benefits from the Phase-out of Residential Oil Heating: A Study from the Aosta Valley Region (Italy). Sustainability. 2019 Jul 2;11(13):3633.

27. Lu Z, Ziviani D. Operating cost comparison of state-of-the-art heat pumps in residential buildings across the United States. Energy and Buildings. 2022 Dec;277:112553.

28. Gibon T, Menacho ÁH, Guiton M. 8 1Luxembourg Institute of Science and Technology (LIST). 2021;

29. Ravina M, Castellana C, Panepinto D, Zanetti MC. MCBioCH4: A computational model for biogas and biomethane evaluation. Journal of Cleaner Production. 2019 Aug;227:739–47.