Politecnico di Torino

MASTER THESIS
Agritech Engineering
A.Y. 2024/2025

Reconversion to Biomethane of an Agricultural Biomass Plant:

The case of “La Falchetta”

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Index

Abstract

This thesis explores the production of biogas from agricultural biomass and the strategic conversion of existing biogas plants to biomethane facilities, within the broader context of the energy transition and circular economy. It provides a comprehensive overview of the Italian agricultural biogas sector, with an emphasis on policy frameworks, regulatory incentives, and the role of the public authority Gestore dei Servizi Energetici (GSE). The core of the work focuses on the case study of the "La Falchetta" plant, originally designed for electricity generation through anaerobic digestion and currently undergoing reconversion to produce biomethane suitable for injection into the distribution gas grid.

The thesis details the technological, biochemical, and microbiological aspects of the anaerobic digestion process, as well as the characteristics of input biomass and process parameters. It also examines the main upgrading technologies for biogas, with a focus on the membrane separation system adopted at "La Falchetta". A thorough technical, environmental, and economic analysis of the reconversion project is presented, highlighting key performance indicators such as energy efficiency, capital and operational expenditures, and CO_2 emissions reduction.

Finally, future development opportunities are discussed, including the integration of biochar into the digestion process and carbon dioxide valorisation strategies. The results confirm the feasibility and sustainability of converting agricultural biogas plants to biomethane production, positioning this transition as a key enabler of climate targets and rural economic resilience.

1. Introduction

The production of agricultural biogas is an integral part of the energy transition and enables the use of agricultural residues, manure, and slurry to produce green energy. This process not only generates renewable energy but also produces digestate as a byproduct, an organic fertilizer rich in essential nutrients.

Between 2008 and 2013, Italy experienced significant growth in agricultural biogas plants, driven by an incentivizing policy particularly favourable to electricity production from renewable sources. These plants benefited from a 15-year incentive system for electricity generation, making the initial investment financially sustainable. However, with the natural expiration of the incentivized period for many of these plants, there is now a crossroads: continue producing electricity without incentives, selling it at market price or accessing the minimum guaranteed price mechanism offered by the GSE, or convert the existing plants from electricity production to biomethane production.

Since the sale of electricity at market price is often insufficient to cover operating and maintenance costs, and the Minimum Guaranteed Price mechanism, which provides a fixed price for energy fed into the grid and is indexed annually, does not ensure significant margins and fails to incentivize efficiency or plant modernization, the conversion of existing plants from electricity production to biomethane production is emerging as a strategic alternative solution.

Unlike biogas, which is primarily used in cogeneration for on-site electricity and heat production, biomethane is a flexible energy carrier with a quality comparable or higher than natural gas, suitable for use in various sectors. Most notably, it can be used in transportation as a renewable fuel or directly injected into the gas network. This versatility, combined with the net reduction in CO_2 emissions and the valorisation of agricultural byproducts, makes biomethane a strategic tool for decarbonization, actively contributing to the energy transition and national energy security.

A representative example of this transition is the "La Falchetta" plant, which has been selected for in-depth analysis in this study, this plant was designed for the production and valorisation of biogas from various agricultural products and byproducts, and it began operations in 2011 with an installed electrical power capacity of 625 kWe. As the incentive period approached its expiration, the plant was acquired by Asja Group, which is now overseeing its conversion to biomethane production, with a production capacity of 300 Sm^3/h. The biomethane will be injected into the national distribution grid and will be allocated for uses other than the transportation sector. The digestate produced will be sent to a separation unit, from which a liquid fraction and a solid fraction will be obtained. Both fractions will be stored and used for land application in agriculture.

2. Biogas production from agricultural biomass

Agriculture plays a pivotal role in the bioenergy sector, providing a renewable source of energy through the transformation of organic residual material. Moreover, the sector also faces the challenge of managing the big amount of residual material produced, which demands significant financial and energy resources for disposal. This issue presents a unique opportunity for the adoption of sustainable practices that not only address management of the farm but also contribute to the global shift towards a circular economy.

By biologically treating agricultural by-products, such as manure, slurry and crop residues, farmers can unlock the potential of residual material valorisation, producing biogas and digestate. This process generates significant economic value by reducing disposal costs and creating valuable by-products. Biogas, which is a renewable gas mainly composed of carbon dioxide and methane, can be used for self-consumption or sold, providing farmers with a new revenue stream. Furthermore, digestate serves as an alternative to mineral fertilizers, offering both cost savings and reducing the reliance on chemical inputs.

From a broader ecological perspective, the adoption of biogas production offers substantial environmental benefits. By replacing fossil fuels with biogas, greenhouse gas emissions are reduced, contributing to global climate goals. Additionally, the use of digestate in agriculture decreases the environmental impact of traditional fertilizers, promoting more sustainable farming practices. In this way, the valorisation of agricultural waste not only provides economic advantages to farmers but also supports the global transition to a more sustainable and circular agricultural system.

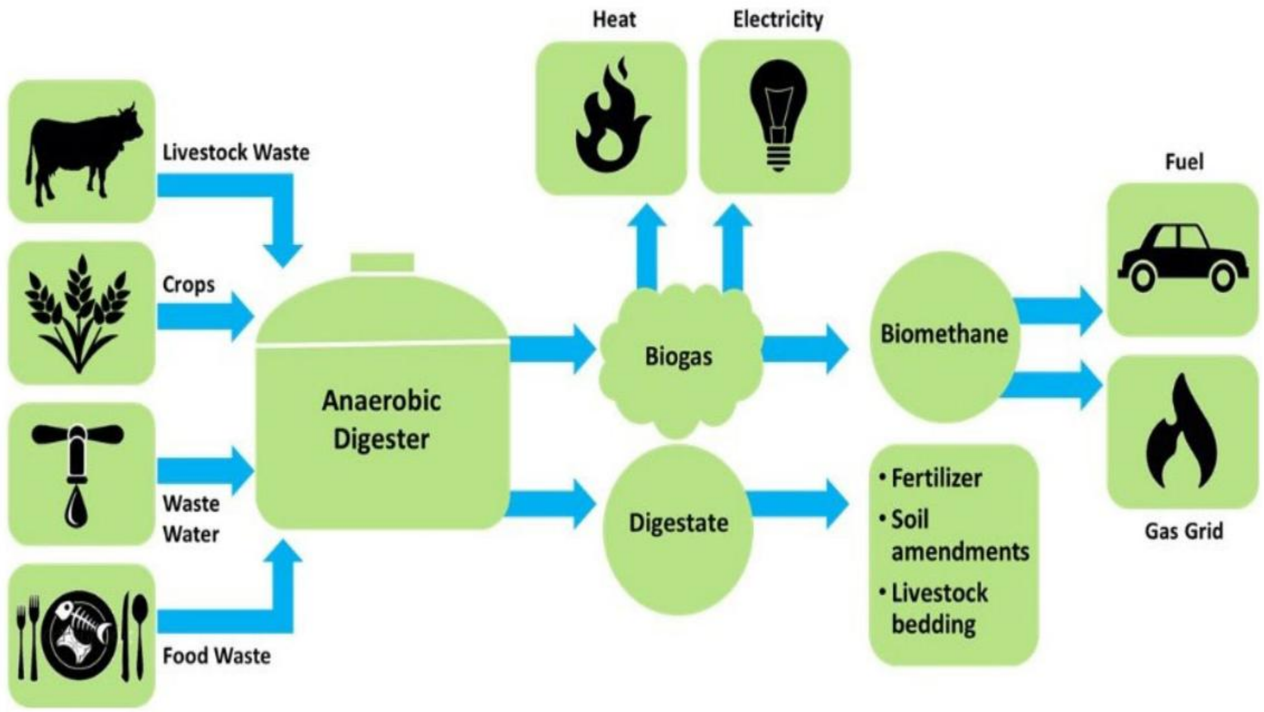

Figure 1 - Anaerobic digestion process flow chart. (1)

2.1. Biogas in Italy

Italy is a country that faces significant challenges in terms of fossil fuel availability, which has historically made it dependent on imports for its energy needs. However, it is strategically located in a climate zone that is highly favourable for the production of energy from renewable sources. This advantageous geographical position, coupled with increasing global concerns about climate change and sustainability, has propelled Italy to invest in renewable energy technologies, including bioenergy. Over the past 15 years, the number of plants powered by bioenergy in Italy has expanded impressively, with a particularly notable surge between 2008 and 2013, a period that saw the country embrace renewable energy on an unprecedented scale.

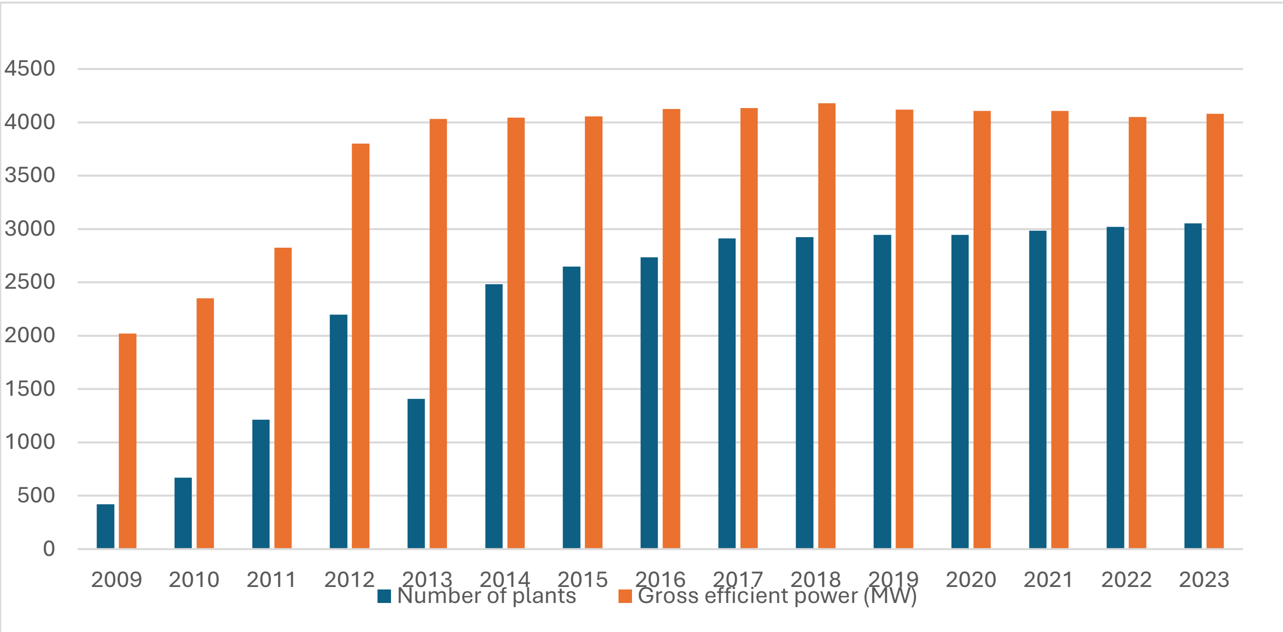

Figure 2 - Number and power of plants powered by bioenergy in operation in Italy. Years 2009-2023. (2)

In particular, the regions of the Po Plane have emerged as the leading areas in terms of both the number of bioenergy plants and the installed electrical capacity. This distribution mirrors the broader geographical concentration of agricultural and livestock activities in the country. The Po Valley, known for its intensive agricultural practices and robust livestock farming, is home to a significant share of Italy's organic biomass resources, which form the basis for biogas production. This region's combination of abundant agricultural byproducts, such as crop residues and animal waste, and favourable climatic conditions creates a unique synergy for the development of bioenergy plants.

Figure 3 - Number and power of bioenergy powered plants by region, own elaboration based on (2).

The expansion of biogas plants in Italy has been greatly supported by a combination of regulatory incentives and financial mechanisms aimed at encouraging the transition to renewable energy.

Biogas production in Italy has gained considerable momentum since the early 2000s, driven by the increasing awareness of the environmental benefits of renewable energy sources and the need to reduce the country's reliance on imported fossil fuels. This trend of growth, while notable in the biogas sector, has also extended to other renewable energy sources, including wind, solar, and hydroelectric power, further reducing the use of natural gas and other fossil fuels. The integration of these renewable sources into Italy's energy mix has not only contributed to energy diversification but also improved energy security, reducing vulnerability to fluctuations in global energy markets.

In recent years, the contribution of biomass energy has strengthened its position within Italy's energy portfolio. Biomass energy now plays a critical role in generating both electricity and thermal energy, with biogas being increasingly used in combined heat and power (CHP) plants. The growing use of biogas has also contributed to Italy's efforts to meet its climate goals by reducing greenhouse gas emissions. The substitution of fossil fuels with biogas helps to significantly lower carbon emissions, making biogas an essential component of Italy's strategy for achieving carbon neutrality by mid-century.

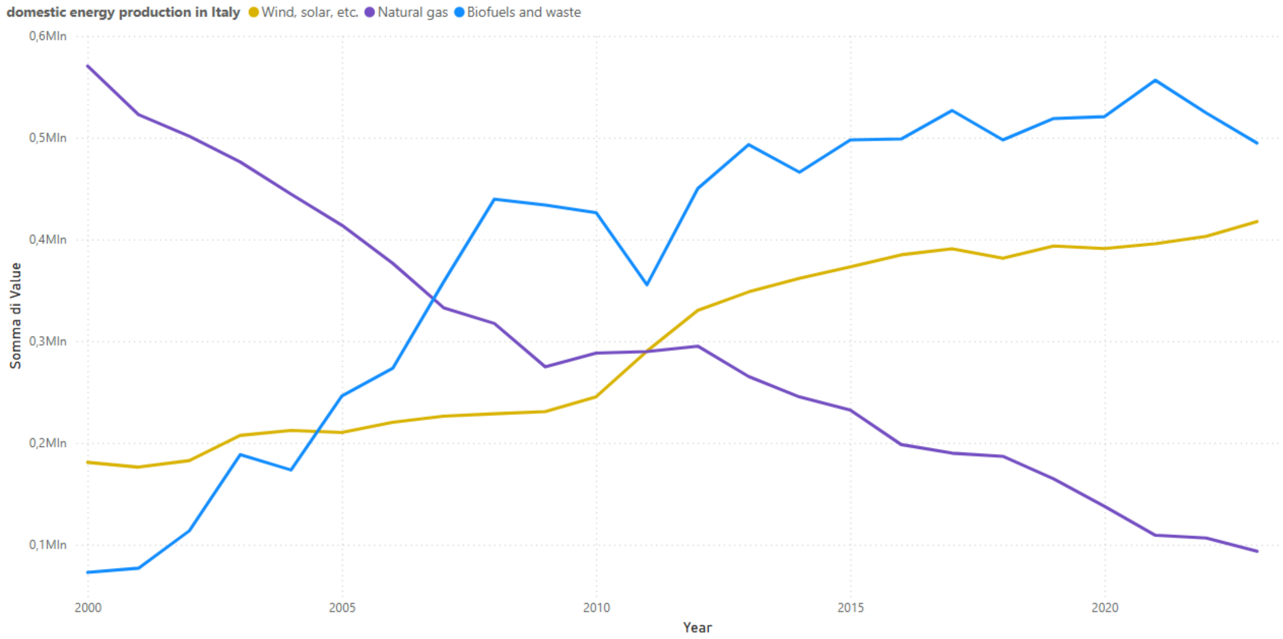

Figure 4 - Evolution of domestic energy production in Italy since 2000, own elaboration based on (3).

In recent years, the contribution of biomass energy has strengthened its position within Italy's energy portfolio. Biomass energy now plays a critical role in generating both electricity and thermal energy, with biogas being increasingly used in combined heat and power (CHP) plants. The growing use of biogas has also contributed to Italy's efforts to meet its climate goals by reducing greenhouse gas emissions. The substitution of fossil fuels with biogas helps to significantly lower carbon emissions, making biogas an essential component of Italy's strategy for achieving carbon neutrality by mid-century.

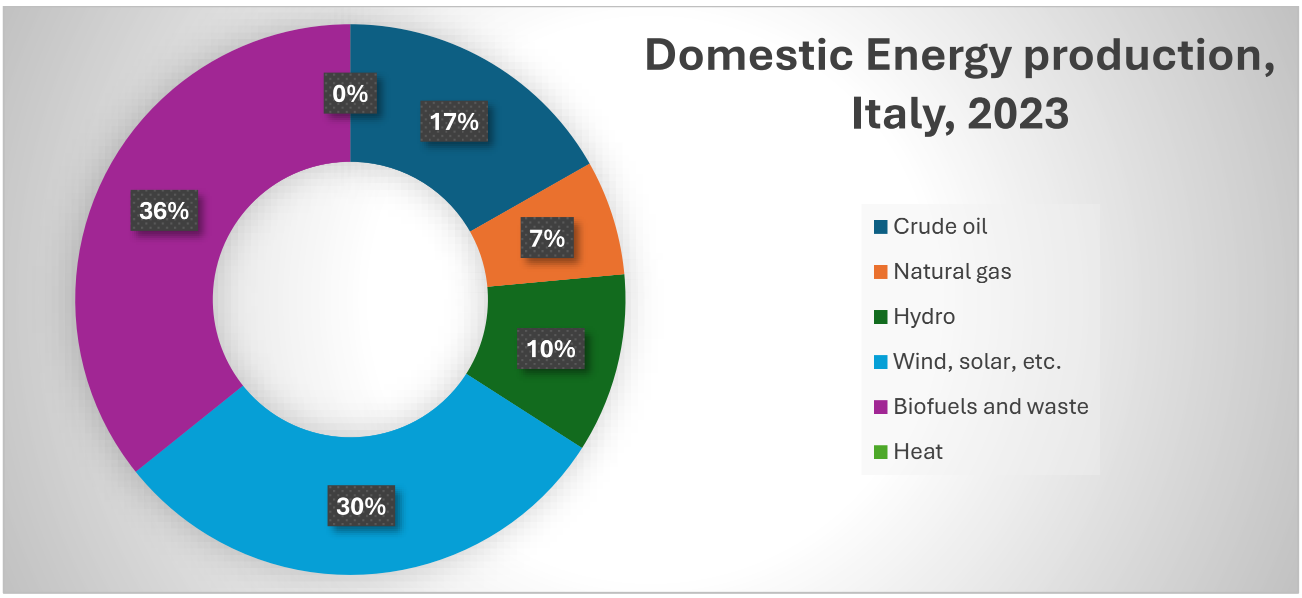

Figure 5 - Domestic energy production in Italy, 2023. (3)

2.1.1. GSE

To promote renewable energy sources, the Gestore dei Servizi Energetici (GSE) was established under Legislative Decree No. 79/1999 as part of broader efforts to liberalize and restructure the Italian electricity market. This joint-stock company, entirely controlled by the Italian Ministry of Economy and Finance, is responsible for promoting and supporting the development of renewable energy sources and energy efficiency across the country. The GSE's main activities include the management and distribution of economic incentives for energy production from renewable sources, including biomethane, photovoltaic, wind, and biomass. Additionally, the GSE monitors the implementation of relevant regulations and promotes initiatives aimed at improving energy efficiency, playing a crucial role in Italy's energy transition towards environmental sustainability and decarbonization.

2.2. Input biomass

Biomass, as defined by the *EU Directive 2009/28/CE*, refers to "*the biodegradable fraction of waste, organic waste from agricultural activities, hunting, fishing, and organic municipal solid waste and industrial waste*." In the context of anaerobic digestion, biomass consists of a wide range of organic materials, primarily derived from agricultural and agro-industrial activities. These materials include residues generated directly from field cultivation, such as stems, leaves, and stalks, which represent the non-harvested fractions of crops. Additionally, significant quantities of biomass originate from the processing of primary agricultural products, where by-products such as husks, seed residues, and bagasse are commonly found. A major category of biomass input is livestock by-products, which includes both liquid slurry and solid manure, materials that are particularly rich in nitrogen and other essential nutrients.

Historically, the use of energy crops such as maize silage has been the most common approach to ensuring a high and stable biogas yield. These crops are specifically cultivated to serve as substrates in anaerobic digesters due to their optimized composition and high methane production potential. However, despite their efficiency, the large-scale cultivation of energy crops has raised concerns regarding their competition with food production, as agricultural land and resources are increasingly diverted toward energy purposes rather than human or animal consumption, inserting itself drastically into the food-energy-climate change trilemma.

This concern has led to a shift in focus towards more sustainable alternatives, emphasizing the importance of utilizing agricultural and industrial by-products rather than dedicating arable land solely to bioenergy production. By prioritizing the valorisation of residual biomass, it becomes possible to reduce environmental impact while maintaining high efficiency in biogas generation.

The characterization of the organic streams entering the digester is a critical factor in optimizing anaerobic digestion performance. Since the type and composition of the feedstock directly influence the biogas yield, as well as the quality and properties of the resulting digestate, a thorough understanding of its characteristics is essential. First of all, for importance, is necessary to estimate the biochemical methane potential (BMP), this test measures the maximum achievable methane yield from a given substrate under ideal anaerobic conditions

Other various analytical approaches can be employed to assess different properties of the input materials. One fundamental method is proximate analysis, which provides insight into parameters such as moisture content, ash content, fixed carbon, and volatile matter. These values are particularly useful in estimating the overall degradability of the material. Additionally, elemental analysis determines the proportions of key chemical elements, including carbon (C), hydrogen (H), nitrogen (N), oxygen (O), and sulphur (S), as well as the carbon-to-nitrogen (C/N) ratio, which is crucial in maintaining microbial balance within the digester.

Beyond basic compositional analysis, a deeper understanding of the biochemical makeup of the feedstock is necessary to optimize digestion efficiency. The chemical composition of biomass is largely defined by the presence of major organic compounds such as lipids, starches, sugars, and lignocellulosic components. Among these, cellulose, hemicellulose, and lignin play a crucial role, as they determine the ease with which the material can be broken down by microbial activity. Lignocellulosic biomass, in particular, is known for its recalcitrance, meaning that it requires pre-treatment or longer retention times for effective digestion. Additionally, the thermo-chemical properties of the material, including the lower heating value (LHV) and thermogravimetric behaviour, provide essential data on the energy potential of the feedstock, which is important for optimizing biogas recovery.

Another significant aspect of substrate evaluation involves assessing its biological characteristics. The respirometric index is often used to gauge the biodegradability of organic matter, while the biochemical methane potential (BMP) test measures the maximum achievable methane yield from a given substrate under ideal anaerobic conditions. These indicators help determine the suitability of a feedstock for digestion and provide valuable information for process optimization.

Given the complexity and variability of organic waste materials, achieving a balanced and efficient substrate mix is one of the key challenges in anaerobic digestion. An excessive proportion of nitrogen-rich materials, such as manure, can lead to ammonia inhibition, whereas an overabundance of lignocellulosic biomass may result in low degradation rates and reduced methane yields. Therefore, a carefully designed feedstock strategy, combining different types of residues to optimize nutrient balance and microbial activity, is essential for maintaining stable and efficient biogas production.

2.3. Biogas generation process

In nature, the anaerobic fermentation of biomass in a humid environment leads to the formation of biogas, a gaseous mixture primarily composed of methane. This biological process is driven by microbial consortia that degrade organic matter in the absence of oxygen, producing biogas as a byproduct of their metabolic activity.

Component	**Formula**	**Content (%)**
Methane	CH_4	50-75
Carbon dioxide	CO_2	25-45
Water vapor	H_2O	2-7
Sulphide	H_2S	0.002-2
Nitrogen	N_2	<2
Ammonia	NH_3	<1
Hydrogen	H_2	<1
Other	/	<2

Table 1 - Biogas composition (averaged data). (4)

The anaerobic digestion plant aims to replicate and optimize this naturally occurring process. Within these structures, organic waste biomass is collected, sorted, and pretreated to eliminate potential contaminants. To maximize both the yield and quality of biogas, it is essential to ensure proper biomass sanitation and an optimal mixing of substrates. The co-digestion of different types of biomasses has been shown to be significantly more effective than the digestion of a single component, resulting in higher methane production.

The anaerobic digestion process is regulated by the activity of specific microbial communities, which require carefully controlled environmental conditions to function efficiently. The absence of oxygen and light is crucial, along with the precise regulation of key factors such as pH, temperature, particle size, and moisture content. Each stage of biomass degradation involves distinct bacterial populations, and maintaining an optimal microbiological balance is fundamental to ensuring an efficient and stable process.

2.3.1. Biochemical aspects

The metabolic degradation process in anaerobic digestion occurs through a sequence of interdependent stages, which can be categorized into four distinct phases.

The first phase, hydrolysis, involves the breakdown of complex organic macromolecules such as proteins, carbohydrates, and lipids into simpler organic compounds, including amino acids, monosaccharides, fatty acids, and glycerol. This transformation is facilitated by hydrolytic bacteria, which either degrade biomass directly or secrete extracellular enzymes (proteases, cellulases, lipases, and amylases) that catalyse the decomposition of organic material.

Enzymes	Substrate	Breakdown products
Proteinase	Proteins	Amino acids
Cellulase	Cellulose	Cellobiose and glucose
Hemicellulase	Hemicellulose	Sugars, such as glucose, xylose, mannose and arabinose
Amylase	Starch	Glucose
Lipase	Fats	Fatty acids and glycerol
Pectinase	Pectin	Sugars, such as galactose and arabinose, and polygalactic uronic acid

Table 2 - Important groups of hydrolytic enzymes. (5)

Hydrolysis is the slowest phase of the process, as it is governed by slow-growing bacteria that are highly sensitive to environmental conditions such as pH, temperature, and substrate composition. For this reason, it represents a major limiting factor for the large-scale implementation of anaerobic digestion, often acting as a bottleneck. The rate of hydrolysis is particularly affected by the structural complexity of the feedstock, with lignocellulosic materials being more resistant due to their rigid polymeric composition.

The second phase, acidogenesis, is the first true stage of fermentation, occurring immediately after hydrolysis and partially overlapping with it. Acidogenic bacteria metabolize the hydrolysis products, converting them into volatile fatty acids (such as butyric, propionic, and valeric acids), ethanol, ammonia, hydrogen, and hydrogen sulphide. This phase leads to a significant drop in pH due to the accumulation of organic acids, which is why it is also referred to as acidic fermentation. The composition of the microbial community at this stage is crucial, as an excessive accumulation of intermediate products like propionic acid can inhibit subsequent phases.

The third phase, acetogenesis, continues the fermentation process. In this stage, volatile fatty acids and other intermediate metabolites are further converted by acetogenic bacteria into acetic acid, carbon dioxide, and hydrogen. Acetogenesis plays a crucial role in maintaining process balance, as it helps prevent the accumulation of inhibitory compounds such as propionic and butyric acids. This phase is sometimes referred to as alkaline fermentation because the presence of ammonia, calcium, and magnesium ions helps buffer the pH, counteracting the acidic conditions generated in the previous stage. However, excessive hydrogen accumulation can create unfavourable conditions, slowing down acetogenesis and affecting methane production.

The final phase, methanogenesis, is the most relevant from an energy production perspective, as it results in methane generation. This occurs through two primary pathways: hydrogenotrophic methanogenesis, where methanogenic archaea reduce carbon dioxide using hydrogen to form methane, and acetoclastic methanogenesis, where acetic acid is cleaved into methane and carbon dioxide. The acetoclastic pathway is the predominant route, as it provides greater process stability by reducing acid concentrations that could inhibit microbial activity. Maintaining optimal conditions such as a neutral pH, a stable temperature, and low hydrogen partial pressure is crucial for ensuring efficient methanogenesis, as disruptions in this phase can lead to process failure due to acid accumulation or the inhibition of methanogenic archaea.

$$CO_2 + 4H_2 \rightarrow CH_4 + H_2O$$

Equation 1 - Carbon dioxide and hydrogen reduction into methane and water. (6)

$$CH_3COOH \rightarrow CH_4 + CO_2$$

Equation 2 - Acetic acid degradation into methane and carbon dioxide. (6)

2.3.2. Microbiological aspects

Microorganisms utilize the substrate to build new cells while simultaneously producing waste compounds, which serve as substrates for the microorganisms involved in the subsequent steps of the process. The primary building blocks of microorganisms include carbon, oxygen, nitrogen, and hydrogen. When the energy source is organic, it also serves as the source of these fundamental elements. In contrast, when the energy source is inorganic, carbon is typically supplied by carbon dioxide, while nitrogen is derived from ammonia. Other necessary nutrients are phosphorus and sulphur. For optimal function, microorganisms require trace elements and vitamins. Different bacterial species have specific micronutrient requirements, and if the substrate cannot provide these essential compounds, they must be supplemented externally. A deficiency in micronutrients, along with overfeeding and temperature fluctuations, is among the primary causes of acidosis in anaerobic digestion systems.

The microorganisms involved in the initial stages of digestion, particularly during acidic fermentation, primarily belong to the genera *Bacillus, Pseudomonas, Clostridium,* and *Bifidobacterium*, with lesser contributions from *Streptococcus* and *Enterobacterium*. In addition, acetogenic bacteria such as *Syntrophomonas* sp. and *Syntrophobacter* sp. play a crucial role in this process. These microbial populations are highly sensitive to environmental variations and exhibit relatively slow growth rates.

Methanogenic bacteria, which are essential in the final phase of anaerobic digestion, occur in different morphological forms, including rod-shaped, spiral, and granular structures. Regulating their growth is fundamental to maximizing methane production, with temperature control being one of the most effective strategies, as different methanogenic species thrive under specific thermal conditions.

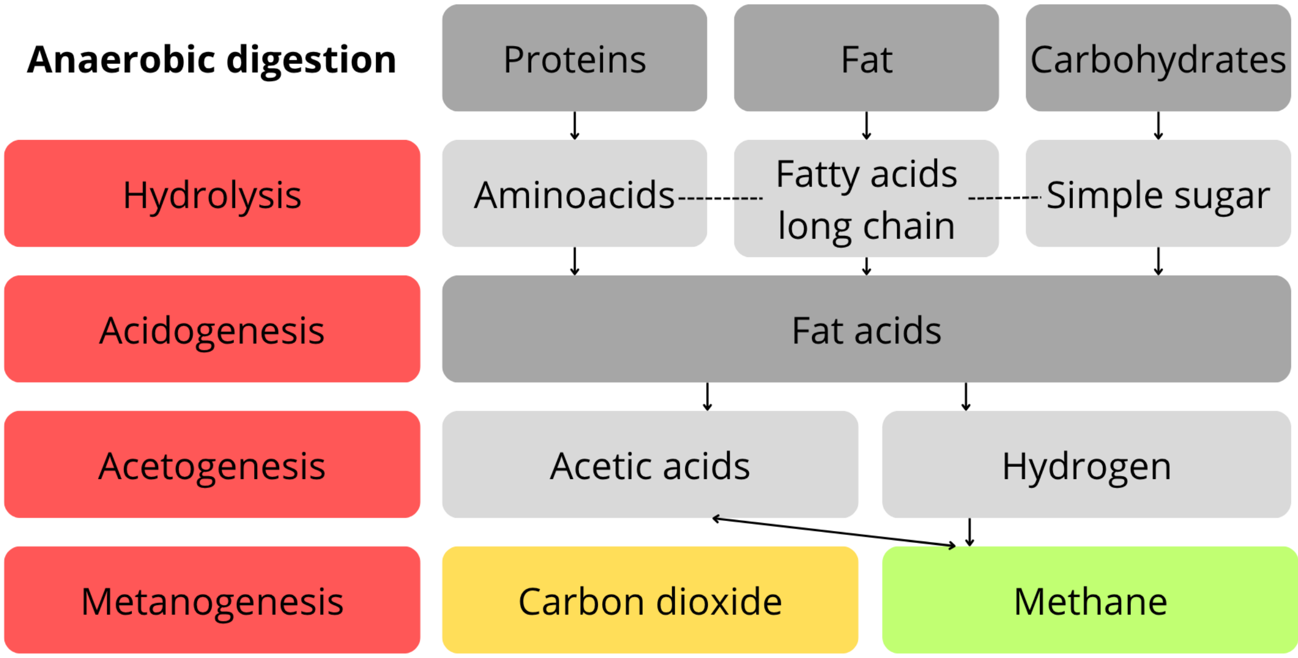

Figure 6 - Metabolic pathway toward biogas formation. (5)

2.4. Process parameters

To ensure the stability of the anaerobic digestion process and maximize biogas production, it is essential to analyse key process parameters and, if necessary, implement corrective measures.

- pH

The pH levels in the anaerobic digestion process fluctuate depending on the stage, making it essential to ensure that the buffering capacity provided by the incoming substrate is optimal. Feeding the digester with nitrogen-rich materials, such as manure, leads to the production of significant amounts of ammonia, which directly affects the system's buffering ability.

Since the entire fermentation process is regulated by pH variations, maintaining optimal conditions is crucial. The initial pH should be slightly alkaline, around 7.5. During the acidogenesis phase, the pH drops below neutral, reaching in critical conditions values below 5, due to the production of volatile fatty acids. The system must be capable of regulating alkalinity, primarily through ammonia generated from the breakdown of complex molecules such as proteins, which helps restore pH levels above neutrality. However, it is important to prevent excessive increases beyond a pH of 8. In the methanogenesis phase, maintaining a near-neutral pH of approximately 7 is critical, as this ensures optimal conditions for methanogenic bacteria, thereby maximizing methane production.

A severe drop in pH, known as acidosis, can inhibit or even halt biogas production, whereas an excessive increase can lead to high ammonia levels, which inhibit both methanogenic and acidogenic bacteria. This imbalance favours the production of hydrogen and hydrogen sulphide at the expense of methane generation. Various corrective measures can be applied in emergency situations to restore pH balance. However, operating at higher temperatures, such as under thermophilic conditions, introduces additional risks, as pH fluctuations can occur more rapidly, significantly reducing the available response time for corrective action.

While alkaline conditions can sometimes be leveraged for alternative biofuel production, such as biohydrogen, acidosis results in a complete process failure with no viable output.

The primary causes of acidosis include overfeeding and temperature fluctuations. If pH levels drop too low, they can be adjusted using quicklime, sodium carbonate, calcium carbonate, or caustic soda. However, the most effective approach is to prevent the excessive accumulation of volatile organic acids.

Studies have demonstrated that the use of sodium bicarbonate as an emergency remedy for acidosis allows for the recovery of the digester without damaging the microbial community, achieving stabilization very rapidly.

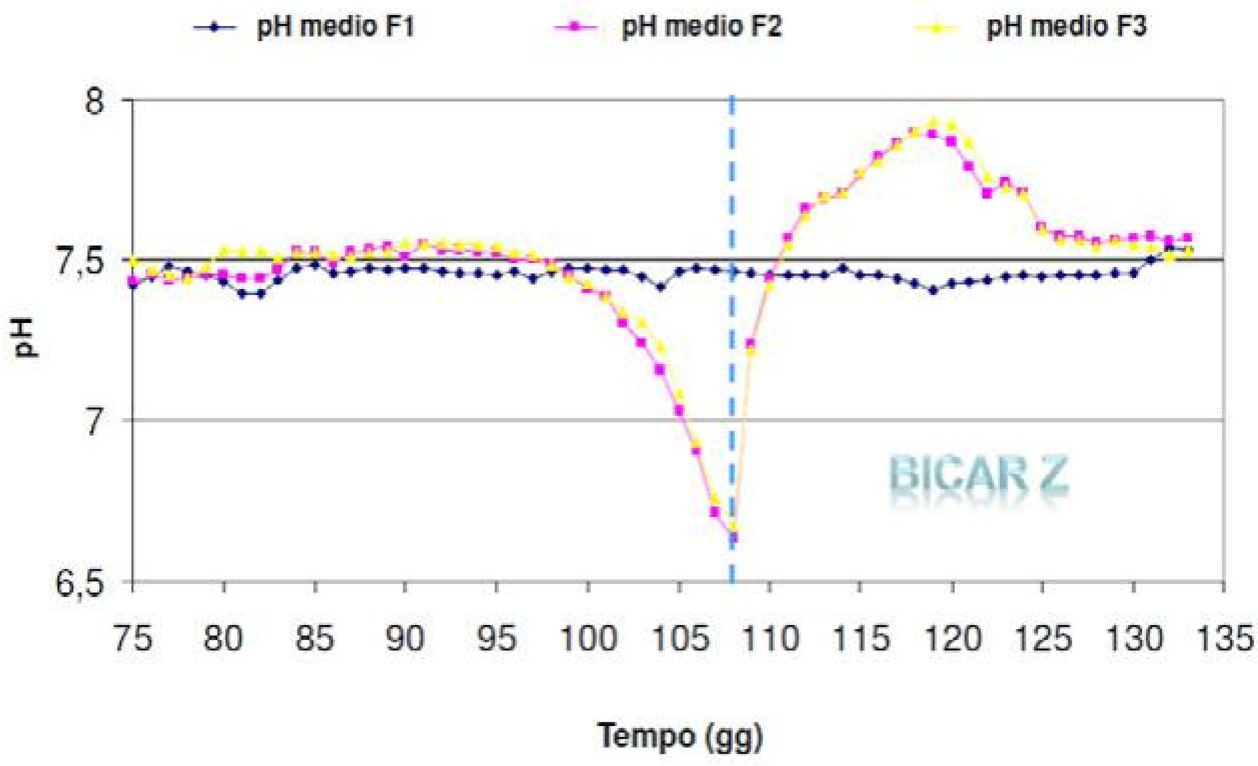

Figure 7 - pH of digesters in acidosis before and after treatment with sodium bicarbonate. (7)

- Temperature

Temperature plays a crucial role in biomass degradation, as it directly affects microbial activity. It is essential to maintain the optimal temperature at which microorganisms grow most rapidly and function efficiently. However, this optimal temperature varies depending on the bacterial species involved.

The majority of the bacteria involved in anaerobic digestion are mesophilic, meaning their ideal growth temperature ranges between 25°C and 45°C. As a result, mesophilic fermentation is the most widely used technology. Since this temperature range is close to ambient conditions, it is easier to maintain, and the process remains stable, typically operating between 30°C and 35°C.

In cases where the incoming biomass requires sterilization or sanitation, primarily to eliminate mesophilic pathogens, thermophilic fermentation is preferred, operating at temperatures between 52°C and 55°C. Under these conditions, thermophilic methanogenic bacteria thrive, while pathogenic bacteria are exposed to temperatures too high for their survival. However, the main drawback of thermophilic fermentation is the high energy demand required to maintain stable process conditions. Moreover, the stability of the process in more uncertain, because of the increased velocity of process: this aspect leads to struggle with the reaction capacity in response to eventual problems.

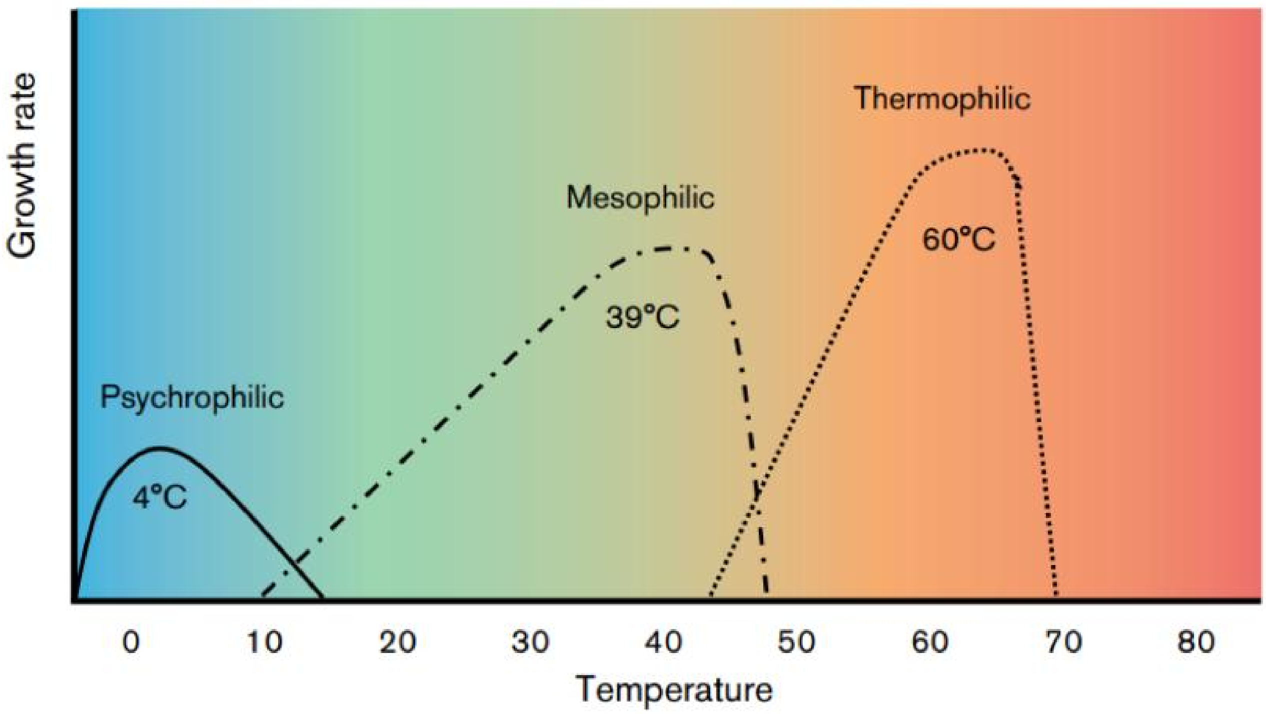

Figure 8 - Temperature ranges of different bacteria species. (5)

Another important category of bacteria to consider is psychrophilic bacteria, which thrive at much lower temperatures. Although their application is less common, they can be strategically advantageous in specific environmental conditions.

Naturally, local ambient temperature trends significantly influence the choice of process temperature, as they determine the energy expenditure required to maintain stable conditions.

Seasonal temperature fluctuations can lead to variations in energy production throughout the year, impacting overall process efficiency.

- C/N ratio and FOS/TAC ratio

The parameters directly linked to the system's buffering capacity and pH regulation during anaerobic digestion are the carbon-to-nitrogen (C/N) ratio and the FOS/TAC ratio (*Flüchtige Organische Säuren / Totales Anorganisches Carbonat*).

Monitoring the carbon and nitrogen content, as well as their ratio in the feedstock, is of critical importance, as it significantly influences the digestion process. This initial information allows for accurate predictions of potential imbalances that could lead to process instability. If the C/N ratio is too high, favouring carbon, it may result in nitrogen deficiency, slowing microbial activity and limiting biogas production. Conversely, if the C/N ratio is too low, favouring nitrogen, excess ammonia can accumulate, leading to toxicity and inhibition of microbial populations.

The FOS/TAC ratio serves as a key indicator of process stability in anaerobic digestion. It represents the balance between volatile fatty acid (VFA) concentration, measured in milligrams of acetic acid per liter (mgAc/l), and the system's buffering capacity (alkalinity), measured in milligrams of calcium carbonate per liter ($CaCO_3$/l). A well-balanced FOS/TAC ratio ensures that acid accumulation does not disrupt microbial activity while maintaining sufficient alkalinity to counteract fluctuations in pH.

Both of these parameters have a direct impact on pH, which is the fundamental variable governing the entire anaerobic digestion process. However, there are no universally optimal values for the C/N and FOS/TAC ratios, as they are highly dependent on the nature of the feedstock. To determine the ideal values for a specific process, a thorough analysis of environmental conditions and substrate composition must be conducted. Only after evaluating these factors can the most suitable balance be established, ensuring stable and efficient process.

- Toxicity

The presence of toxic compounds in the digestion environment can lead to the inhibition or slowdown of methane production. The growth and reproduction of bacteria involved in anaerobic digestion are particularly sensitive to several inhibitory factors, which can compromise process efficiency.

Key inhibitors include excessive ammonia concentrations and high alkalinity, which can disrupt microbial balance and inhibit methanogenic activity. Heavy metals are poisonous elements that interfere with the hydrolysis phase by inhibiting the enzymes responsible for breaking down complex organic matter. Hydrogen sulphide (H_2S) is another major inhibitor, as it directly affects methanogenic bacteria, reducing their efficiency in methane production. Additionally, the presence of pesticides and antibiotics in the feedstock poses a significant risk, as these substances can suppress microbial populations, destabilizing the entire digestion process.

- Oxygen

The presence of oxygen is a critical factor in anaerobic digestion, as the process relies entirely on oxygen-free conditions. Methanogenic bacteria are highly sensitive to oxygen exposure and will die if they come into contact with air.

By definition, any unintentional introduction of oxygen into the system disrupts the process, leading to a slowdown or inhibition of acetogen activity, which in turn negatively impacts biogas production. However, in some cases, a small, controlled amount of oxygen is deliberately introduced above the liquid surface in the digester. This technique promotes natural desulfurization by enabling the conversion of hydrogen sulphide (H_2S) into elemental sulphur instead of sulfuric acid. Preventing sulfuric acid formation is crucial, as it can be highly corrosive and damaging to the system's infrastructure.

2.5. Output digestate

Beyond biogas production, anaerobic digestion also generates digestate as a byproduct. This material is a homogeneous mixture with high moisture content due to the breakdown of dry matter. The organic fraction is stabilized, rich in nutrients, sanitized, and free from strong odours, making it highly suitable for agricultural application as a soil amendment.

One key effect of anaerobic digestion is the transformation of nitrogen compounds. In the initial feedstock, approximately 60% of the nitrogen is in organic form, with the remaining 40% as ammoniacal nitrogen. However, in the resulting digestate, these proportions are reversed. While the increased ammoniacal nitrogen content enhances immediate nutrient availability for crops, it also reduces the long-term nitrogen supply, as organic nitrogen undergoes slower mineralization.

The liquid fraction of the digestate contains a higher concentration of ammoniacal nitrogen, making it suitable for direct field application as a fertilizer. The solid fraction, on the other hand, retains more of the organic nitrogen and can be further processed for various uses.

In agricultural biogas plants, where the feedstock consists of organic biomass and livestock manure, regulations governing digestate land application are generally less restrictive compared to digestate from industrial plants. This distinction is outlined in the "Effluent Decree", which sets quality standards based on chemical-physical, agronomic, environmental, and microbiological parameters, including Salmonella testing.

Digestate can be considered a valuable resource with market potential, providing additional revenue streams. However, large-scale biogas production can lead to an oversupply of digestate, exceeding the available land for agronomic use. To address this challenge and to meet increasingly stringent regulatory and incentive requirements, some players are investing in thermal treatment of the solid fraction to produce biochar. This carbon-rich product can be used in agriculture to enhance soil quality or as a renewable alternative to fossil coal for energy production.

2.6. Biomethane: a new opportunity

Biomethane is an energy vector obtained from the upgrading process of the biogas, which consists in splitting the CH_4 from the CO_2 and the other gases, which are the components of the resulting off-gas. This gas has vast potential for use in different sectors, as its chemical composition does not differ significantly from high-methane natural gas, it can be fed directly into the grid or be used as a biofuel.

Biomethane can achieve a higher degree of purity than that of conventional natural gas, where the degree of purity is defined as the methane content relative to the total gas volume. This is especially evident when comparing biomethane to natural gas imported from Algeria and other North African countries, which typically exhibits a lower methane concentration.

Gas composition	Biogas	Biomethane	Natural gas
Methane	50-75%	**94-99.9%**	**93-98%**
Carbon dioxide	25-45%	0.1-4%	1%
Nitrogen	<2%	<3%	1%
Oxygen	<2%	<1%	-
Hydrogen	<1%	Traces	-
Hydrogen Sulphide	20-20 000 ppm	<10 ppm	-
Ammonia	Traces	Traces	-
Ethane	-	-	<3%
Propane	-	-	<2%
Siloxane	Traces	-	-
Water	2-7%	-	-

Table 3 - Biogas, biomethane and natural gas comparison. (8)

In the past years despite these promising prospects, biomethane production technologies had not yet achieved widespread deployment at a national or European level, but in the last years some players reached an industrial standardized production of systems necessary for the biomethane diffusion. The primary driver for the development of these plants remains governmental incentives aimed at facilitating the transition to cleaner energy. For this reason, attention to the biomethane sector has grown significantly, attracting interest from stakeholders eager to capitalize on the opportunity, as well as from various governmental and non-governmental bodies responsible for regulating the economic dynamics of this industry.

2.6.1. Biomethane definition

Different agencies have published their own definition of biomethane, but they all agree with each other:

Italian Ministry of Ecological Transition (article 2 of the DM 15 September 2022)

"*Biomethane is the fuel obtained from the purification of biogas so that it is suitable for feeding into the natural gas grid".* (9)

European Commission

"Biomethane is the purified version of biogas, produced from the breakdown of organic matter. It is one of the main renewable gases of the future and available today to help decarbonise the EU's energy system". (10)

European Biogas Association (EBA)

"*When carbon dioxide and trace gases in biogas are removed, a methane rich renewable natural gas substitute is left in the form of biomethane. Biomethane can be injected into the gas grid, used as a vehicle fuel or used for combined heat and electricity generation*". (11)

International Energy Agency (IEA)

"Biomethane (also known as "renewable natural gas") is a near-pure source of methane produced either by "upgrading" biogas (a process that removes any CO_2 *and other contaminants present in the biogas) or through the gasification of solid biomass followed by methanation".* (12)

2.6.2. Characteristics

Biomethane has a chemical composition practically equal to the methane derived from fossil fuels, it is derived from biogas in which the methane content varies between 40% and 80% depending on the raw material. After the purification process, the methane content in BM increases significantly to almost 100%.

Biomethane has an LHV of around 36 MJ/m^3. Moreover, due to their indistinguishability, biomethane can be used as a substitute for natural gas without the need of any change in the distribution grid system or in the end-user equipment. (13) (14)

2.6.3. Current situation

The development of biogas, and consequently biomethane, has progressed unevenly across the globe. This phenomenon is driven by two primary factors: firstly, the policies that finance and incentivize these technologies, aiming for a transition towards more sustainable energy production; and secondly, the availability of biomass that can be used to produce the feedstock for the digester. The competition between production for human consumption and energy consumption of certain crops can cause imbalances and tensions.

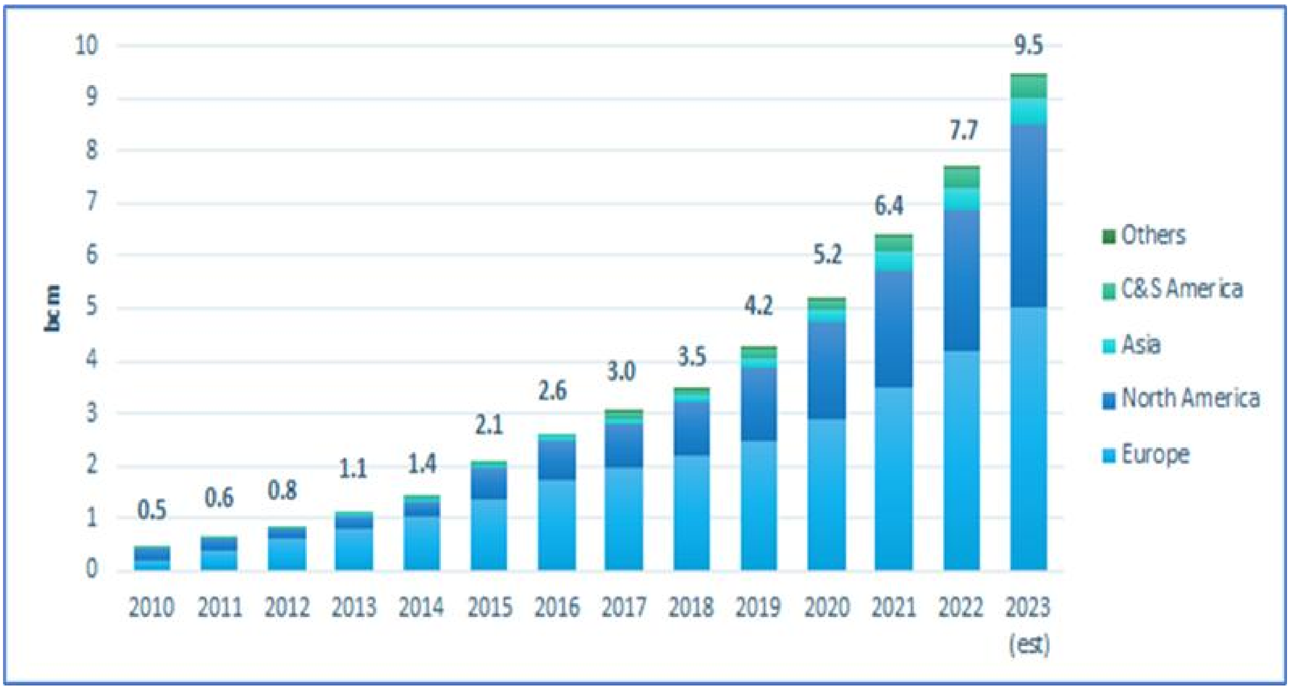

Figure 9 - Evolution of global biomethane production (2010-2023). (15)

Currently, the biomethane market is very small, but it is gaining a growing interest across the globe because of its potential to provide a clean form of energy that can be used in a wide range of sectors and can be distributed using the existing infrastructure

For this reason, government policies to support the spread of biomethane are flourishing, with the aim of injecting it into natural gas grid networks and the decarbonising the transport sector or hard to abate industries.

Europe currently ranks first in the world share of biomethane use, this is due to the European Commission's policies to reduce net GHG emissions by at least 55% in 2030, compared to 1990 levels.

The EU's work on a scale-up of BM production has led to a growth to 4.9 billion m^3 in 2023, with an installed capacity of 6.4 billion m^3/year by the first quarter of 2024. This represents the largest increase in BM production to date, EU aims to reach a production of 35 billion cubic meters per year by 2030.

Italy currently has 115 biomethane plants connected to the natural gas grid, with a combined production capacity of nearly 67,000 standard cubic meters per hour (Smc/h). However, this figure does not account for off-grid facilities, which distribute biomethane via tankers and cryogenic trucks.

National production currently stands at approximately 570 million cubic meters per year, significantly below the 2030 target of 5.7 billion cubic meters set by Italy’s National Energy and Climate Plan (PNIEC). On a broader scale, the EU aims to reach 35 billion cubic meters annually by 2030 under the REPowerEU initiative. (16)

This growing momentum underscores the critical role of biomethane in achieving national and continental climate objectives. To bridge the existing gap and meet the ambitious 2030 targets, further investments, policy stability, and technological innovation will be essential. Strengthening infrastructure and incentivizing plant reconversions, such as the case of "La Falchetta", represent key strategic actions to accelerate this transition.

3. La Falchetta plant

This chapter presents an in-depth technical analysis of the La Falchetta biogas plant, a facility dedicated to the production of biogas from agricultural biomass. The plant is designed to process a diverse mix of organic substrates, primarily composed of energy crops, livestock manure, and agro-industrial residues. The chapter outlines the key design features and operational processes of the plant, emphasizing the role of co-digestion and integrated energy recovery systems. Particular attention is given to the plant's feedstock management, digester configuration, biogas purification line, and cogeneration unit, as well as digestate handling and storage. The La Falchetta plant serves as a representative case study of a medium-scale, on-farm anaerobic digestion system optimized for energy efficiency and sustainable nutrient recycling.

3.1. Design

The design and configuration of a biogas plant are primarily influenced by the nature and composition of the feedstock entering the digester. Among the critical components of the process are storage units, which play an essential role in ensuring a consistent and manageable supply of substrates. In agricultural biogas plants, the most commonly used feedstocks are plant-based materials and livestock manure. These substrates typically require minimal to no pretreatment, making them particularly suitable for on-farm digestion systems.

The existing facility at "La Falchetta" was specifically dimensioned based on the quantities of biodegradable materials available on-site. The plant works with the following annual feedstock input:

Biomass	**Quantity**	**Unit of measure**
Maize silage	4 000	ton / year
Bovine manure and slurry	3 000	ton / year
Rumen content	900	ton / year
Triticale silage	2 500	ton / year
Vinasse	800	ton/ year
Maize flour	700	ton/ year
Total	11 900	ton/ year

Table 4 – Estimated annual feedstock inputs.

The choice of reactor configuration is closely linked to the total solids content and particle size of the incoming material. While high-solids feedstocks are processed through dry digestion systems, the pumpable substrates, with lower total solids content, undergo wet anaerobic digestion.

The plant operates through a co-digestion process, combining multiple organic matrices to enhance process efficiency and methane yield. Solid substrates are stored and then introduced into the system via a feed hopper. Liquid substrates are pumped directly into the digester.

Following its production, the biogas undergoes dehumidification and is subsequently utilized for energy generation. The gas is combusted in a combined heat and power (CHP) unit to simultaneously produce electricity and thermal energy. Part of this energy is used to satisfy the plant's internal energy demands, with any surplus either fed into the national power grid or supplied to district heating systems. Alternatively, the biogas may be diverted to upgrading units where it is purified into biomethane.

In the event of maintenance operations or unexpected shutdowns, the system is equipped with an emergency flare where excess biogas is safely combusted to prevent overpressure and ensure operational safety.

Lastly, the system is projected to ensure an adequate infrastructure for the storage of the digestate and its further use with agronomic purposes.

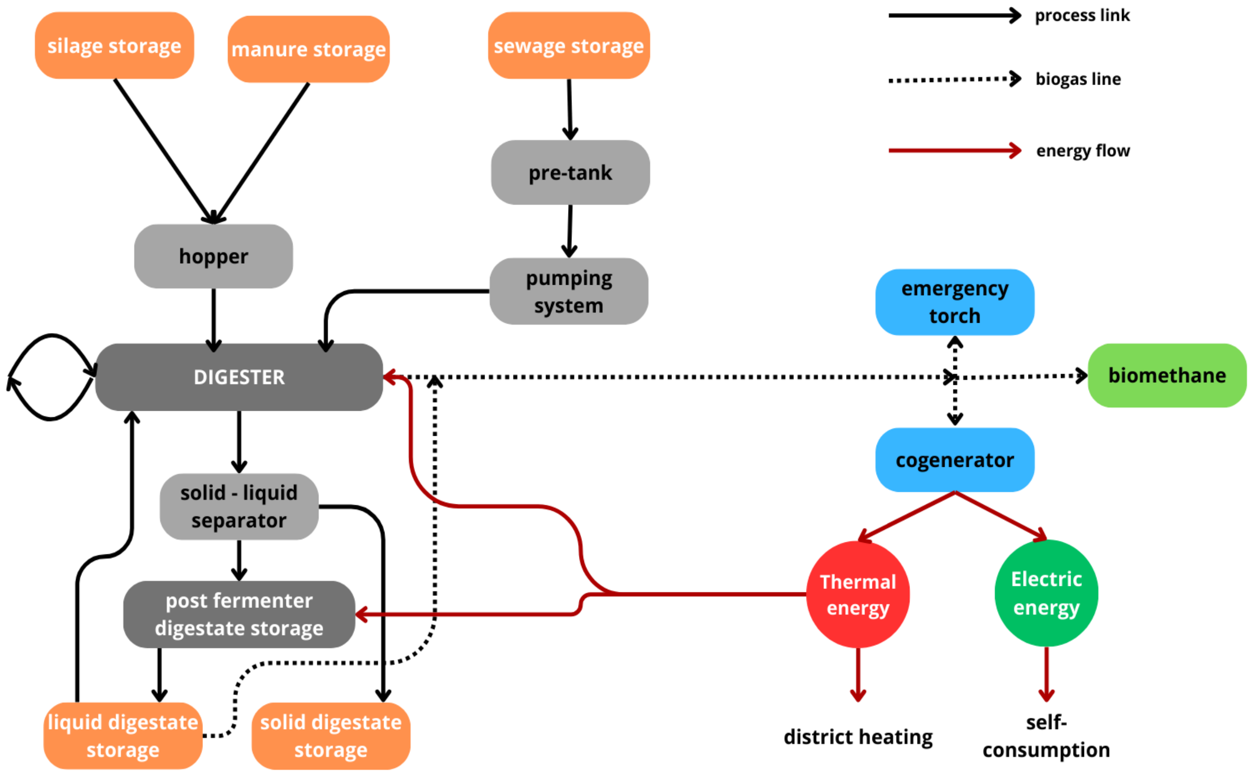

Figure 10 - Agricultural plant system diagram. (17)

3.2. Operation

This section provides an analysis of the current operational configuration of the plant, with a detailed examination of each functional section:

- Input Biomass

The current feedstock mix includes maize silage, triticale silage, bovine by-products, vinasse, and depending on seasonal availability other agricultural biomasses.

Among the five existing silage trenches, the two largest are designated for storing maize silage, while two others store triticale silage. The fifth trench is used for the storage of manure, rumen content, and the solid fraction of the separated digestate, which is deposited in a separate pile directly discharged from the separator.

In addition, two underground vertical silos are used to store vinasse. Liquid biomass bypasses this phase and is sent directly to the subsequent loading section.

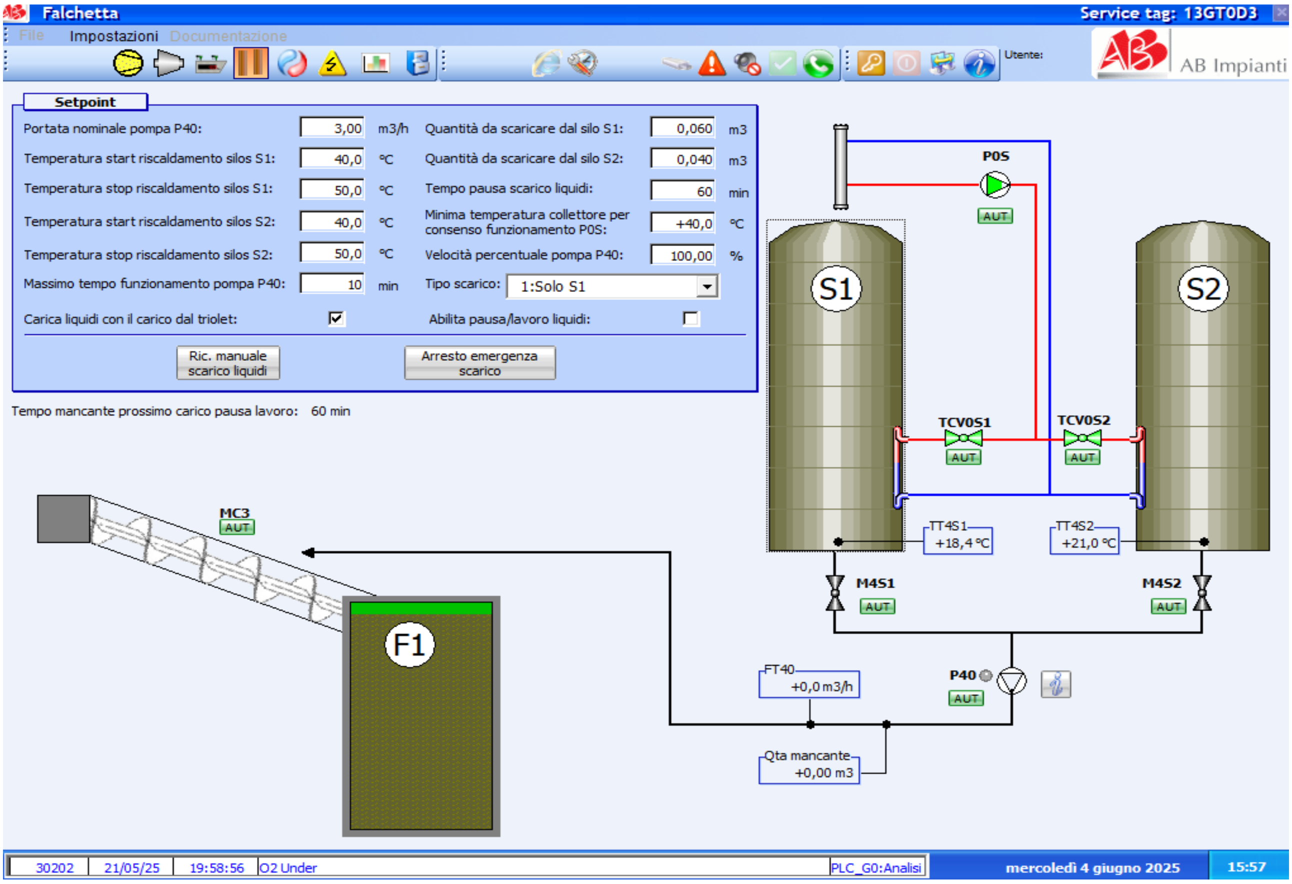

Figure 11 - Viewing of vinasse silos from the control and monitoring software.

• Biomass Loading

Solid biomass is introduced into the digester via a loading hopper, which performs two daily loading cycles to maintain continuity in the process. The liquid feedstock is loaded through a covered underground pre-tank made of reinforced concrete. Livestock effluents are discharged through an access hatch and then transferred to the anaerobic digestion system by a pump. The resulting mixture has a consistency similar to heterogeneous slurry. Inside the fermenters, agitators ensure continuous movement of the substrate, enhancing material exchange and digestion efficiency.

Figure 12 - Loading hopper.

The agitators also prevent phase separation between the solid and liquid components, as well as the formation of surface foam, both of which can hinder the fermentation process. The plant operates under a co-fermentation regime, where the digester receives a blend of various digestible organic substances.

Figure 13 – Agitator.

• Digesters

The digestion system at La Falchetta consists of coaxial, insulated, reinforced concrete tanks with reinforced concrete roofs. The acidogenic fermentation phase occurs in the outer tank, which has a diameter of 30 meters and a height of 6 meters. Methanogenesis takes place in the inner tank, which has an 18-meter diameter and the same height. Both tanks are equipped with stainless steel radiant ring heating systems, vertical and lateral agitators, biogas domes fitted with desulfurization units, and inspection hatches for routine maintenance and safety.

The plant operates at a mesophilic temperature of 42°C, maintained by the integrated heating system. The digesters are externally insulated with expanded polystyrene panels to reduce thermal losses.

Depending on retention times, typically between 30 and 60 days, the substrate transferred to the second digester may still have unexploited biogas potential. For this reason, the second fermenter is also equipped with a heating system to continue fermentation. The residence time, calculated based on the geometric volume and operating conditions, is considered adequate for full methane potential exploitation. Further biogas recovery occurs in downstream sections, enhancing total energy yield.

The digestate is temporarily stored in a circular tank with a 16-meter diameter and 6-meter height. Biogas is collected in a gas holder with a dual-membrane flexible roof, providing a storage volume of approximately 2,000 m^3.

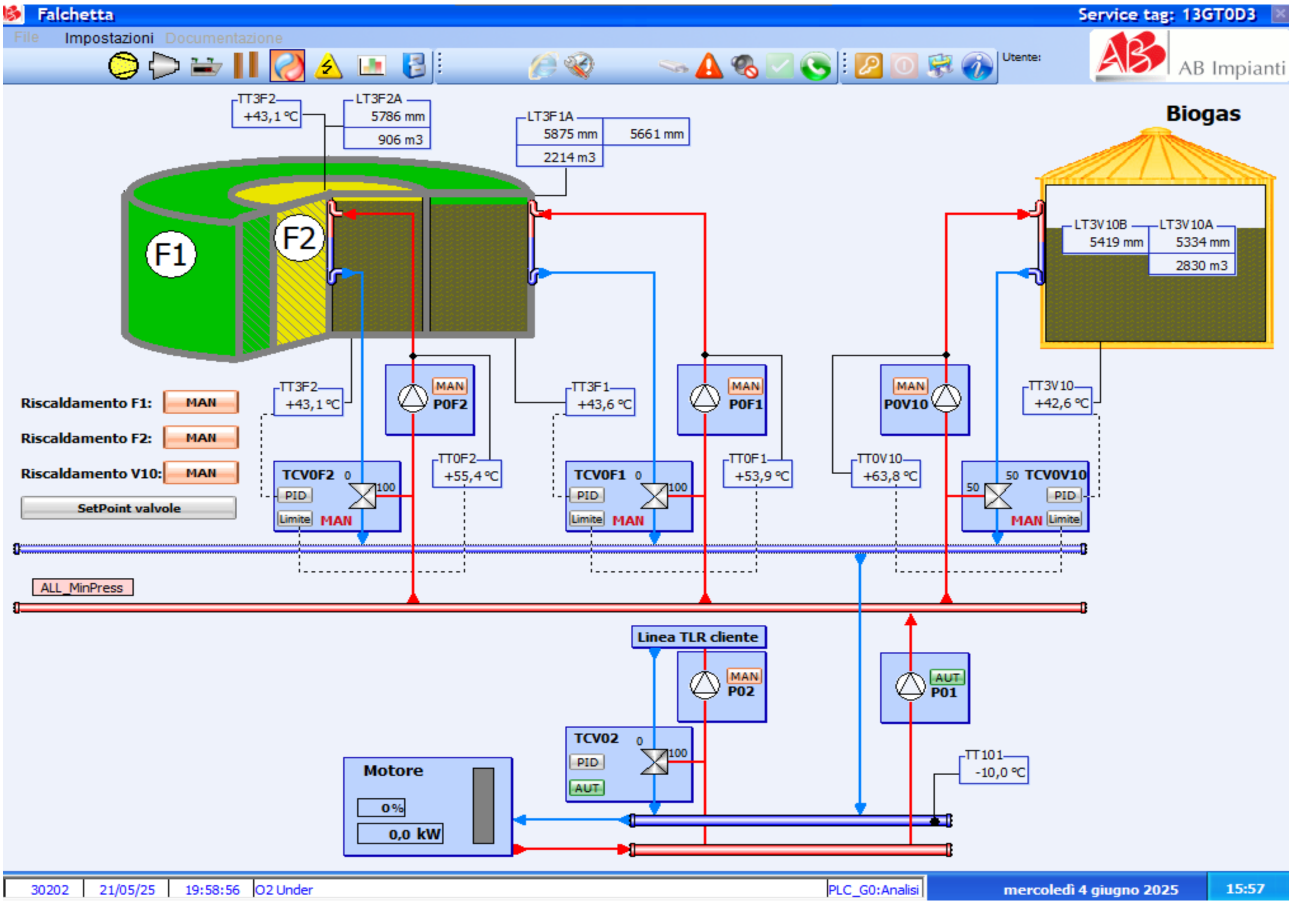

Figure 14 - Viewing of the biogas production system from the control and monitoring software.

• Biogas Purification Line

Biogas production is estimated at approximately 320 m^3/h. The gas rises above the substrate level and accumulates in the gas dome space within the fermenters.

To ensure continuous gas collection, a slight overpressure of approximately 0.04 bar is maintained using a pressure relief system. The biogas flows from the dome into the pipeline, where it is directed toward desulfurization and treatment units.

Desulfurization is carried out by dosing iron hydroxide and ferric chloride, which chemically bind hydrogen sulphide (H_2S) and neutralize it. An antifoaming agent is also added to prevent process instability.

Removing H_2S is critical, as it would otherwise corrode engine components, particularly in lower-temperature zones such as combustion chambers and valve seals.

The treated gas is transported through an underground pipeline laid with appropriate slope gradients. As the biogas cools and condenses, moisture is removed in a drainage pit equipped with overpressure and underpressure safety valves.

• Cogeneration Unit

The purified biogas is conveyed to the cogeneration unit, comprising an internal combustion engine coupled with a synchronous alternator. The installed engine has a nominal electrical power output of 625 kW.

Assuming a methane concentration of 52–54%, biogas consumption is estimated at 320 m^3/h. The system operates with an electrical efficiency of approximately 40%. Assuming 8,500 annual operating hours (excluding scheduled maintenance), the maximum gross electrical output is estimated at 4.9 GWh/year.

Net electricity (gross production minus internal consumption) is fed into the national grid via a delivery substation, in compliance with CEI 11-20 and Enel DK5740 standards. The cogenerated thermal energy is used to meet the plant's internal heating needs and can be optionally used for heating farm buildings located near the facility.

• Solid-Liquid Separator

At the end of the digestion process, key nutrients as nitrogen, phosphorus, and potassium remain in the digestate, making it an effective organic fertilizer.

The fermentation process also reduces pathogen content, allowing the digestate to be safely applied to farmland.

The digestate is separated using a screw press separator installed near the storage area for solid bovine by-products.

This system operates by compressing the material via an auger within a cylindrical filter screen: the liquid fraction is drained through the mesh and directed to storage tanks, while the solid fraction is compacted and stored separately.

• Digestate Storage

The liquid fraction is stored initially in a first tank, which is equipped with a gas recovery membrane, and then transferred to the second and the third one. Tank number 2 is a fully buried concrete structure, while tank number 3 is a circular concrete structure currently covered with a natural surface crust.

The solid fraction is discharged from the screw press separator directly onto a designated storage platform. This platform consists of a concrete trench with three retaining walls and is located adjacent to the silage trenches used for biomass storage.

4. Policy and incentives

In order to promote and achieve the decarbonization goals set by Italy and Europe, political attention has increasingly focused on the potential of biomethane as an alternative energy source. While past initiatives have facilitated the spread of biogas production, current actions are now aiming to further enhance the value of the products derived from the biological treatment of biomass. These efforts are directed toward maximizing the energy potential and environmental benefits of biogas, particularly through the upgrading of biogas to biomethane, which is a more sustainable and versatile fuel. By advancing the production and utilization of biomethane, Italy and Europe are taking significant steps toward achieving their carbon reduction targets and transitioning to a more sustainable energy system.

In 2022 the European Commission launched the REPowerEU Plan, whose implementation is helping the EU to save and produce clean energy, diversifying its energy supplies. As a renewable and dispatchable energy source, increasing the production and use of biomethane also helps to address the climate crisis.

The structure of biomethane policies differs widely among countries, depending on their priorities, political decisions dictated by sensitivity on the subject of energy transition, and market dynamics. A crucial aspect of policy formulation is the targeted application of biomethane, whether for road transportation, industrial processes, or integration into the natural gas grid, as each sector requires a tailored support framework. Additionally, the availability of feedstock and consequently the method of biomethane production significantly impacts the design and implementation of incentive mechanisms. There are multiple approaches and policy tools available to foster the development of biomethane production and utilization.

Biomethane production is heavily influenced by policies and incentives that span multiple areas and work following different mechanisms.

	Regulatory	**Economic**	**Voluntary**
Enforcing	Legislation	Taxes	
	Directive	Green certificates	-
	Standard	Procurement	
	Goal		
Encouraging		Subsidies	Education
	Goal		Information
		Green certificates	Cooperation
			R&D

Table 5 - Categorization of policies according to the model regulatory/economic/voluntary and enforcing/encouraging. (18)

4.1. Biomethane market incentives

Economic incentives are the most widespread instrument used by governments, they influence both individual and collective decision-making by encouraging or discouraging specific behaviours. They play a fundamental role in shaping economic activity and outcomes at both the microeconomic level (businesses) and the macroeconomic level (governments).

Incentives are generally designed to provide financial advantages or mitigate costs, allowing governments to steer economic behaviour toward achieving key policy goals such as climate resilience, energy security, and the reduction of greenhouse gas emissions.

They can operate directly on the support of biomethane production, but also by promoting its demand in the market. Furthermore, it should not be forgotten that incentives to support measures falling within the agriculture-waste-environment panorama can have indirect but significant effects on the development of the biomethane sector. For example, incentives in favour of organic fertilizers, biomass production or the application of biogenic CO2, are not negligible in the system of biomethane incentives.

The most widespread types of incentives are:

- FiT

A Feed-in Tariff (FiT) is a financial incentive designed to support the production of biomethane. It guarantees producers a fixed payment per unit of energy (typically per kilowatt-hour or cubic meter) that they inject into the grid per fixed unit of time, it is above the market price payment, based on assumed full cost of production: CAPEX and OPEX costs, feedstock cost and grid-connection costs.

Typically, the subsidy period is limited to 10 or 15 years, ensuring long-term revenue stability and encouraging investment in renewable energy projects.

Italy has a FiT scheme (19), but in 2022 a new scheme entered into force for biomethane plants that produce up to 250 m3/hour.

- FiP

A Feed-in Premium (FiP) is a financial incentive for biomethane, but unlike a Feed-in Tariff (FiT), it does not offer a fixed price. Instead, it provides an additional payment over the selling price, it is a variable top-up payment covering the difference between the biomethane production cost and the price that producers receive when selling their biomethane at the price of natural gas. It is connected to methane market dynamics, allowing producers to sell their energy in the competitive market while receiving a bonus to ensure profitability. The new scheme introduced in Italy in 2022 determines that installations of >250 m3/h, or voluntary plants of smaller size, can apply for a FiP scheme (19), where the premium price is based on the reference price, monthly gas price, and monthly Guarantees of Origin price.

- Tendering

A tendering incentive for biomethane is a competitive bidding process in which producers submit offers to supply biomethane at the lowest possible price, and the government or regulatory body, that allocates a capped budget, selects the most cost-effective proposals to receive financial support. This system is possible under both feed-in-tariff and feed-in-premium. It ensures that public funds are allocated efficiently while promoting biomethane production.

- CfD

A contract-for-Difference (CfD) is a financial support mechanism designed to stabilize revenues for biomethane producers. It helps reduce market price volatility by ensuring that producers receive a guaranteed price for their energy, regardless of market fluctuations. The strike price, set by the government, may be determined through a competitive bidding process. When the market reference price falls below the strike price, the government compensates biomethane producers by covering the difference. Conversely, when the reference price exceeds the strike price, producers return the surplus to the government. This mechanism ensures price stability, benefiting both biomethane producers and consumers.

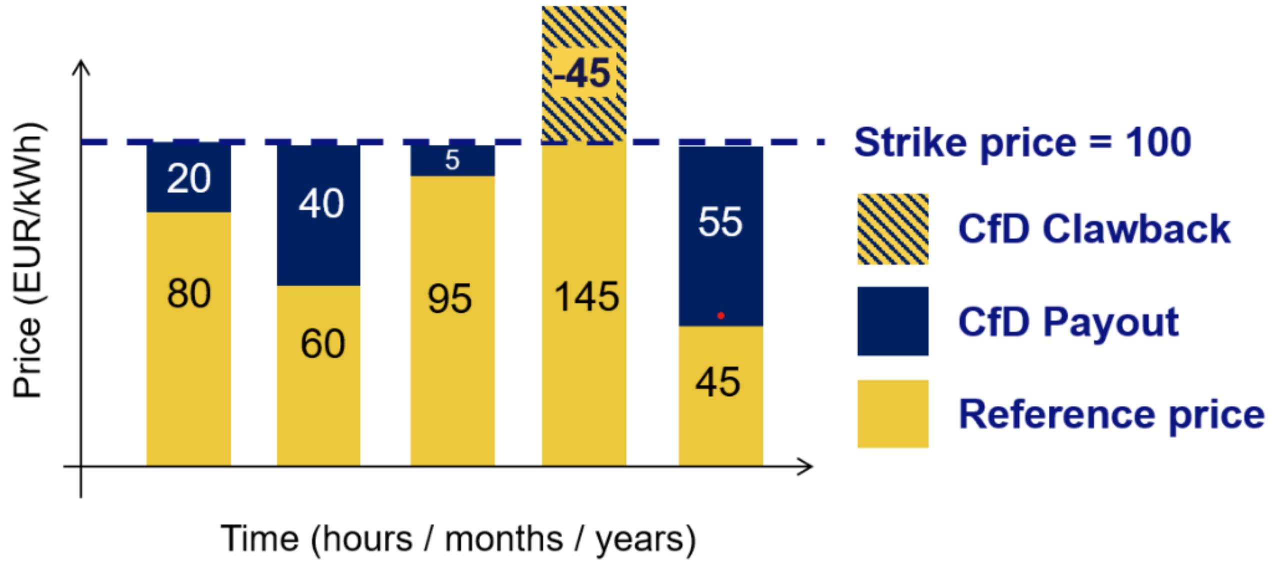

Figure 15 - How a contract for difference works (20)

- CapEx support

CAPEX (Capital Expenditure) support is a financial incentive aimed at reducing the upfront investment costs of biomethane production facilities. Instead of subsidizing the ongoing production or sale of biomethane (as in FiTs or CfDs), CAPEX support helps cover initial infrastructure and equipment costs, making projects more financially viable from the start.

CAPEX support can coexist and be used in combination with other kinds of incentives already described.

Italy has a €1.7 billion CAPEX investment support scheme (19) covering 40% of investment costs to upgrade existing biogas plants to biomethane plants and for building new plants.

- Biomethane mandates

Mandates are regulatory requirements that oblige energy suppliers, industries, or fuel providers to include a minimum percentage of biomethane in their energy mix. These mandates help drive demand, ensure market stability, and accelerate the transition to renewable energy sources. Italy has had a mandate for biomethane since 2018. (19)

- GHG intensity targets

GHG (Greenhouse Gas) emission targets are legally binding or voluntary goals set by governments or international organizations to reduce carbon dioxide, methane, and other greenhouse gas emissions over a specific period. These targets play a crucial role in climate policies, influencing biomethane production and utilization. Italy has developed the “Biogas Done Right” concept to reduce the GHG intensity, this approach is rooted in sustainable farming practices, aiming to enhance land use efficiency and crop yields while simultaneously promoting biogas and biomethane production. By integrating cover crops into crop rotations, either before or after traditional food and feed crops, farmers can generate additional biomass for energy, improve soil fertility, and enhance carbon sequestration.

Furthermore, the anaerobic digestion (AD) of cover crops, manure, and agricultural residues produces biofertilizers, supporting organic farming and improving nutrient recycling. This concept focuses on AD systems and the utilization of digestate, making it particularly influenced by agricultural policies that shape sustainable farming and renewable energy development.

In Italy, eligibility for public incentives in the biomethane sector is subject to a mandatory requirement in the reduction in greenhouse gas emissions compared to fossil fuel benchmarks. (19)

- Tax exemptions

Tax exemptions serve as a key incentive for biomethane investments, primarily within the highly taxed road transport sector. It is a type of incentive that is not present in Italy (19), but other European countries followed this path to promote the scale-up of biomethane utilization, meanwhile it is not a type of incentive sufficient as stand-alone solution.

4.2. Ministerial Decree September 15, 2022

The term biomethane was first introduced in Legislative Decree No. 28 of March 3, 2011, which transposed Directive 2009/28/EC on the promotion of energy from renewable sources into national legislation. This decree established the initial framework for the development of biomethane without explicitly defining its possible end uses. However, Article 33 included specific provisions on the production of fuels derived from waste and by-products, thereby laying the groundwork for the advancement of advanced biofuels.

The provisions outlined in Legislative Decree No. 28 were later implemented through the Ministerial Decree of December 5, 2013, the first regulatory measure introducing incentives for biomethane. This decree provided financial support not only for biomethane used in the transport sector but also for biomethane injected into the natural gas grid without a designated end use and for biomethane utilized in high-efficiency cogeneration plants for electricity production. However, under this five-year incentive scheme, investment in new biomethane facilities did not meet expectations, likely due to technical and economic constraints, as well as an incentive structure that did not ensure adequate returns for investors.

To address these shortcomings, the Ministerial Decree of March 2, 2018, was introduced. Recognizing biomethane as a strategic resource in the transition away from fossil fuels, this decree established a more comprehensive incentive framework aimed at fostering both its production and utilization. The decree introduced measures to promote: biomethane injected into the natural gas grid without a predefined use, supported by guarantees of origin; biomethane designated specifically for the transport sector; advanced biofuels other than biomethane, intended for use in transportation; conversion of existing biogas plants to biomethane production.

The Decree introduced the system of Certificates of Release for Consumption (CIC), instruments that certify the effective release to the market of specific quantities of biofuels. Each CIC is granted for 10 Gcal of conventional biofuels or 5 Gcal of advanced biofuels, thereby promoting the use of more sustainable renewable sources.

There is also a differentiation of the advanced biomethane, that is produced from raw materials listed in Annex 3 of Legislative Decree 152/2006, including organic waste and agricultural by-products. In this specific case, a preferential treatment was granted through a rewarding mechanism. For advanced biomethane, in fact, a double recognition of CICs was provided for each Gcal produced and released for consumption, in order to encourage the development and use of advanced sustainable energy production technologies.

The system established that fuel suppliers, who are required to release a minimum quota of biofuels to the market, could fulfil this obligation either by producing biofuels directly or by acquiring CICs through the BIOCAR platform or through the Biofuels Certificates of Release for Consumption Market.

Building upon the March 2, 2018 decree, and in alignment with the investment support measures set forth in the National Recovery and Resilience Plan (PNRR), the Ministerial Decree of September 15, 2022, introduced further incentives to support the expansion of biomethane production facilities.

The September 15, 2022, decree is designed to incentivize the injection of biomethane into the natural gas grid through capital grants (CAPEX-support incentive), covering up to 40% of eligible investment expenditures and production-based incentives, secured through a tendering procedure and applied as a tariff or premium on net biomethane output. (21)

These financial incentives are available for both new biomethane production facilities, whether agricultural or waste-based; and the full or partial conversion of existing agricultural biogas plants, previously dedicated to electricity generation, into biomethane production facilities.

4.2.1. Access to incentives

To qualify for incentives, plants must meet specific sustainability criteria, including a minimum 65% reduction in greenhouse gas (GHG) emissions for biomethane used in the transport sector and at least an 80% reduction for biomethane intended for other applications. (22)

Eligible plants can be newly built or, in the case of agricultural facilities, converted from the solely biogas production. However, the conversion of plants that process organic waste is not permitted.

The GSE is responsible for implementing the measures outlined in the decree, including managing competitive procedures for accessing incentives. The GSE has published the applicable regulations and calls for participation on its official website.

To ensure compliance with sustainability requirements and track progress toward set objectives, the GSE has established a dedicated platform for managing applications and monitoring biomethane production, specific for plants participating in DM “Biometano 2022”.

Access to these incentives is granted exclusively through public competitive procedures (reverse auctions) managed by the GSE. In these auctions, plants compete by offering discounts on the incentive tariff. The allocation of available production capacity is based on the level of discount proposed, and in the event of a tie, additional priority criteria apply.

The auction base for the tariff is defined by the GSE and published in the tender together with the maximum admissible specific costs.

The Ministerial Decree of 15 September 2022 establishes five competitive procedures for the allocation of the total available funds. Should the entire production capacity not be exhausted by the fifth procedure, the Decree provides for the possibility of launching additional procedures until all available resources have been allocated. The last of the 5 procedures has been published on April 17, 2025.

	Type of plant	Intervention category	
		New construction	Reconversion
Agricultural plant	PC ≤ 100 Smc/h	37 875,00	14 461,36
	100 ≤ PC ≤ 500 Smc/h	33 284,09	14 461,36
	PC ≥ 500 Smc/h	14 920,45	13 313,64
Organic waste plant	Every PC	57 386,36	17 215,91

Table 6 - Reference tariffs set as auction base [€/MWh] published in tender 5 of the Ministerial Decree of September 15, 2022. (23)

To participate in competitive procedures, plants must hold the necessary authorization for construction and operation, must accept the connection cost estimate provided by the relevant network operator (for plants connecting to gas transmission and distribution networks) and must ensure that the biomethane produced meets the sustainability criteria established by both European and national regulations.

The GSE evaluates applications within 90 days after the closure of the competitive procedure and publishes the ranking of projects eligible for incentives. Approved applicants must comply with all declared requirements and priority criteria for the entire incentive period.

4.2.2. Capital contribution

The contribution is granted for CAPEX (capital expenditure), covering the design and implementation of the project. It corresponds to 40% of the eligible expenses as specified, within the limits of the maximum admissible costs defined in the relevant tender in which you are participating. To qualify for the capital grant, the plant must become operational by June 30, 2026.

	Type of plant	Intervention category	
		New construction	Reconversion
Agricultural plant	PC ≤ 100 Smc/h	129,35	
	PC > 100 Smc/h	123,73	
Organic waste plant	Every PC	69,74	

Table 7 -Specific maximum values of the capital contribution (40% of the investment cost) [€/Sm3/h], based on the type of biomethane production plant, the intervention category and the production capacity (PC) published in tender 5 of the Ministerial Decree. (23)

4.2.3. Incentive tariff

The incentive for the net quantity of biomethane produced and injected into the grid, calculated as the gross production minus the energy consumption of auxiliary services, operates through two distinct incentive mechanisms, depending on the plant's production capacity.

Plants with a production capacity exceeding 250 Sm^3/h, as well as plants injecting biomethane into natural gas networks other than those subject to a third-party connection obligation, are eligible only for the Premium Tariff. This tariff is determined as the sum of the average monthly price of natural gas and the average monthly price of Guarantees of Origin, which certify the intended final use of biomethane. For plants benefiting from the Premium Tariff, the responsibility for selling biomethane lies with the applicant.

Plants with a production capacity of up to 250 Sm^3/h that inject biomethane into networks with a third-party connection obligation can opt either for the Premium Tariff or, alternatively, the All-Inclusive Tariff. Under the All-Inclusive Tariff, the GSE guarantees the purchase of biomethane injected into the grid with a third-party connection obligation and subsequently manages its sale on the market.

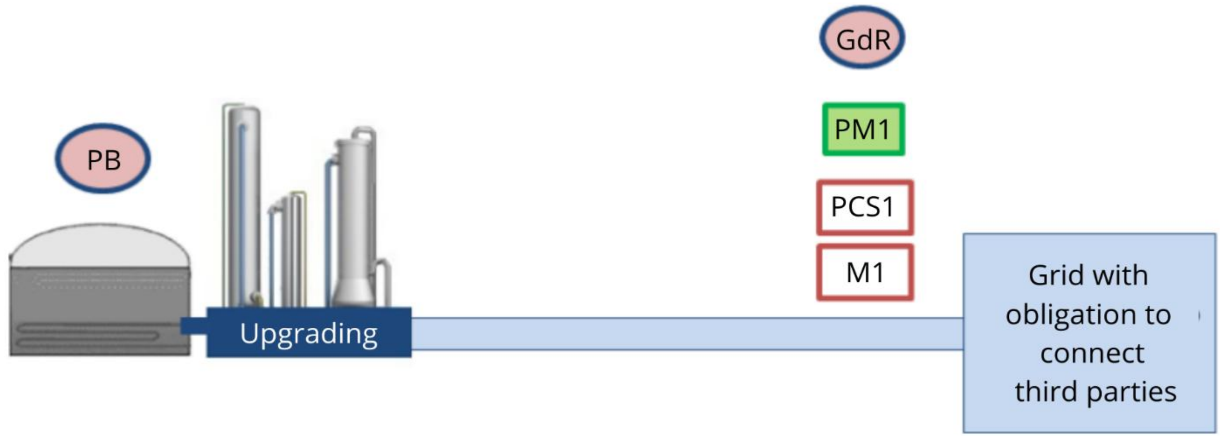

Figure 16 - Biomethane production plant directly connected to a grid with third-party connection obligation. (24)

The All-Inclusive Tariff consists of a single comprehensive tariff, which includes both the economic value derived from the sale of natural gas and the value of the Guarantees of Origin.

The applicable tariff is calculated starting from the reference tariff, which represents the €/MWh value set as the baseline in each competitive procedure. This reference tariff is then adjusted based on the percentage discount offered by the applicant during the bidding phase. Additionally, a further reduction applies if the project fails to meet the maximum commissioning deadlines outlined in Section 5.2 of the implementation rules of the Ministerial Decree of September 15, 2022.

Both the All-Inclusive Tariff and the Premium Tariff are granted by the GSE starting from the plant's commercial operation date and remain valid for a period of 15 years. (25)

It is important to highlight that the incentive tariff scheme represents a valuable opportunity for sectors that are particularly challenging to decarbonize. The regulation allows for the recognition of biomethane self-consumption not only when used directly at the production site but also allows under specific contractual conditions the utilization at a different site by end-users in hard-to-abate sectors. This framework permits the producer, acting under the instructions of the final customer through a biomethane purchase agreement, to enable the transfer of the associated benefits of on-site self-consumption, provided that the guarantees of origin are transferred at a zero monthly average price. Such measures aim to support and stimulate the integration of biomethane into industrial value chains that face significant obstacles to direct electrification or carbon mitigation. (26)

4.3. Authorizations

As of December 30, 2024, Legislative Decree No. 190 entered into force, establishing the administrative frameworks for the construction and operation of renewable energy plants, as well as for the modification, enhancement, full or partial refurbishment of existing installations. It also applies to all associated works and infrastructure essential for their development and operation.

The decree identifies three distinct administrative regimes for the implementation of such projects: free activity, Simplified Authorization Procedure (PAS), Single Authorization (AU).

Under the free activity regime, applicable to small-scale systems or minor interventions that do not significantly alter the urban or landscape context, no communication or formal declaration is required.

For medium-sized systems or interventions not eligible under free activity but still not subject to complex approval processes, the Simplified Authorization Procedure (PAS) applies, as outlined in Article 8 of the decree. This procedure only requires the submission of a formal notice to the municipality, along with the necessary technical documentation. If the municipality does not request further documentation within 30 days of submission, the principle of *tacit consent* applies, allowing the project to proceed.

The most comprehensive regime is the Single Authorization (AU), which involves a coordinated review by all competent authorities and results in the issuance of a unified permit. This regime is required for large-scale plants or installations with a significant territorial impact, as specified in Article 9 of the decree.

4.4. Sustainability decree

The Ministerial Decree of September 15, 2022, establishes specific eligibility and exclusion criteria for accessing financial incentives, particularly emphasizing compliance with sustainability standards and the reduction of greenhouse gas emissions. These criteria play a crucial role in promoting environmentally responsible practices across the energy sector, particularly within the biomethane supply chain.

With the decree of 7 August 2024, also known as the sustainability decree, the provisions already issued in the decree of 14 November 2019 are updated: in particular, it establishes updated criteria and procedures for the certification of biomethane sustainability, focusing on the reduction of greenhouse gas emissions, traceability, and the integrity of the mass balance system, which allows for the mixing of raw materials with different sustainability characteristics while preserving overall compliance.

Two technical standards are essential for implementing this framework: the UNI/TS 11567 and the UNI/TS 11429.

The first one defines the qualification of economic operators in the biomethane chain. It outlines the requirements for sustainability compliance, traceability of the product, and application of the mass balance approach. It includes guidance on individual and group certification, with the latter allowing smaller suppliers to participate in collective schemes coordinated by a central operator. It also defines minimum information obligations, verification criteria, and documentation for compliance audits. (27)

The second specifically addresses the mass balance system for biofuels and bioliquids. It sets out rules for documentation and management of flows, ensuring that sustainability characteristics are preserved and verifiable across production batches. It also includes requirements for defining the system boundaries, managing yields and losses, and ensuring correspondence between inputs and outputs within the system. (28)

Compliance with these standards is mandatory for access to financial incentives provided under the 2022 Ministerial Decree, which include CAPEX support and production-based tariffs. To qualify, plants must demonstrate at least 65% GHG savings for transport sector or 80% for other uses, compared to fossil fuel benchmarks.

Together, UNI/TS 11429 and 11567 create a harmonized framework for verifying the environmental sustainability of biomethane, ensuring both legal compliance and transparency across the supply chain. These standards help quantify CO_2 savings, prevent greenwashing, and reinforce market credibility by linking sustainability claims to certified traceable evidence.

Ultimately, adherence to these guidelines contributes to the broader goal of reducing greenhouse gas emissions and promoting a more sustainable energy sector.

5. Upgrading technologies

The upgrading process is designed to remove unwanted components and impurities from raw biogas, enriching its methane content and making the resulting mixture fully compatible with natural gas grid injection. Depending on the initial composition of the biogas, upgrading may involve the removal of carbon dioxide, water vapor, and trace substances such as oxygen, nitrogen, hydrogen sulphide, ammonia, or siloxanes (off-gas).

There is no universally superior technology; rather, the most appropriate solution depends on the specific application. The optimal techno-economic balance is strongly influenced by factors such as the quality and quantity of the incoming biogas, the intended use of the biomethane, and the plant's operational regime.

5.1. Membrane separation

Membranes are made of polymers and typically consist of very thin hollow fibers. These fibers are bundled into modules containing thousands of individual strands, forming a selective barrier that is permeable to carbon dioxide, water, and ammonia, while allowing only minimal passage of methane. This upgrading technology is currently the most widely adopted on the market, as it effectively combines membrane type and design with a multistage approach, essential for achieving the required level of biomethane purity.

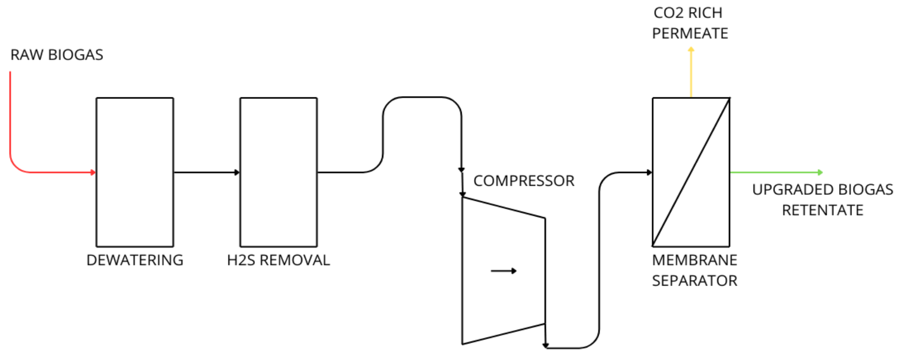

Figure 17 - Process flow diagram of the membrane separation technique. (29)

The raw biogas is normally cleaned before compression to remove water and hydrogen sulphide. In cases where ammonia, siloxanes and volatile organic carbons are expected in significant concentrations, these components are also commonly removed before the biogas upgrading. The water is removed to prevent condensation during compression and hydrogen sulphide is removed since it will not be sufficiently separated by the membranes. The water is commonly removed by cooling and condensation while hydrogen sulphide commonly is removed with activated carbon.

After that, the biogas is compressed to 6-20 bar, depending on the site specifications and on the manufacturer of the upgrading unit. Since oil lubricated compressors are commonly used, it is important to have an efficient oil separation after compression, also useful for removing the oil naturally occurring in the biogas.

In a membrane unit, the main part of the remaining water after compression is separated from the biomethane together with the carbon dioxide, so a gas dryer is commonly not needed to further decrease the dew point.

Figure 18 -Membrane upgrading unit in Foligno.

5.2. Pressure swing adsorption (PSA)

Pressure Swing Adsorption (PSA) is a technology based on the selectivity of a solid adsorbent, which acts as a molecular sieve, and on its regeneration, achieved by reducing the total pressure within the adsorption column. The result of this process is a gas stream enriched in the lighter component and purified of the heavier one.

The PSA process alternates between Adsorption phases, during which the gas exiting the column is enriched in the lighter component (methane) while the heavier one (carbon dioxide) is selectively retained by the adsorbent; and Regeneration phases, during which the adsorbed heavier component is desorbed and released in a separate gas stream.

The adsorbent material used must meet at least one of the following criteria: high selectivity toward CO_2, the adsorbent should exhibit stronger surface interactions with CO_2 than with CH_4

(equilibrium-based adsorbents); and pore size exclusion, the adsorbent's pores should allow CO_2 to diffuse through, while restricting CH_4 due to its larger molecular size (kinetic adsorbents).

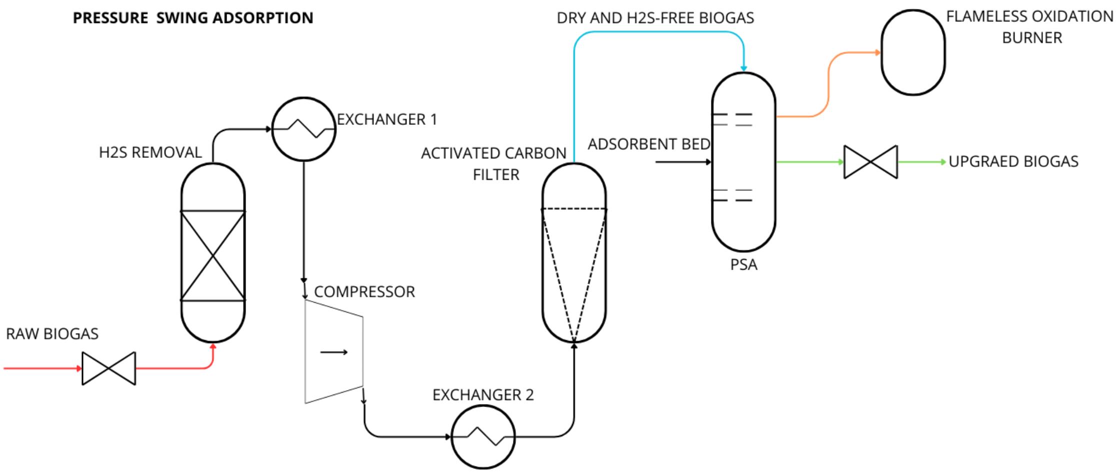

Figure 19 - Process flow diagram of the PSA technique. (30)

To avoid compromising the adsorption efficiency, water and hydrogen sulphide must be removed upstream of the PSA unit.


Figure 20 - PSA upgrading unit in Genova.

The PSA cycle typically consists of four phases:

1. Pressurization: raw biogas is injected into the system at ~1 bar until the operating adsorption pressure is reached.

2. Adsorption: CO_2 is retained within the adsorbent bed. Operating pressures range between 4–10 bar. The process halts when the bed approaches saturation with CO_2.

3. Depressurization: pressure is lowered to initiate desorption.

4. Regeneration: the adsorbent bed is regenerated by applying a vacuum (typically 0.1–0.2 bar), releasing the adsorbed CO_2. This phase lasts about 2–3 minutes, after which the bed can be reused for a new cycle.

Compared to thermal regeneration, pressure-based regeneration is faster and more energy-efficient.

This technology can produce biomethane with methane content above 97%. From a plant design perspective, PSA systems are compact, require relatively low capital investment, and are suitable for small-scale installations. However, one of the main limitations of PSA lies in its methane recovery efficiency.

5.3. Pressurized water scrubbing

The Pressurized Water Scrubbing (PWS) process operates on a straightforward principle: carbon dioxide and hydrogen sulphide are significantly more soluble in water than methane, allowing for their selective absorption into a water stream, thereby enabling the separation of methane from the raw biogas mixture.

Two main plant configurations are commercially available. The first is a once-through system, which uses water continuously without regenerating the process fluid. The second is a regenerative adsorption system, in which the same water is reused cyclically after undergoing a regeneration process.

Although hydrogen sulphide is a polar compound and therefore soluble in water, it is strongly recommended to remove H_2S prior to the upgrading process, due to its high corrosivity when dissolved in aqueous solution, which can compromise the integrity and lifespan of equipment.

During operation, the biogas is injected under pressure and at a low temperature (approximately 10°C) into the bottom of an absorption column. These conditions enhance the relative solubility of CO_2 compared to CH_4, thereby increasing the efficiency of the separation process. To regenerate the absorbent water, the system uses a flash evaporation step, which releases a gaseous stream containing a non-negligible amount of methane. This stream is typically recirculated back to the absorber inlet to maximize methane recovery.

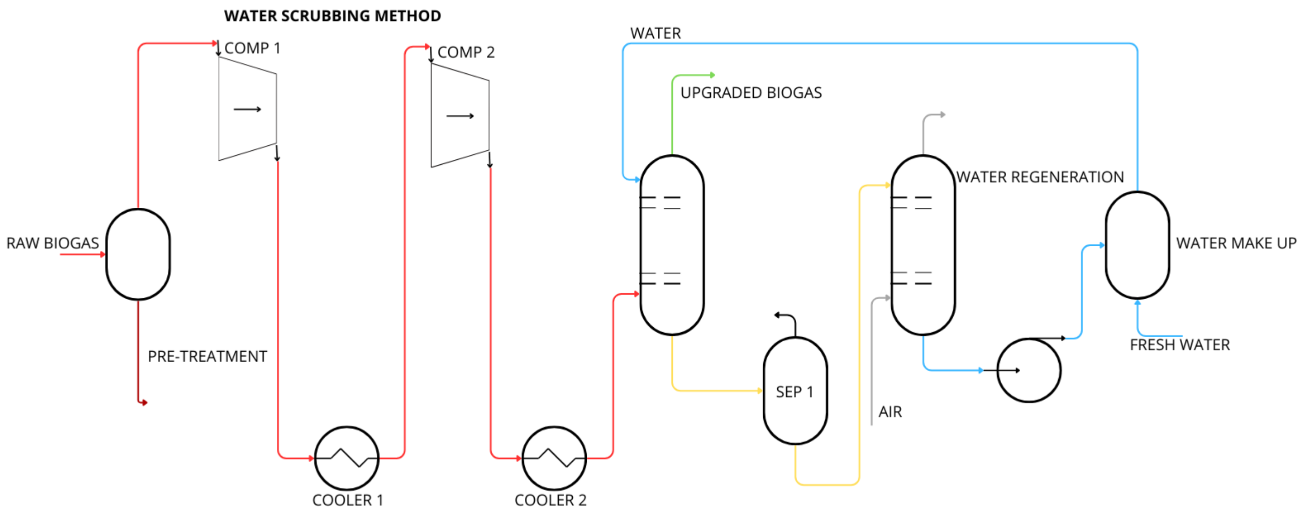

Figure 21 -Process flow diagram of the water scrubbing method. (31)

Subsequently, a desorption or stripping phase is carried out, during which atmospheric air is introduced into a separate column to purge a portion of the water. This prevents the accumulation of dissolved gases and maintains process stability. To ensure continuous operation, a certain volume of make-up water must be added to compensate for system losses.

The biomethane stream exiting the absorption column generally achieves a purity greater than 98%, and thanks to the recirculation of the flash gas, methane recovery rates of 98–99% can be attained.

5.4. Scrubbing with organic solvents

This technology can be fully classified under the same category as the previously described Pressurized Water Scrubbing (PWS) process, as it also relies on physical absorption. The main difference lies in the replacement of the water stream with an organic solvent, such as methanol, N-methylpyrrolidone (NMP), or polyethylene glycol ethers (PEGs).

By using these solvents and appropriately setting the process parameters, it is possible to achieve CO_2 solubility levels up to five times higher than those attainable with water. As a result, significantly lower solvent flow rates are required to achieve effective separation. The operating pressure remains similar to that used in conventional PWS systems, typically in the range of 6–8 bar, while the operating temperature is maintained around 20°C

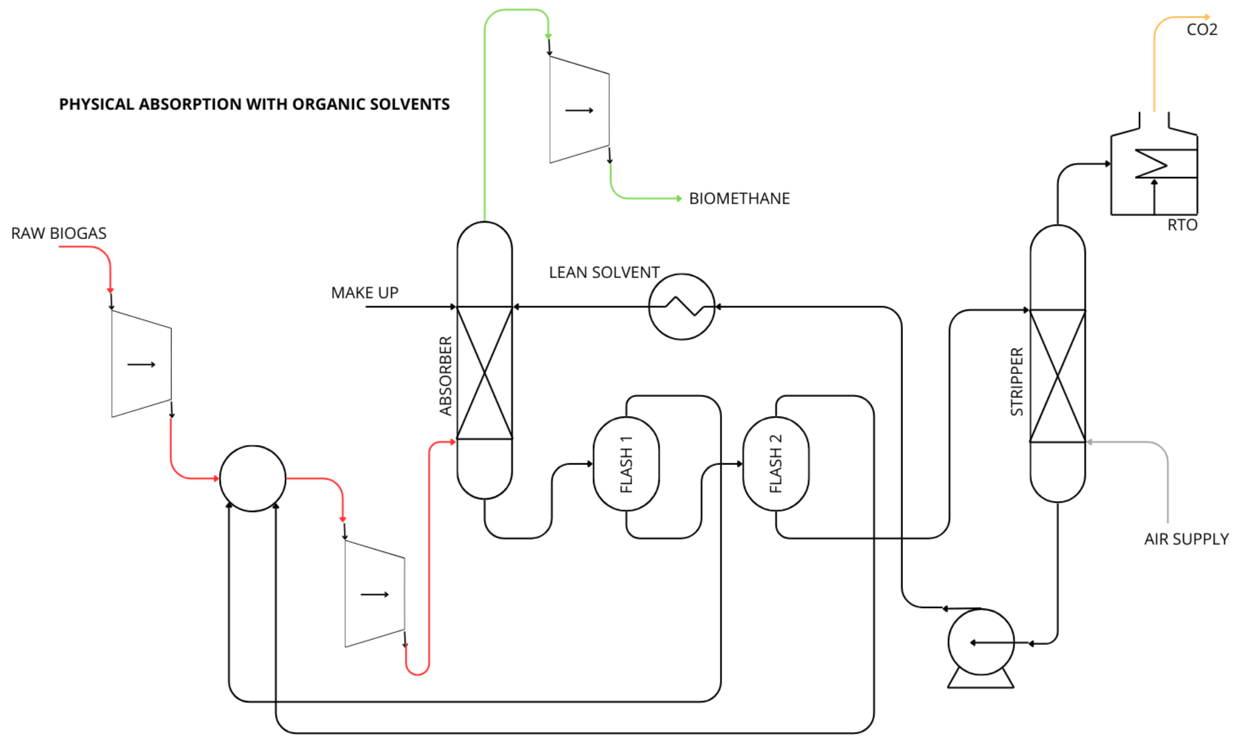

Figure 22 -Process flow diagram of the physical absorption method with organic solvents. (32)

In terms of methane purity and recovery, the performance of this configuration is fully comparable to that of water-based scrubbing systems. Ongoing research is focused on the development and characterization of new classes of solvents, including various ionic liquids, many of which function essentially as physical absorbents.

5.5. Amine scrubbing

The principle behind this method is the use of a chemical reagent that selectively binds to carbon dioxide. Initially, the gas is physically absorbed into the liquid phase, after which the targeted components undergo a chemical reaction with the absorbent solution, forming stable compounds within the liquid. This chemical reaction is highly selective, enabling the separation of only the undesired components, which exhibit a strong chemical affinity for the chosen solvent. As a result, the process can be operated at significantly lower pressures compared to other scrubbing techniques.

The most widely used absorbent in commercial applications is a solution of methyldiethanolamine (MDEA) activated with piperazine, commonly referred to as activated MDEA (aMDEA). In this configuration, the biogas stream is introduced into the absorption column in direct contact with the amine solution. Following the absorption process, the purified methane-rich gas exits from the top of the column, while the CO_2-laden solvent is directed to a regeneration stage.

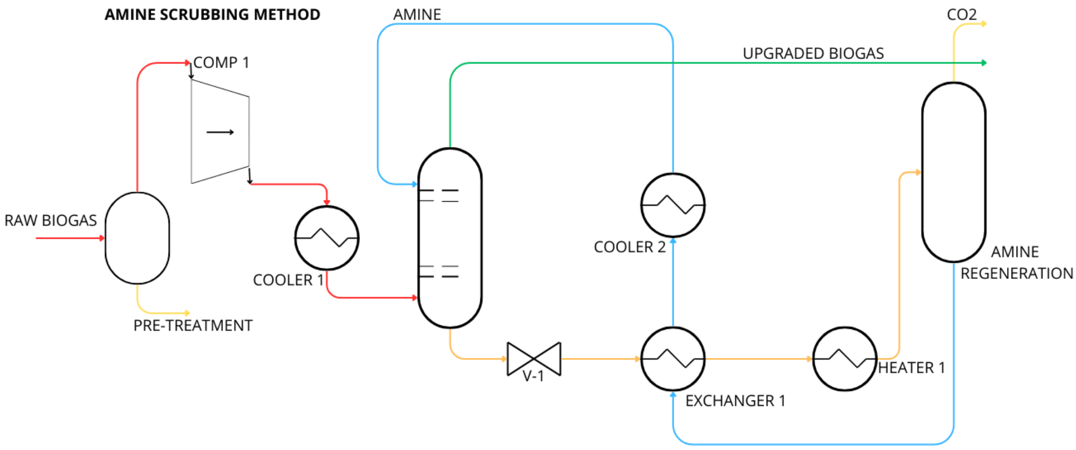

Figure 23 - Process flow diagram of the amine scrubbing method. (31)

Figure 24 - Upgrading plant for chemical absorption of potassium carbonate (Anzio), property of Asja.

As with other upgrading techniques, the absorbent is regenerated for reuse; however, the high selectivity and reactivity of amines, while beneficial for separation efficiency, represent a significant drawback in terms of energy demand. The regeneration phase requires considerable thermal energy to reverse the chemical bonds formed between CO_2 and the solvent, which can impact the overall process economics.

5.6. Cryogenic treatment

The cryogenic separation method relies on the principle that, at a fixed pressure, different gases condense at different temperatures. In this approach, compression plays a critical role in enhancing the thermodynamic efficiency of the subsequent cooling process. As the temperature drops, the components of the gas mixture begin to exhibit different phase change behaviours; notably, carbon dioxide condenses or sublimates at significantly higher temperatures than methane. For instance, CO_2 transitions to a solid or liquid state near -78.2°C under standard conditions, while methane remains in the gaseous phase until approximately -161.5°C. This temperature differential is exploited to achieve separation: by selectively condensing CO_2 while maintaining methane in the vapor phase, the process enables an efficient physical separation of the two gases without the use of chemical solvents. The cooling step is thus pivotal in isolating high purity biomethane and serves as the cornerstone of the cryogenic upgrading method.

5.7. Comparison and choice

It is not possible to identify a single upgrading technique as universally superior; instead, the selection must be based on the specific characteristics and requirements of the installation site. The analysis of some key performance indicators shows how all scrubbing technologies offer similar performance in terms of methane purity and recovery efficiency, but they differ significantly in terms of energy consumption and process complexity. Pressure Swing Adsorption typically exhibits lower methane recovery rates, yet it is easier to operate and does not require the continuous presence of specialized personnel. On the other hand, membrane separation technologies offer high flexibility in process layout and are particularly well-suited for small-scale plants, where the biomethane can be utilized at delivery pressure, eliminating the need for further compression.

Technology	**Biomethane purity [%]**	**Consumes [kWh/Nm^3]**
Pressure Swing Adsorption	98-99	0,2-0,3
Pressurized Water Scrubbing	98	0,23-0,3
Scrubbing with organic solvents	98	0,21-0,23
Amine scrubbing	99,8	0,12-0,14
Membrane separation	98	0,2-0,25

Table 8 - Upgrading technologies Key Performance Indicators. (33)

In addition, all the upgrading technologies analysed show a similar trend of decreasing unit capital and operating costs as the biomethane throughput increases, highlighting the importance of scale in economic optimization.

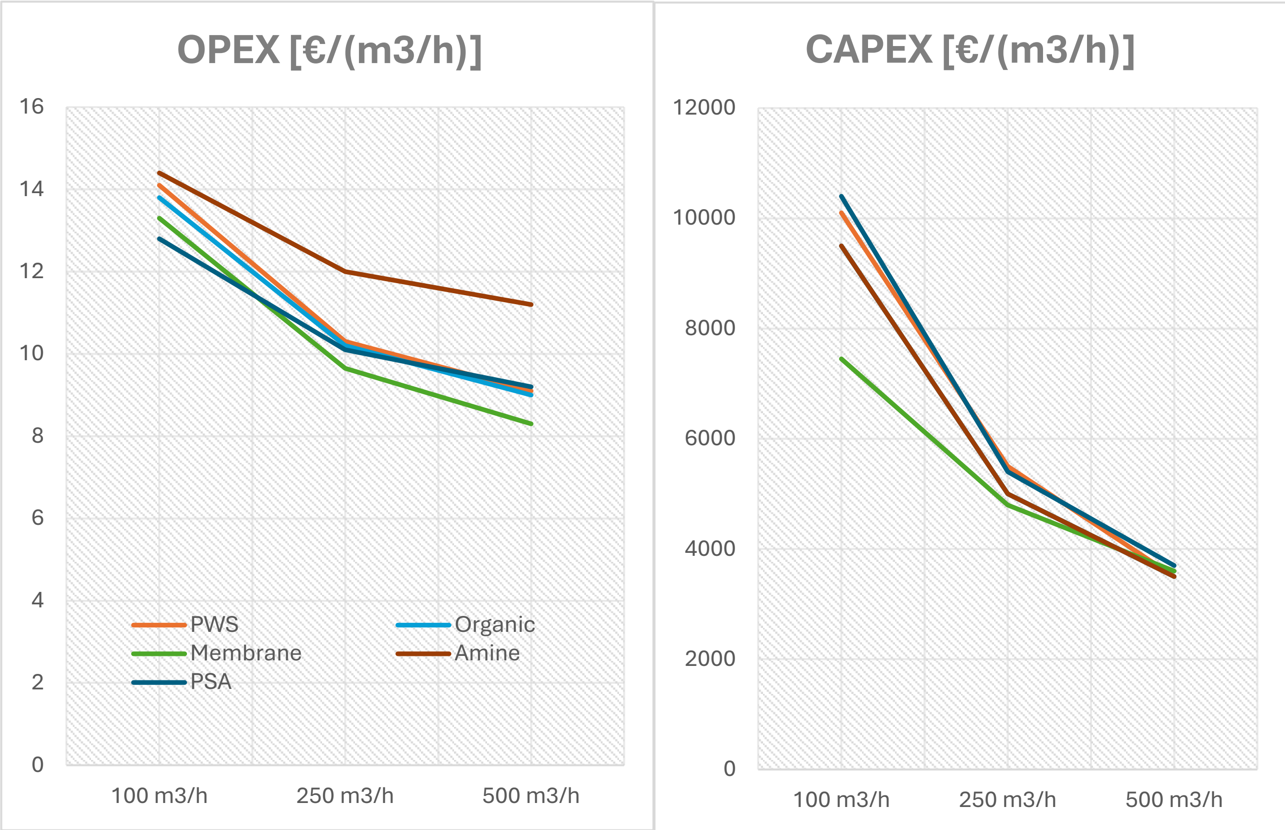

Figure 25 - CAPEX and OPEX expenditures for different technologies and streams. (29)

For the La Falchetta plant, a system based on polymeric membranes, made of materials such as polysulfone, polyimide, and polydimethylsiloxane, was selected. While this technology requires high operating pressures, typically in the range of 6–20 bar, and is therefore associated with a significant energy demand, its selection was motivated by a combination of proven reliability, widespread commercial use, and solid technical performance.

Additional factors influencing the decision included the system's independence from secondary chemical agents, the absence of solid or liquid waste byproducts, aside from the off-gas, and the operational flexibility that allows the system to dynamically respond to fluctuations in process conditions.

6. Reconversion of the La Falchetta plant

The existing facility at La Falchetta will be upgraded to include a biogas upgrading process, enabling the conversion of biogas produced through the anaerobic digestion of livestock effluents and agricultural biomass into biomethane. This upgraded biomethane will be injected into the national gas grid and will be used in cogeneration systems.

The digestate resulting from the anaerobic digestion process will be separated into liquid and solid fractions. These will be used primarily for agronomic application on the surrounding farmland, with a portion supplied to third-party agricultural operators.

The proposed biomethane production system will employ standard wet anaerobic digestion technology, widely used in agricultural contexts, combined with a membrane-based upgrading unit. The raw biogas will undergo dehumidification and purification, before entering the upgrading section, where it will be refined to meet biomethane quality standards for grid injection.

The facility will be capable of producing approximately 300 Nm^3/h of methane contained in the biogas, of which about 250 Nm^3/h will be injected into the national gas grid. The remaining portion will be consumed on-site to meet the electrical and thermal energy demands of the process.

6.1. Authorization path identified

Under the current Italian regulatory framework, the La Falchetta plant, with the nominal production capacity of the upgrading system indicated on the nameplate of 300 Sm^3/h, qualifies for the Simplified Authorization Procedure (PAS). In contrast, biomethane plants with a production capacity exceeding 500 Sm^3/h are subject to the Single Authorization (AU) regime.

Accordingly, the following prerequisites for the applicability of PAS have been verified: urban planning compatibility, legal entitlement to use the land, and compliance with the capacity threshold. These conditions confirm the project’s alignment with approved urban development plans and existing building regulations, adherence to applicable safety and hygiene standards, and the availability of the land required both for the plant itself and for the construction of related infrastructure.

In the Piedmont Region, Regulation 10/R is currently in force, which governs, among other aspects, the agronomic use of soil improvers derived from livestock effluents, as well as the action plan for areas designated as vulnerable to nitrates from agricultural sources.

The regulation defines the areas and time periods suitable for field spreading of both liquid and solid fractions, with the aim of limiting nitrate leaching and preventing the eutrophication of water resources.

To comply with the guidelines set out in the regulation, a minimum storage period of 90 days for solid digestate and 180 days for liquid digestate must be ensured.

Considering these restrictions, the proposed conversion project includes only minor modifications to the digestate storage section.

On March 12, 2021, the Piedmont Region issued DGR 15-2970, which provides guidelines for the assessment of environmental and territorial sustainability within the administrative review process for facilities involved in the recovery of organic waste (EER 20 01 08) for the production of biogas and biomethane.

However, from a strictly legal perspective, this regulation does not apply to the facility under consideration, which operates exclusively with biomass and by-products, rather than waste. Furthermore, as confirmed by the Italian Ministry of the Environment and Energy Security (MASE), the regional provisions concerning non-suitable areas are not applicable to sites deemed suitable under Article 20 of Legislative Decree No. 199/2021.

Nevertheless, due to the technological and infrastructural similarities between this facility and those covered by the regional guidelines, it is appropriate to make reference to this regulatory framework for context and completeness.

Moreover, since the plant operates in an inter-company configuration, meaning that Asja is the sole owner of the anaerobic digestion and upgrading plant, but not of the agricultural company supplying the organic feedstock, it was necessary to establish long-term contracts for the multi-year supply of biomass, in order to ensure that the entire system can be classified within at least one of the categories permitted by the various regulatory procedures.

6.2. Project proposal

The planned intervention largely maintains the structure of the existing plant, while introducing several significant modifications aimed at integrating the biomethane production process. The main actions include:

- The enlargement of the feed hopper, to improve substrate handling and processing capacity
- The expansion of the biogas cleaning section and construction of a new biomethane production unit
- The replacement of the current cogeneration unit with a lower-capacity model, along with relocation of the associated technical room
- The installation of a tent-like plastic cover (not designed for gas recovery) over one of the digestate storage tanks

The upgraded facility will include the following components:

Section	Description
Incoming storage (I)	3 silage storage trenches
Loading matrices (L)	Pre-tank for loading sewage Loading hopper
Digestion (D)	Primary digester (2 concentric digesters) Post-fermenter with gasometer
Gas line and biogas cleaning (G)	Chiller for dehumidification of the cogenerator line Chiller for dehumidification of the upgrading line Activated carbon tanks Emergency torch
Energy production (E)	Cogenerator
Biomethane production (B)	Membrane upgrading system Membrane compressor
Solid-liquid separation (S)	Digestate separator
Digestate storage (V)	Solid digestate storage platform Solid digestate storage trench 3 liquid digestate storage tanks, of which: n.1 with cover and gas recovery (Post-fermenter) n.2 completely underground n.3 with cover without recovery
General plant services (T)	Technical room for pumping matrices Firefighting room 2 technical rooms Weighs

Table 9 - Sections of the reconverted plant

6.2.1. Incoming storage

The proposed design modification includes a change in the digester feedstock, resulting in an increase in the quantity and of input materials. However, the existing storage section will be retained, as it remains sufficient and effective even following the planned upgrades.

Of the four existing silage trenches, the three larger ones will continue to be used for storing incoming biomass. This biomass will be compacted and covered with PVC sheets to ensure optimal preservation conditions. The smaller trench will be dedicated to the storage of separated solid digestate.

Figure 26 - Underground silos for the vinasse storage that will remain in operation.

It is important to emphasize the critical role of biomass covering operations in establishing ideal conditions for ensiling. The PVC sheets serve to prevent rainwater infiltration and limit oxygen ingress. The oxygen naturally present within the biomass mass is consumed during the initial stages of ensiling by aerobic bacteria, which initiate acetic fermentation, lowering the pH to values between 4 and 5.

From the second day after silo filling, lactic acid fermentation begins, gradually intensifying until reaching, after approximately 15 to 20 days, a critical level of acidity with pH from 4.2 to 3.8. This environment is essential to inhibit the activity of butyric and proteolytic bacteria, as well as deamination phenomena, all of which would otherwise significantly reduce the energy value of the preserved biomass.

6.2.2. Loading matrices

The liquid fraction will be loaded into the digester always with the same system of pump and pre-tank already existent, while the stored solid feedstocks are fed into the digester using a hopper system. Although the existing hopper would technically remain adequate even after the planned increase in feedstock volumes, it would require a significantly higher number of loading cycles. This increased operational demand would necessitate the continuous presence of an operator, including during nighttime hours.

Figure 27 - Pre-tank for the liquid biomass storage and feeding.

Figure 28 - Feeding hopper for the solid biomass.

To address this issue, the proposed project includes the enlargement of the hopper, thereby reducing the number of loading cycles needed. This adjustment ensures a consistent and sufficient supply of feedstock to the digester while avoiding a nighttime working shift, thereby supporting the optimal performance and stability of the anaerobic digestion process.

6.2.3. Digestion

The digestion section will not undergo substantial modifications, it will remain equipped with a three-stage anaerobic digestion system consisting of insulated, reinforced concrete fermenters. The first two digesters are arranged coaxially and are dedicated to sequential acidogenic and methanogenic phases. The outer fermenter has a diameter of 30 meters, while the inner unit measures 18 meters in diameter; both share the same height of 6 meters. A third fermenter, also heated, ensures the completion of the degradation process and maximizes biogas recovery which is accumulated inside the gasometer.

All digesters operate under mesophilic conditions, approximately 42 °C, maintained through radiant ring heating systems. Substrate mixing is ensured by vertical and lateral agitators, which prevent stratification and optimize microbial activity. The tanks are thermally insulated to minimize heat losses and improve energy efficiency. The biogas produced is collected in domes placed atop the fermenters, with a dedicated gas holder allowing for buffer storage. Digestate from the process is directed to a dedicated storage tank before subsequent handling and use.

Calculations confirm that the existing configuration, remains adequate even following the planned increase in feedstock input. Specifically, the current setup in combination with the proposed interventions ensure a hydraulic retention time of approximately 33 days.

Figure 29 - La Falchetta plant with its gasometer over the third digester.

6.2.4. Gas line and biogas cleaning

The biogas cleaning section will undergo significant modifications. Most notably, an activated carbon system will be installed for the removal of hydrogen sulphide. Although in this case H_2S formation is partially mitigated through the utilization of iron hydroxide and ferric chloride (which neutralize hydrogen sulphide by chemically binding to it), a dedicated activated carbon filtration unit will still be implemented to ensure more comprehensive purification.

The new activated carbon desulfurization unit will consist of two tanks, each with a capacity of 4 m^3. This system effectively removes the residual H_2S, along with VOCs, siloxanes, and other trace contaminants. These compounds are adsorbed onto the surface of the activated carbon and subsequently oxidized through a selective oxidation reaction, catalysed by the presence of metal oxides impregnated onto the carbon substrate.

To maximize performance, the activated carbon is selected for its high specific surface area and is chemically functionalized with various metal oxides to ensure efficient removal of H_2S, VOCs, and siloxanes from the biogas stream.

In addition, since the raw biogas exiting the digester contains a high moisture content, chillers will be installed: one along the line feeding the cogeneration unit and another on the line directed toward the upgrading section. These chillers operate by cooling the biogas to temperatures around 4–5°C, thereby inducing water condensation and enabling the removal of the majority of water vapor from the gas stream.

Lastly, the existing emergency flare will be retained to ensure safety in case of operational anomalies or excess gas production.

Figure 30 - Chiller for the biogas dehumidification.

6.2.5. Energy production

In light of the new plant configuration, the currently installed 625 kWe engine is oversized for the facility's updated energy demands. Therefore, it will be replaced with a 200 kWe cogeneration unit, adequately dimensioned to cover the electrical and thermal self-consumption of the plant. This new cogenerator will be installed in a dedicated container, to be installed adjacent to one of the existing livestock barns.

According to regulatory requirements, the energy consumed by auxiliary services must be deducted from the total energy associated with the injected biomethane, unless it is supplied by renewable sources specifically dedicated to the plant and not supported by public incentives. In this case, the energy required for auxiliary operations will be entirely generated from biogas, thus qualifying as renewable.

Electricity from the national grid will only be drawn during maintenance or downtime of the cogeneration unit.

The thermal energy demand of the facility will also be met by the biogas-fueled cogeneration system, which will include a heat recovery system capable of extracting energy from the refrigeration water of the motor and from the exhaust gases at approximately 180°C.

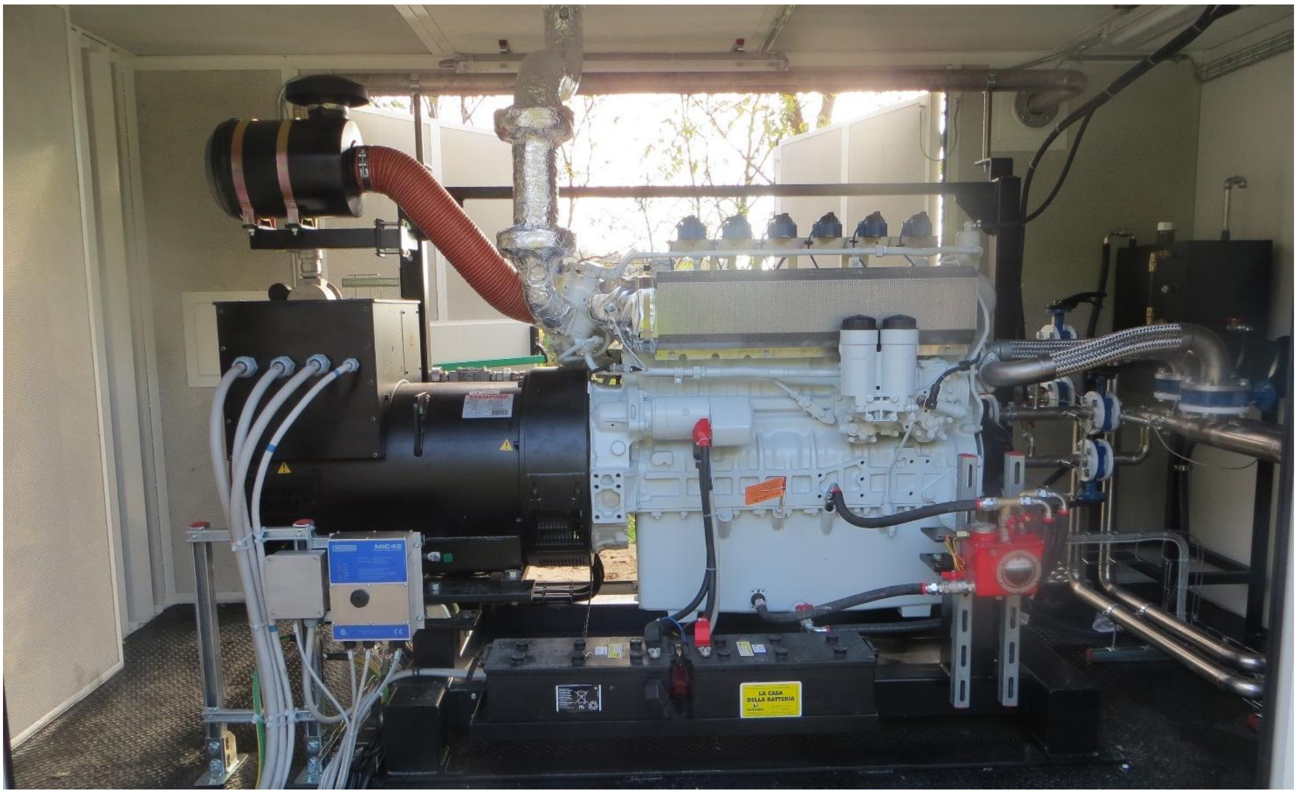

Figure 31 – New cogeneration unit of 200kWe.

6.2.6. Biomethane production

The biomethane section of the plant will be entirely newly constructed. It will receive incoming biogas and subject it to an upgrading process aimed at separating CO_2 from CH_4. In this specific case, a membrane-based upgrading system has been selected, which operates at a working pressure of approximately 11 bar. Consequently, a dedicated gas compression unit will also be installed.

The upgrading unit will be mounted on a reinforced concrete foundation located near the existing cogeneration system. It will consist of a metal container measuring 10.00 x 2.44 meters, housing both the membrane modules for CO_2 removal and the control panels governing the upgrading process. The activated carbon filters and gas compression station will be installed adjacent to the membrane container.

Given the volume of biogas to be treated, a three-stage membrane configuration will be implemented. Prior to entering the refining system, the raw biogas must undergo pre-treatment, including the removal of water vapor and undesired trace components, to protect the membrane integrity and ensure process efficiency.

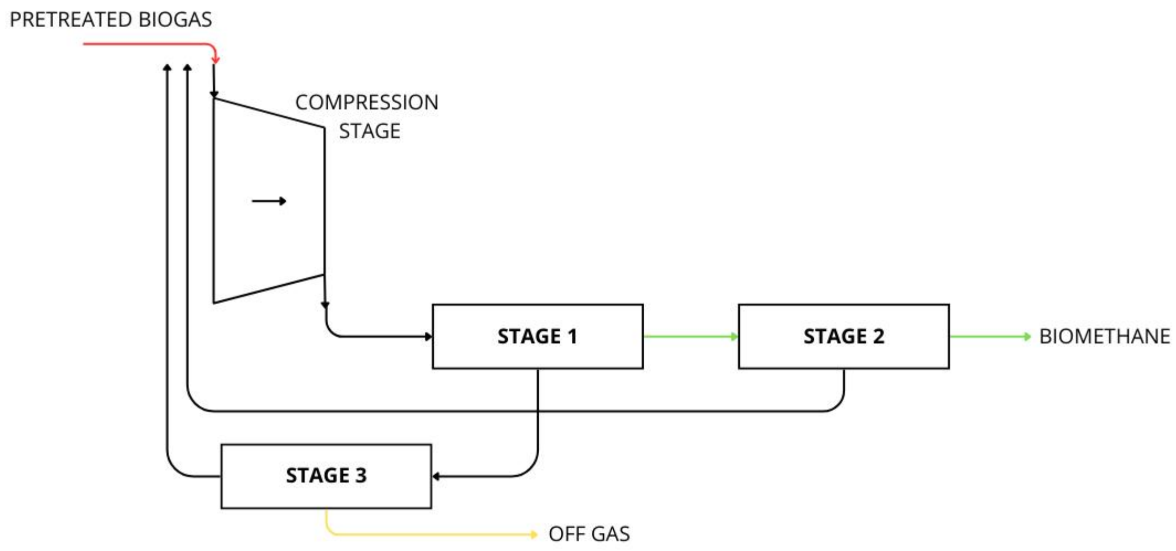

Figure 32 - Membrane upgrading system scheme.

The permeate from the second membrane stage and the retentate from the third stage will be recirculated to the suction side of the gas compressor. The gas mixture continues cycling through the system until the desired methane concentration is achieved in the final output stream.

The flexibility of membrane technology allows for a system capable of dynamically adapting to changing process conditions, maintaining high performance even under partial load conditions. Performance remains stable even in the event of variations in the composition or quantity of the gas stream to be treated, thanks to the modular configuration of multiple membrane filtration stages and the ability to operate under differential pressure regimes.

At the outlet of the membrane upgrading system, two gas streams are generated: purified biomethane and a residual stream known as off gas.

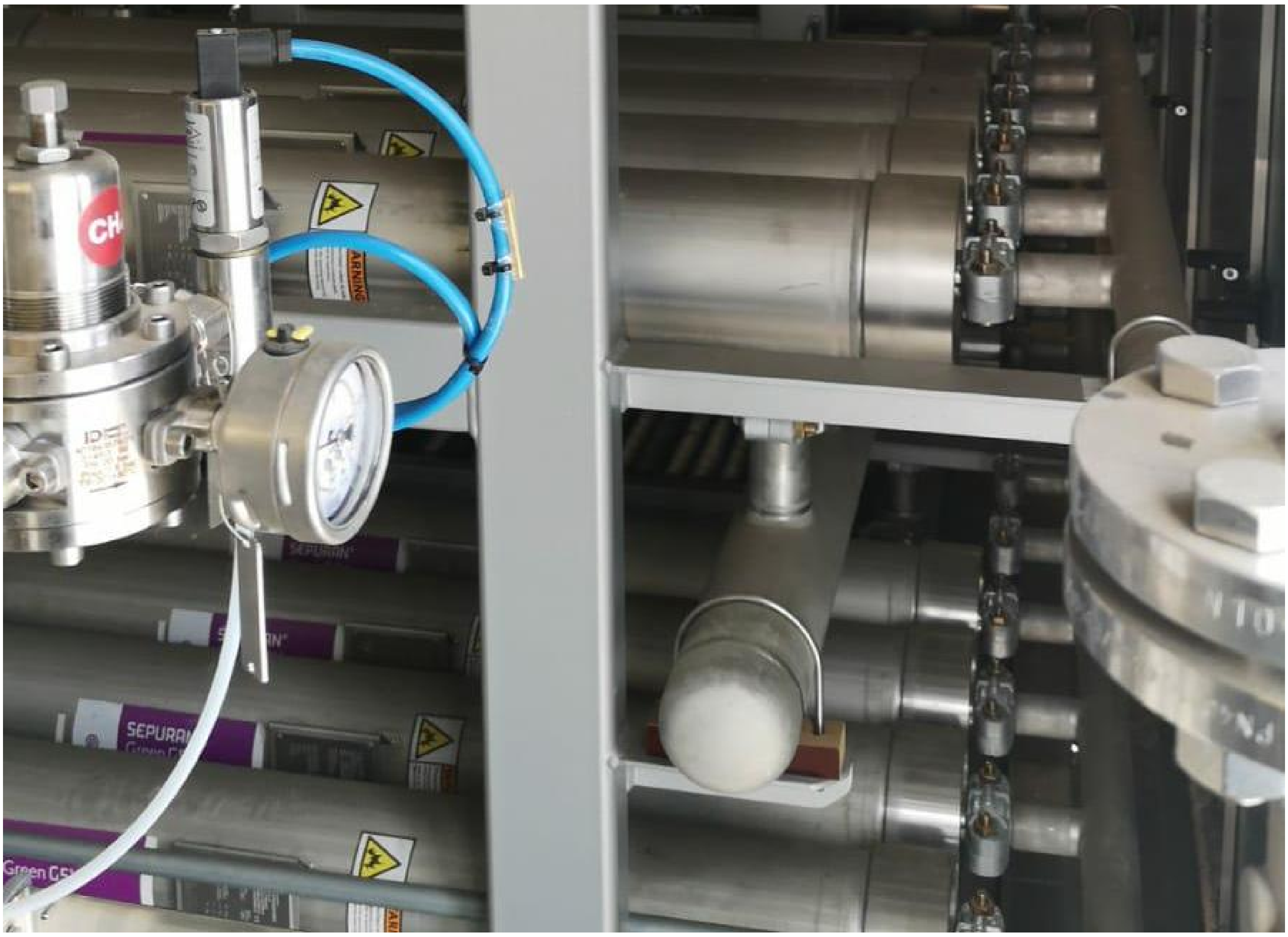

Figure 33 - Membrane upgrading unit from Asja plant in Legnano.

The upgrading plant will be sized to treat the entire volume of biogas produced by the anaerobic digestion section. Under full load conditions and considering the maximum production capacity of the digestion unit, the system will be capable of producing up to 300 Sm^3/h of biomethane.

The methane recovery efficiency is expected to exceed 99%, with very high CO_2 separation efficiency. The biomethane produced will meet all the specifications required for grid injection, in accordance with the standard UNI/TS 11537:2019 – *Injection of biomethane into the natural gas transportation and distribution networks*. Compressor operation will be regulated using frequency inverters, allowing the system to automatically modulate the pressure according to process requirements. In the presence of contaminants in the raw biogas, for instance, the system can increase the pressure to maintain separation efficiency, which can also serve as an indicator of undetected impurities in the gas stream.

- Technical specifications for the introduction of biomethane into the grid

To regulate the injection of biomethane into the natural gas grid, a set of regulations establishes the technical specifications that must be met, covering both the physico-chemical properties and the technical requirements for injection into transport and distribution networks.

The minimum characteristics that biomethane must meet for grid injection are defined by the UNI/TS 11537 standard.

Characteristic	Symbol	Value	Unit of measure
Higher heating value	HHV	34,95-45,28	MJ/Smc
Wobbe index	WI	47,31-52,33	MJ/Smc
Relative density	d	0,555-0,7	-
Water dew point ≤ -5°C at 7000kPa			
Dew point of hydrocarbons ≤ 0°C in the pressure range 100kPa and 7000kPa relative			
Oxygen content	O_2	≤0,6	%mol
Carbon dioxide content	CO_2	≤2,5	%mol
Hydrogen sulphide content	H_2S	≤5	mg/Smc
Sulfur content from hydrogen sulphide and carbonyl sulphide	-	≤5	mg/Smc
Sulfur content from mercaptans	-	≤6	mg/Smc
Total sulphur content		≤20	mg/Smc

Table 10 - Chemical and energetic characteristics of biomethane. (34)

Additionally, content limits for various elements are established to ensure safety and compliance with regulatory standards.

Characteristic	Symbol	Value	Unit of measure
Total volatile silicon	Si	0,3-1	mg/Smc
Carbon monoxide	CO	≤0,1	%mol
Ammonia	NH_3	≤10	mg/Smc
Amines	-	≤10	mg/Smc
Hydrogen	H_2	≤1	%Vol
Fluorine	F	≤3	mg/Smc
Chlorine	Cl	≤1	mg/Smc
Compressor oil	-	-	-
Dust	-	-	-

Table 11 - Content limits in biomethane. (34)

Figure 34 - Biomethane injection into the grid.

- REMI cabin station

A REMI station will be installed to manage the injection of biomethane into the natural gas grid.

The primary parameter to be measured at the point of delivery is the Higher Heating Value (HHV), which is determined through the continuous measurement of the gas's physical properties by a gas quality analyzer, as specified by the SNAM network code for plants with a daily flow rate below 100,000 Smc.

Gas quality analysis will be carried out near the upgrading system, in order to simplify operational logistics.

Only biomethane that meets quality standards will be sent to the REMI station, where fiscal metering and official grid delivery will take place.

It should be noted that both the REMI station and the injection area will be designed and authorized independently by the network operator.

Figure 35 - REMI cabin station from Asja's plant in Genova.

6.2.7. Digestate storage

The digestate produced from the post-digester will be directed to the solid-liquid separation system, that will remain the same already existent.

The infrastructure for biomass storage will not undergo major changes, the liquid fraction will be sent to the existing Storage Tank 1, which is already equipped with a gas recovery cover, and subsequently transferred to existing Tanks 2 and 3.

Tank 3, that is currently covered with a natural crust, will be equipped with a tent-type plastic cover, without gas recovery, the intervention aims to reduce odour and ammonia emissions during the digestate storage phase.

Additionally, for the purpose of calculating the required storage time, the volumes of all three tanks, together with the secondary digester, are taken into account obtaining a retention time for the liquid fraction of the digestate equal to 181,2 days.

Based on the available storage volumes, the overall storage time for the non-stackable digestate will exceed the minimum requirement of 180 days established by Regional Regulation 10R/2007, thereby complying with the environmental protection limits.

As for the solid fraction of the digestate, the plant is already equipped with a storage platform, which will be maintained. The solid fraction of the digestate will therefore be discharged from the screw press separator directly onto the existing storage platform, which essentially consists of a three-walled trench. The platform is located adjacent to the silage storage trenches. In order to ensure sufficient storage capacity for the solid fraction of the digestate, it is planned to use, in addition to the platform, the smaller-sized trench.

Based on the available storage volumes of the pit and the trench dedicated to the storage of the solid fraction of digestate, a retention time of 137 days is obtained.

The guaranteed storage period exceeds the minimum threshold of 90 days required by the current regulation 10R/2007, thereby complying with the environmental protection limits.

Figure 36 - Solid-liquid separator next to the digestate's trench.

7. Data elaboration

This chapter presents the technical and analytical elaboration of the data collected during the reconversion project of the "La Falchetta" biogas plant. The objective is to assess the plant's performance in terms of material and energy flows, operational efficiency, environmental impact, and economic viability. The analysis is structured around key components including mass and energy balances, operational data, and sustainability indicators. These metrics provide a quantitative foundation for evaluating the effectiveness of the biomethane conversion process and for comparing the upgraded system with the former electricity production setup.

7.1. Mass balance

The new feeding plan includes an average supply consisting of approximately 8,100 tons per year of livestock by-products such as cattle slurry and manure, pig manure and slurry, and bovine ruminal content, along with 3,730 tons per year of agri-food industry by-products and 10,800 tons per year of plant-based crops such as maize, triticale, and grain sorghum.

The recipe includes:

Description	**Quantity [t/y]**	**Quantity [t/d]**
Bovine rumen content	1 100	3,0
Wholemeal corn mash	2 000	5,5
Corn flour	3 000	8,2
Fruit and vegetables residues	730	2,0
Corn silage – whole plant	4 300	11,8
Triticale silage	3 000	8,2
Sorgum silage - grain	1 500	4,1
Cattle manure - straw	4 000	11,0
Cattle slurry	1 500	4,1
Pig slurry	1 500	4,1
TOTAL MATRICES	**22 630**	**62,0**
Rainwater	3 000	8,2
Separate liquid digestate ricirculation	18 250	50,0
TOTAL INLET	**43 880**	**120,2**

Table 12 - Description of the digester's feeding recipe.

The reported values represent average quantities; the composition of the input feedstock may vary slightly depending on the seasonality and availability of the input materials. The formulation remains flexible, adapting to supplier management constraints while remaining in full compliance with regulatory requirements, particularly the mandatory reduction of CO_2-equivalent emissions by at least 80% compared to the fossil-based reference system.

It is noteworthy that the calculation includes approximately 8 tons per day of rainwater, a quantity that is naturally dependent on meteorological conditions, as well as 50 tons per day of recirculated liquid digestate drawn directly from storage tank 1 equipped with a gas holder. This specific fraction of digestate bypasses the conventional flow path through tanks 2 and 3 and is instead reintroduced directly into the digester.

The incoming mass flow can be calculated based on the proposed feedstock mix and the operating mechanism of the plant. Given that the input mixture comprising biomass, water, and recirculated digestate, contains 5.2 kg of nitrogen per ton, the total nitrogen content of the inflow can also be determined.

The mass flow at the inlet, along with the corresponding nitrogen content, can be summarized as follows:

INLET		Quantity [t/y]	Quantity [t/d]	N content [kg_N/ton]	N content [kg_N/y]
	Solid content	8 496	23,3	-	-
	H_2O	14 134	38,7	-	-
FEEDSTOCK		22 630	62,0	5,3	119 100
Air		5	0,01	753,5	3 790
Water		3 000	8,2	-	-
Total Solids		8 496	23,3		-
Total water		17 134	46,9		-
	Solid content	1 220	3,3	-	-
	H_2O	17 030	46,7	-	-
RECIRCULATION		18 250	50,0	5,7	104 030
	Solid content	9 721	26,6	-	-
	H_2O	34 164	93,6	-	-
TOTAL		**43 885**	**120,2**	**5,2**	**226 920**

Table 13 - Summary of mass flow at the inlet.

From this data, it is possible to estimate the expected production of biogas and methane. The daily input is derived by dividing the annual input by 365 days. Knowing the total solids content of each feedstock, the volatile solids percentage of the TS, and the biochemical methane potential (BMP, expressed in cubic meters of methane per ton of VS), it is possible to calculate the methane production per ton as well as the methane output on a daily or annual basis.

Description	Quantity t/y	CH_4 Nm^3/t	CH_4 Nm^3/h	CH_4 Nm^3/y	Biogas Nm^3/t	Biogas Nm^3/h	Biogas Nm^3/y
Bovine rumen content	1 100	49,07	6,2	53 976	84,9	11	93 384
Wholemeal corn mash	2 000	262,241	59,9	524 811	524,8	120	1 049 621
Corn flour	3 000	275,06	94,2	825 178	529,0	181	1 586 880
Fruit and vegetables residues	730	17,10	1,4	12 483	28,5	2	20 805
Corn silage whole plant	4 300	118,66	58,2	510 233	228,2	112	981 217
Triticale silage	3 000	97,65	33,4	292 950	187,8	64	563 365
Sorgum silage, grain	1 500	88,21	15,1	132 314	176,4	30	264 629
Cattle manure, straw	4 000	37,63	17,2	150 519	68,4	31	273 672
Cattle slurry	1 500	18,10	3,1	27 144	31,2	5	46 800
Pig slurry	1 500	7,97	1,4	11 952	11,7	2	17 576
TOTAL MATRICES	**22 630**	**112,3**	**290,1**	**2 541 560**	**216,4**	**559**	**4 897 949**

Table 14 - Expected productions of biogas and biomethane.

The biogas produced through anaerobic digestion will primarily consist of methane, along with carbon dioxide, nitrogen, and a small fraction of hydrogen sulfide (H_2S). Based on the biogas yields assumed, it is possible to estimate the expected daily production.

By subtracting the mass of biogas produced and taking into account its nitrogen content, calculated from the average biogas composition, it is then possible to determine the nitrogen content of the outgoing biogas stream.

Gas	Density [kg/m^3]	Quantity [% vv tot]	Quantity [Nm^3/y]	Quantity [t/y]
N_2	1,067	0,1	4 897	5,2

Table 15 -Nitrogen content in the biogas mixture.

OUTLET		Quantity [t/y]	Quantity [t/d]	N content [kg_N/y]
	CH_4	1 801	4,9	-
	CO_2, N_2 and other gases	4 531	12,4	5 990
	Water vapour	31	0,1	-
BIOGAS		6 363	17,4	5 990
Water condensate		337	0,9	1 680
Biogass losses		68	0,2	-
	Solid content	3 389	9,3	-
	Water	33 795	92,6	-
DIGESTATE		37 117	101,7	219 250
TOTAL		**43 885**	**120,2**	**226 920**

Table 16 - Summary of mass flow at the outlet.

A comparison between the tables 16 and 19 shows that the total input mass and the corresponding nitrogen content are equal to those at the output. During the process, a series of chemical reactions and physical phase changes occur; however, these do not alter the overall mass or nitrogen content of the system.

What does change is the energy content and the form of energy of the reactants and products. For this reason, a mass balance alone is not sufficient to fully describe the anaerobic digestion process.

7.2. Energy balance

The energy carrier generated by the anaerobic digestion process is biogas, which will be partially directed to the upgrading section for biomethane production, while another portion will be used to power the CHP (combined heat and power) unit, covering the plant's electrical and thermal demands.

The expected annual biogas production is approximately 4 897 949 normal cubic meters Nm^3, corresponding to 2 541 560 Nm^3 of biomethane per year. A portion of this biomethane will be injected into the grid, while an undesired fraction may be lost through hydraulic seals or venting systems.

Considering a LHV of 9.44 kWh/Sm^3 and converting the flows from normal cubic meters to standard cubic meters by multiplying by 1.0548 (Sm^3/Nm^3), a methane energy balance can be carried out.

CH_4	[Sm^3/y]	[MWh/y]
Methane produced per year	2 680 841	25 307
Methane lost in biogas (fugitive emissions)	26 808	253
Methane captured and used	533 460	5 036
Methane self-consumed	516 108	4 872
Methane flared due to upgrading shutdown	19 534	184
Methane lost in off gas of the upgrade system	10 643	100
Methane fed into the network in biomethane	2 117 883	19 993

Table 17 - Methane balance.

It is estimated that approximately 79% of the producible methane will be injected into the gas grid, while nearly 20% will be used in the CHP unit. The remaining fraction, approximately 1%, accounts for inevitable losses, which will be minimized as much as technically feasible.

The plant's internal consumption will be fully met by the electricity generated by the CHP unit, except during malfunction events when grid electricity may be temporarily required. The CHP unit planned for the reconverted plant will have a nominal electrical capacity of 200 kWe and is expected to operate for 8,500 hours per year, equivalent to 97% annual uptime, accounting for routine maintenance and service shutdowns.

The electricity produced is required not only to operate all auxiliary systems, such as the separator and upgrading section, but also to supply non-auxiliary services, including lighting.

Electric Energy	[kWh]	[kW] – 8760h
Biologic unit auxiliaries	473 375	54,0
Pretreatment and gas cleaning auxiliaries	110 107	12,6
Upgrading and compression auxiliaries	1 011 000	115,4
Separation auxiliaries	9 279	1,1
Generators electric auxiliaries	57 312	6,5
Electric consumption non auxiliaries	23 669	2,7
Total electric energy consumption	1 684 742	192,3
Gross energy production CHP	1 613 473	184,2
Self-consumption electric Energy	1 613 473	184,2
Electricity bought from the grid	49 353	5,6
Electricity inputs to the grid	0	0,0
Electricity grid balance	-49 353	-5,6

Table 18 - Electric Energy balance.

As shown in the energy balance, the electricity generated by the CHP unit will not be sufficient to meet all consumption needs. Therefore, electricity will occasionally need to be drawn from the grid, primarily during CHP downtime, though such imports will remain limited in scale.

The thermal energy output from the CHP unit will be generated at full load via two recovery systems: an engine cooling water heat exchanger and an exhaust gas heat exchanger, with a combined output of approximately 244 kWt. Additional thermal energy will be recovered from the compressors in the upgrading system.

As for thermal energy use, the main auxiliary load is the digester heating system. Non-auxiliary thermal uses, such as office space heating, will be minor in terms of thermal demand.

Thermal Energy	kWh	kW - avg
Cogenerator	1 817 260	207
Compressor recovery	594 935	68
Available thermal energy	2 412 195	275
Auxiliaries' thermal consumption	1 645 377	188
Civil corporate thermal utilities	6 365	1
Dissipated energy	760 453	86

Table 19 - Thermal Energy balance.

According to the thermal balance, the plant will be capable of producing more heat than it consumes. The surplus thermal energy could be used, depending on seasonal needs, to heat the nearby La Falchetta estate.

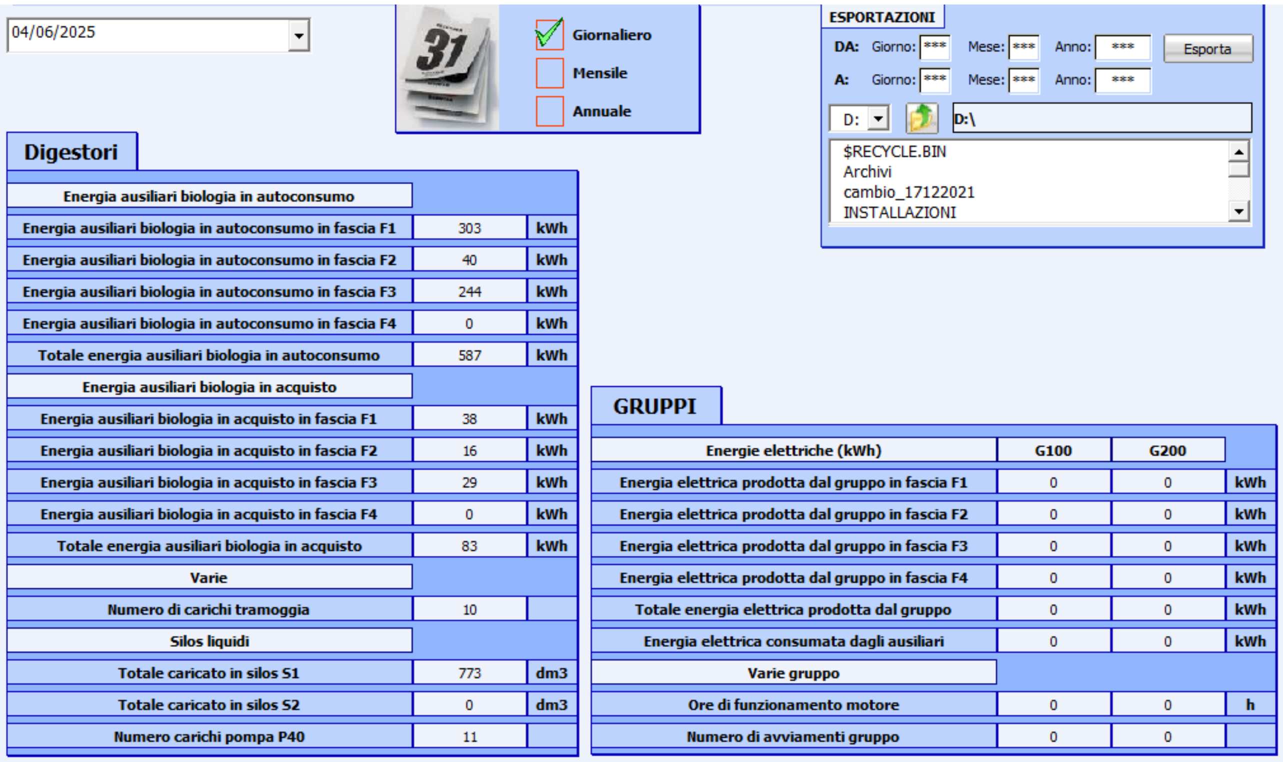

Figure 37 - Viewing of daily auxiliaries' self consumption from the control and monitoring software.

7.3. Data from operation

The La Falchetta plant is currently still operating in biogas mode, as the previous incentive scheme remains valid through 2025. The acquisition by Asja Group in 2024 marked a significant strategic shift, which began with a transition in feedstock management. The plant is now monitored in real time by operators, enabling continuous analysis of biomass input, biogas composition, and energy balance. Following the planned conversion, the upgraded plant is expected to be managed via a dedicated control system, ensuring long-term performance tracking and the identification of potential operational issues.

To support this, a customized dashboard was developed using Power BI, allowing for automated, real-time data extraction directly from the plant's operational database. Feedstock inputs to the digester are logged, and their composition is displayed on the dashboard. It can be observed that the displayed compositions do not match the one used for the mass balance calculations. This is because average composition values were adopted at the design stage, although these may vary over time depending on availability and seasonality. In fact, a broader dataset analysis reveals that both the quantity and composition of the feedstock fluctuate over time. These variations are strategically managed to achieve optimal operating conditions and maximize biogas yield.

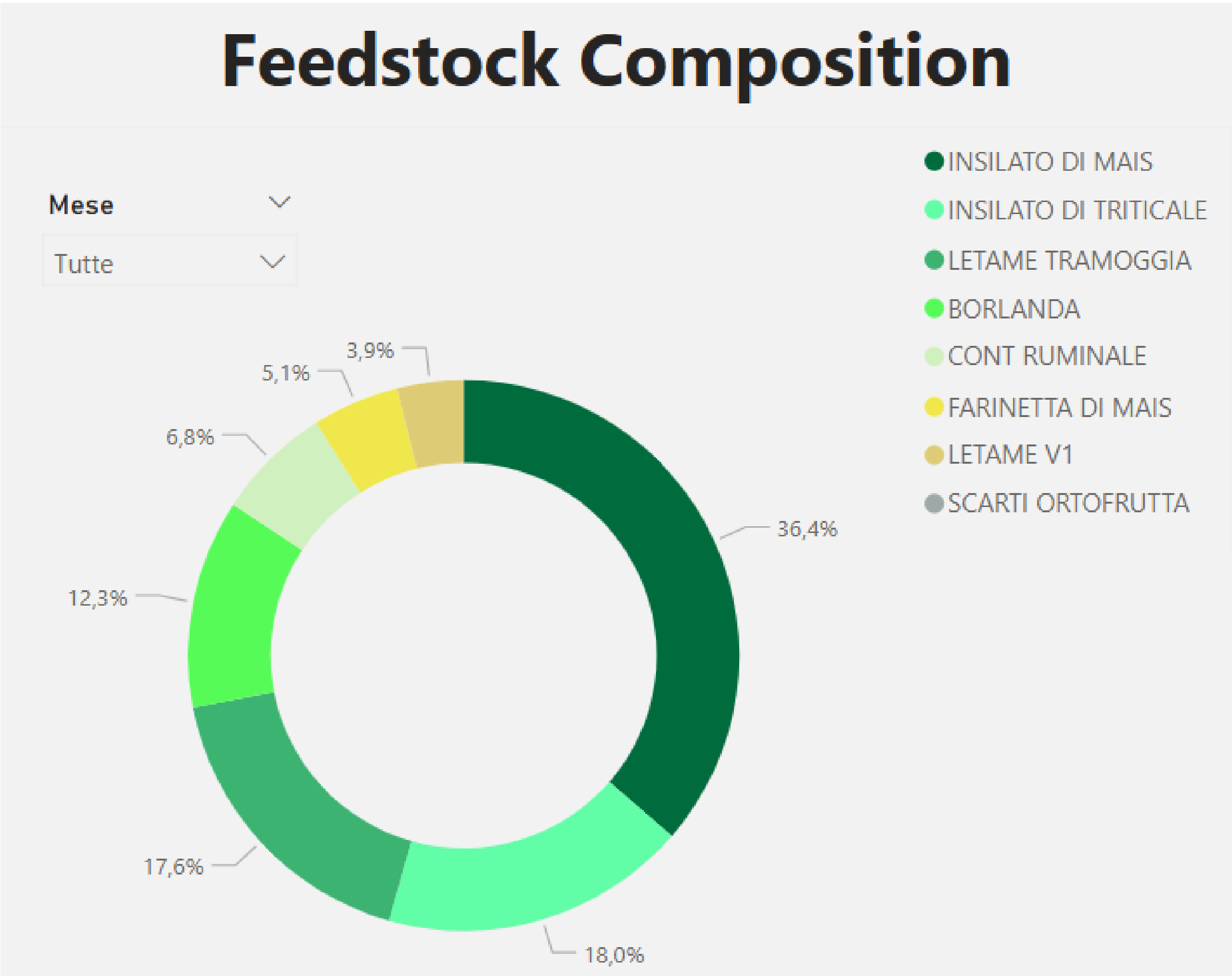

Figure 38 - Average biomass composition over the entire dataset, own elaboration.

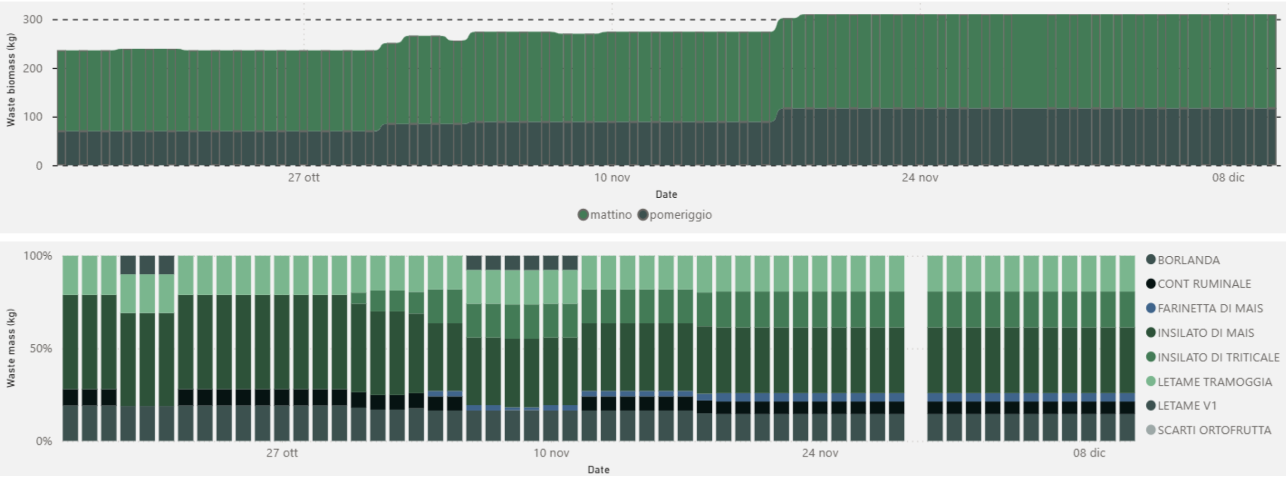

Figure 39 - Fluctuations of biomass quantity and composition, own elaboration.

Similarly, the implementation of Power BI enables the extraction and visualization of data related to the plant's energy balance. In its current configuration, the facility continues to operate with a 625 kW combined heat and power unit for electricity generation. This tool provides continuous monitoring of energy production, allowing for the early detection of any malfunctions or operational anomalies.

Moreover, the ability to select specific time windows within the dashboard allows for the extraction of targeted information, which is particularly useful for the preparation of monthly or annual operational budgets and economic analyses.

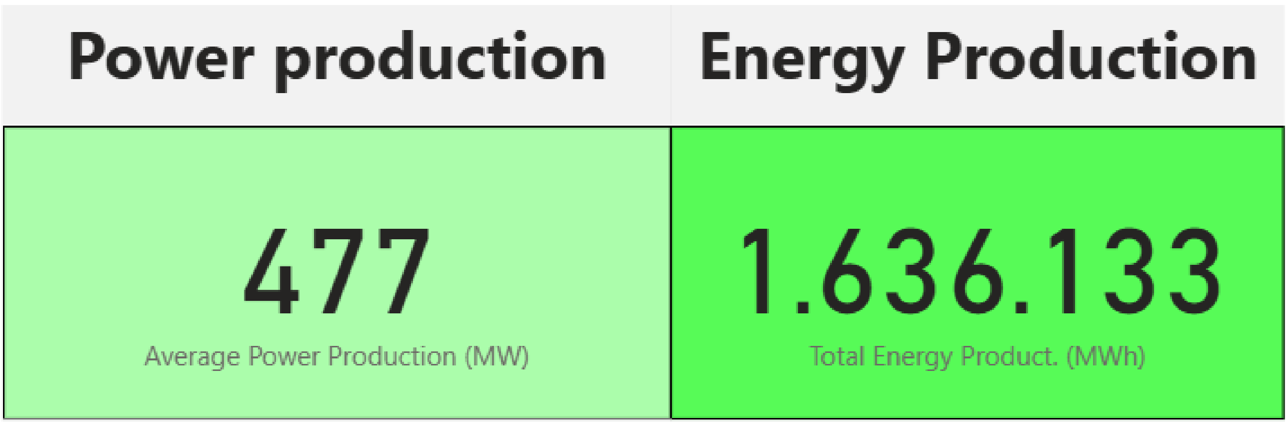

Figure 40 - Average power production and total energy production over the entire dataset, own elaboration.

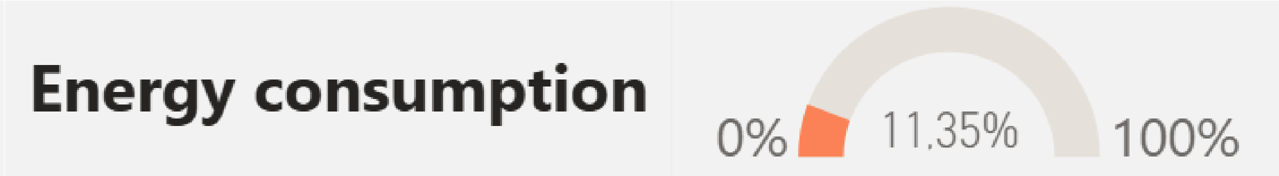

Figure 41 - Energy consumption, expressed as percentage of the total energy produced, own elaboration.

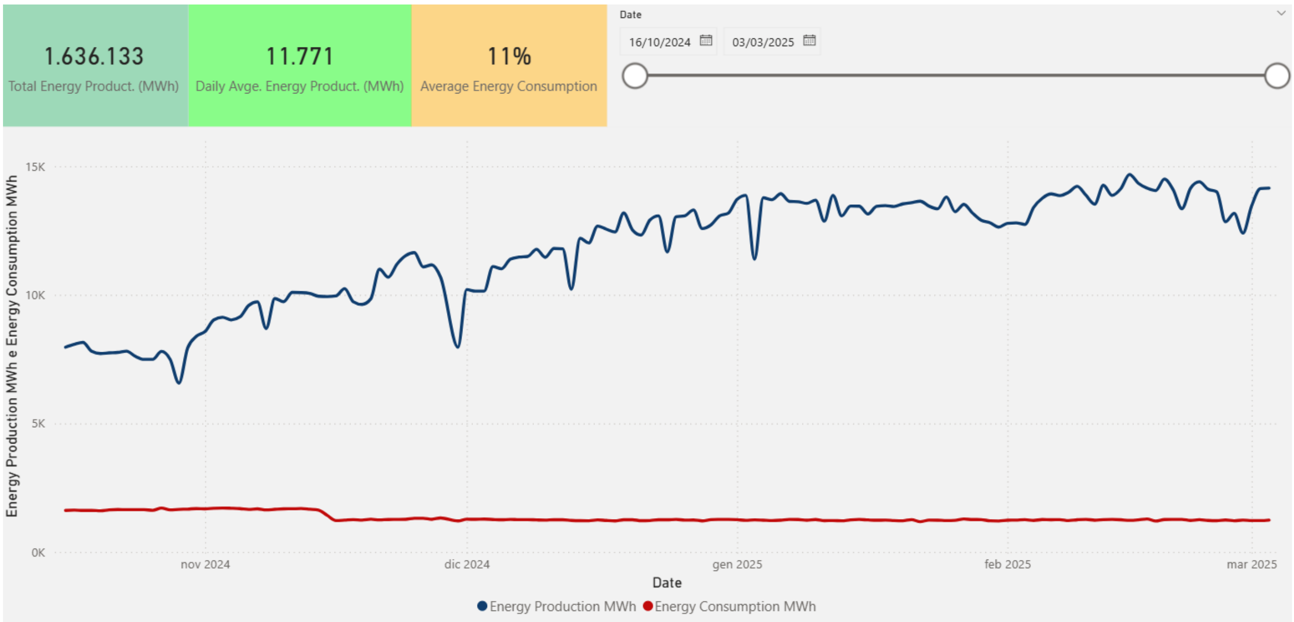

Figure 42 - Historical of energy production and consumption, own elaboration.

Furthermore, monitoring the absorbed energy represents a critical indicator of the plant's operational integrity. Under normal working conditions, energy consumption (represented by the red line) tends to remain relatively constant. In contrast, the increasing trend in energy production (blue line) clearly reflects the improvements implemented by Asja. The dataset used to generate these graphs begins at the time of Asja's acquisition of the plant and serves as tangible evidence of how a tailored feedstock strategy, specifically designed for the characteristics of the plant, can lead to significant gains in production without increasing energy demand. This results in higher net biogas and ultimately improving the facility’s cash flow.

7.4. Environmental and sustainability analysis

The reconversion of the La Falchetta plant is part of the broader set of actions implemented to meet sustainability goals aimed at mitigating the rising atmospheric pollution caused by greenhouse gases.

Moreover, to qualify for government incentives, the GSE requires that the plant reconversion leads to a reduction in CO_2-equivalent emissions of at least 80%.

This reduction will be achieved primarily through the use of biomass; however, calculations show that ancillary project works, such as the installation of a tent cover over the liquid digestate storage tank, also contribute significantly to the overall emissions balance. The emissions balance is assessed by comparing the "before" (ante operam) and "after" (post operam) scenarios, enabling a clear evaluation of the environmental benefits achieved through plant upgrading..

The calculation of CO_2-equivalent emissions was carried out by applying the Global Warming Potential (GWP) values of the relevant pollutants.

GHG	Lifetime - years	GWP – 20 years	GWP – 100 years
CO_2	150	1	1
CH_4	12	81	28
N_2O	109	273	273
CF_4	50 000	5300	7380
HFC – 152a	2	591	164

Table 20 - GWP from IPCC ar6 (35)

In the scenario before the reconversion, the following sources of emissions must be taken into account: those associated with the fossil fuel supply chain or the national gas grid, emissions from fossil gas combustion, direct emissions from the cogeneration unit, emissions related to the storage of separated digestate, as well as emissions from the emergency flare and hydraulic seals.

These emissions represent the baseline scenario against which the effectiveness of the reconversion project is assessed. By quantifying each emission source in the ante operam condition, a comprehensive inventory is established that captures the environmental footprint of the existing cogeneration system.

Therefore, the quantification of emissions in the *ante operam* scenario can be summarized as follows:

TOTAL EMISSIONS – BEFORE RECONVERSION

Component	kg
CO_2	4 384 671
CH_4	49 355
N_2O	248
$CO_{2\,eq}$	5 856 204
NO_X	6 902
SO_X	1 757
CO	5 176
PM	2 034
TOC	3 960
NH_3	3 649

Table 21 - Emissions calculated before the reconversion intervention.

In the *post-conversion* scenario, the following emission sources must be considered: emissions associated with the purchase of electricity from the national grid, direct emissions from the cogeneration unit, off-gas from the upgrading system, emissions related to the storage of digestate and from the solid-liquid separator, emissions from the flare, and from the hydraulic seals.

Therefore, the quantification of emissions in the *post operam* scenario can be summarized as follows:

TOTAL EMISSIONS – AFTER RECONVERSION

Component	kg
CO_2	78 526
CH_4	38 138
N_2O	157
$CO_{2\,eq}$	1 193 855
NO_X	1 923
SO_X	513
CO	1 477
PM	18 577
TOC	1 227
NH_3	618

Table 22 -Emissions calculated after the reconversion intervention.

From the comparison carried out on greenhouse gases, the following results can be highlighted:
a significant increase in particulate matter emissions and an increase in NH_3 emissions of approximately 1 ton/year, offset by a notable reduction in GHG emissions, in particular: N_2O reduced by 0.1 t/year, CH_4 reduced by 11 t/year, NO_x reduced by 5 t/year and CO_2 reduced by 4,306 t/year.

This translates into a total reduction of CO_2-equivalent emissions of approximately 4,662 t/year, demonstrating that the planned project leads to a substantial improvement in emission performance and ensures compliance with the emission reduction targets required for incentive eligibility.

EMISSION BALANCE

GHG	Before	After	Delta	Percentage
CO_2	4 384 671	78 526	-4 306 145	- 98%
CH_4	49 355	38 138	-11 217	- 23%
N_2O	248	157	-91	- 37%
NO_x	6 902	1 923	-4979	- 72%
SO_x	1 757	513	-1 244	- 71%
CO	5 176	1 477	-3 699	- 71%
PM	2 034	18 577	16 543	+ 813%
TOC	3 960	1 227	-2 733	- 69%
NH_3	3 649	4 618	969	+ 26%
$CO_{2\text{-eq}}$	**5 856 204**	**1 193 855**	**-4 662 349**	**- 80%**

Table 23 - Emission balance ante/post operam.

7.4.1. Reduction against fossil counterpart

In order to access the incentives established by the Ministerial Decree of 15 September 2022, biomethane production plants intended for uses other than the transport sector must achieve a reduction of at least 80% in greenhouse gas emissions compared to the corresponding fossil fuel supply chain.

This reduction is calculated using a standardized methodology that considers the total emissions generated throughout the life cycle of the fuel, comparing them to those of the relevant fossil-based alternative. The formula used is as follows:

$$GHG\ Reduction\ (\%) = \frac{FFC - E}{FFC}$$

Equation 3 - GHG emissions reduction against fossil counterpart.

Where *FFC* represents the emissions from the fossil fuel chain, and *E* corresponds to the total emissions associated with the production of biomethane prior to energy conversion.

In the case where a single substrate is used in anaerobic digestion, the value of *E* is determined by the following expression:

$$E = E_{ec} + E_l + E_p + E_{td} + E_u - E_{sca} - E_{ccs} - E_{ccr}$$

Equation 4 - Formula for the calculation of the total emissions associated with the production of biomethane prior to energy conversion for a single substrate.

where:

E_{ec} is the emission from the extraction or cultivation of raw materials.

E_l is the annualized emissions resulting from changes in carbon stock due to land-use change.

E_p is the emission from processing.

E_{td} is the emission from transport and distribution.

E_u is the emission during fuel use.

E_{sca} is the emission saving due to soil carbon accumulation through improved agricultural management.

E_{ccs} is the emission reduction due to CO_2 capture and storage.

E_{ccr} is the emission reduction due to CO_2 capture and replacement.

In the case of co-digestion involving *n* different substrates, the emissions are calculated as:

$$E = \sum_{1}^{n} (S_n \, x \, E_n)$$

Equation 5 - Formula for the calculation of the total emissions associated with the production of biomethane prior to energy conversion for multiple substrates.

Where E_n is the GHG emission factor for substrate *n*, and S_n is its share of the total energy content, calculated as:

$$S_n = \frac{P_n \, x \, W_n}{\sum_{1}^{n} W_n}$$

Equation 6 - Formula for the calculation of the share of the total energy content.

where:

W_n is the raw material weighting factor n.

$$W_n = \frac{I_n}{\sum_1^n I_n} \, x \, \frac{1 - AM_n}{1 - SM_n}$$

Equation 7 - Formula for the calculation of the raw material weighing factor Wn.

P_n is the energy yield per kg of wet input of substrate *n*, expressed in MJ.

I_n is the annual input of substrate *n* to the digester, in t/year.

AM_n is the average annual moisture content of substrate *n*.

SM_n is the standard moisture content for substrate *n*.

This methodology enables a weighted allocation of emissions based on the composition and energy characteristics of the substrates used, ensuring a transparent assessment in line with European sustainability standards.

7.5. Economic analysis

In order to assess the investment required for the reconversion of the La Falchetta plant, an economic analysis must be conducted that takes all relevant factors into account.

As a first step, it is useful to calculate the Payback Time (PBT), which represents the period required to recover the total amount of capital invested. Naturally, the objective is to minimize this duration. The PBT is defined as the point in time, denoted as τ, at which the cumulative discounted cash inflows equal the initial investment:

$$-I + \sum_{t=1}^{\tau} \frac{B_t}{(1+i)^t} = 0$$

Equation 8 - Payback time equation.

Where:

I is the initial invested capital

B_t is the net cash flow

i is the inflation rate

t is the time in which each net cash flow is considered

The Payback Time is an intuitive yet limited indicator, as it does not account for the time value of money beyond the break-even point. It may be misleading if considered in isolation, since two investments with the same payback period could generate very different economic returns after the capital has been recovered.

On the other hand, the Internal Rate of Return (IRR) provides a more comprehensive view of long-term profitability, as it incorporates the effects of inflation and the overall duration of the investment.

The IRR is the discount rate *i* that makes the cash flow equal to the investment cost, it satisfies the following equation, where the letters have the same meanings as before:

$$-I + \sum_{t=1}^{n} \frac{B_t}{(1+i)^t} = 0$$

Equation 9 - Internal Rate of Return equation.

It is expressed as a percentage and represents the average annual return on the invested capital over a given period. In essence, it serves as a measure of the investment's efficiency. For instance, if the IRR is 10% over a 10-year operational period, it means that the capital has yielded a return 10% higher than the initial investment.

Cash flow refers to the net amount of cash and cash-equivalents moving into and out of the business over a specific period.

The Net Income is calculated by subtracting interest and taxes from EBIT (Earnings Before Interest and Taxes). EBIT itself is obtained by deducting depreciation and the provision for plant decommissioning from EBITDA (Earnings Before Interest, Taxes, Depreciation, and Amortization).

To determine the total plant expenses, two cost categories are considered: the CAPEX (capital expenditures) investment costs and OPEX (operating expenditures) ongoing operating and maintenance costs.

7.5.1. Capex

The capital expenditure (CAPEX) refers to the initial investment required for the project, which includes the costs of the design phase, the procurement of components, and the construction work. This expenditure is typically incurred during the first year of the plant’s operational life and is then amortized over a defined depreciation period. In this case, depreciation has been calculated over the entire expected lifetime of the plant, using the following formula:

$$Dep. Rate = \frac{Total\ Plant\ Cost\ (€)}{Plant\ Lifetime}$$

Equation 10 - Depreciation rate equation.

The largest cost item in this investment incurred for the installation and assembly of the upgrading section and the replacement of the CHP engine.

In addition to the main functional sections, further costs were sustained for the electrical systems, the connection of the plant to existing infrastructure, and the installation of newly introduced components.

These capital expenditures were partially offset by capital grants provided under the Ministerial Decree of September 15, 2022. In particular, call *5* of the decree stipulates that 40% of the investment is covered by public incentives supporting the implementation of biomethane production technologies.

7.5.2. Opex

Operating expenses (OPEX) represent the ongoing costs associated with the operation and maintenance of the plant. They encompass all expenditures incurred during the plant's operational phase. Although the upgrading section is technically capable of continuous operation, its functioning is directly tied to the anaerobic digestion process; hence, it ceases operation during any plant shutdown.

For this reason, the capacity factor (CF), defined as the ratio between the actual operating hours and the total hours in a year, is a useful indicator. For La Falchetta, the capacity factor is calculated on the cogenerator working hours:

$$CF = \frac{8\ 500}{8\ 760} \approx 97\%$$

Equation 11 - Capacity factor calculation.

Operational costs must therefore be adjusted based on the effective runtime of the plant and are multiplied by the capacity factor.

The most significant operational cost arises from the biomass to feed the digester, which includes expenses related to purchase, transportation, and management of stock biomass. Interestingly, energy costs are not a major financial burden, thanks to the circular configuration of the system, which allows it to meet its own energy demand through self-produced electricity.

Notable operating costs include regular operation and maintenance of the upgrading unit, of the CHP engine, which also lead to temporary plant downtime, and specialized maintenance of process equipment and the electrical system.

It is also essential to account for general overhead costs, such as employee salaries, utility bills, and insurance. These categories may represent a more substantial share of the overall budget than initially anticipated and should not be underestimated in the financial analysis.

Indicator	Definition	Formula	Unit
CAPEX	Capital expenditures	-	€
OPEX	Operational expenditures	-	€/y
EBITDA	Gross operating profit	$\text{EBITDA} = \text{incomes} - \text{outcomes}$	€
EBIT	Net operating profit	$\text{EBIT} = \text{EBITDA} - (\text{depreciation} + \text{decomissioning provision})$	€
Net Income	Income after interests and taxes	$\text{Net income} = \text{EBIT} - \text{interests} - \text{taxes}$	€
Cash Flow	Net cash flow	$\text{Cash flow} = \text{net income} + \text{depreciation} + \text{provisions}$	€
PBT	Payback time	$\text{PBT} = -I + \sum_{t=1}^{\tau} \frac{B_t}{(1+i)^t} = 0$	y
IRR	Internal rate of return	$\text{IRR} = -I + \sum_{t=1}^{n} \frac{B_t}{(1+i)^t} = 0$	%

Table 24 - Resume of economic indicators.

7.5.3. Incomes

The La Falchetta plant produces biomethane and injects it into the grid, benefiting from the incentive scheme established by the Ministerial Decree of September 15, 2022.

This means that the plant's revenues derive both from the sale of biomethane to the grid and from the incentive tariff awarded for each unit of biomethane injected.

With access to incentives, the sale of biomethane is the responsibility of the applicant, who will receive a premium tariff, having won the auction under Call N. 5 with a 1.05% reduction from the base rate set by the GSE. This tariff is calculated as the eligible reference tariff minus the monthly average price of natural gas and the monthly average price of the guarantees of origin.

Tariff	Description	Amount
Reference tariff	Value set as a starting point for the auction in the single competitive procedure, expressed in €/MWh.	123,73 €/MWh
Offered tariff	Calculated by applying to the reference rate the percentage reduction offered (1,05%) during participation in the procedure.	122.43 €/MWh
Applicable tariff	calculated by applying to the offered rate any further reduction foreseen in the event of failure to comply with the maximum times defined.	122.43 €/MWh – eventual reduction
Premium tariff	difference between the applicable rate and the sum of the average monthly price of natural gas and the average monthly price of guarantees of origin.	(122.43 €/MWh – eventual reduction) – (average energy price + guarantees of origin)

Table 25 - Tariffs involved in the calculation of the premium.

Unlike the plant's previous configuration, where revenues were generated from the sale of electricity produced by the CHP unit, the current configuration no longer generates direct income from heat and electricity. Instead, these energy carriers now play a key role in reducing operational costs, thereby indirectly contributing to the increase in net profit.

During the initial conversion phase, costs are primarily represented by the total investment, net of the capital grant provided by the GSE. During the operational period of the upgraded plant, up until the expiration of the incentive period, revenues are expected to exceed operating expenses. Even when accounting for depreciation, the overall financial outlook of the investment is strongly positive.

8. Future implementations

In this chapter, we delve into several innovative techniques that can be employed to enhance the efficiency and sustainability of the biomethane production process.

8.1. The use of biochar in anaerobic digestion

The incorporation of biochar as an additive in anaerobic digestion processes can offer several advantages, including enhanced digester performance, increased methane yield, improved process stability, reduction of the lag phase, and an in-situ biogas purification and upgrading effect. Although the engineering benefits of biochar have been well documented, its environmental impact within anaerobic digesters remains relatively underexplored. Nevertheless, preliminary findings suggest that its use may contribute to a reduction in carbon emissions.

One of the key advantages of biochar lies in its ability to be introduced directly into anaerobic reactors without requiring the installation of additional infrastructure, thereby lowering operational costs and supporting its scalability for industrial applications. Moreover, due to its intrinsic nutrient retention properties, biochar can be utilized to enhance nutrient recovery during phases of substrate-induced inhibition and to minimize nutrient losses both prior to and following the land application of digestate.

- Increasing methane production

The mechanisms underlying the enhanced methane production observed with the addition of biochar are not yet fully understood. However, it is generally assumed that this improvement is primarily due to two factors: the promotion of the biochemical conversion of volatile fatty acids into methane, and the simultaneous acceleration of the degradation rate of complex organic molecules, facilitated by the porous structure of biochar.

It is important to highlight that excessive biochar addition may have adverse effects. In particular, the adsorption of organic matter onto the biochar surface can decrease substrate availability for methanogenic microorganisms, potentially limiting the overall efficiency of the anaerobic digestion process.

- Improve system stability

The acceleration of volatile fatty acid degradation plays a critical role in enhancing process stability. The accumulation of VFAs can lead to acidification, which exerts inhibitory effects on methanogenesis and may compromise, or even halt,the anaerobic digestion process. Biochar contributes to maintaining a more stable and favorable environment for methane production by mitigating the accumulation of VFAs and thus preventing the onset of process imbalances.

- Reduce lag period

The addition of biochar facilitates communication between bacteria and methanogenic archaea by acting as an electron-conductive bridge, thereby promoting *Direct Interspecies Electron Transfer* (DIET). This phenomenon enhances the initiation of the methanogenesis process, significantly reduces the lag phase, and ultimately leads to improved overall digester performance.

- In-situ biogas purification and upgrading

Biochar has the capacity to adsorb contaminants such as carbon dioxide and hydrogen sulfide, owing to its high specific surface area and porous structure. This effect, primarily demonstrated at laboratory scale, offers promising prospects for reducing the operational costs associated with conventional biogas upgrading technologies.

Furthermore, biochar can support biological upgrading of biogas through the bioconversion of CO_2 into methane by enabling the immobilization of hydrogenotrophic archaea. This process not only contributes to a reduction in CO_2 emissions but also enhances the calorific value of the resulting biogas.

- Buffering effect

Biochar is an effective additive in anaerobic digestion processes due to its strong buffering capacity, which is closely linked to its high porosity and specific surface area. These physical characteristics contribute to stabilizing the pH of the system, an essential factor in maintaining optimal conditions for the growth and metabolic activity of methanogenic microorganisms, which typically operate best within a pH range of 6.5 to 7.5.

The buffering effect of biochar primarily arises from the combination of its physical and chemical properties. Its high adsorption capacity allows it to retain H^+ and OH^- ions, thereby regulating the pH within the digestion medium. Moreover, the surface of biochar is rich in acidic and basic functional groups (such as –COOH and –OH), which interact with the ions present in the system and help neutralize excess acidity.

Additionally, the mineral composition of biochar plays a significant role in enhancing its buffering potential. In particular, the presence of calcium carbonate ($CaCO_3$) provides a natural alkalinity source, effectively neutralizing volatile fatty acids (VFAs), whose accumulation could destabilize the anaerobic digestion process. The high cation exchange capacity (CEC) of biochar further strengthens its role as a buffer, promoting ionic equilibrium through efficient interaction with cations and anions in the system.

- Microbial immobilization

The physical and chemical structure of biochar enhances microbial adhesion and proliferation. The formation of biofilms on its porous surfaces creates a protected and stable microenvironment, increasing microbial density and improving the overall resilience of the anaerobic digestion system.

Moreover, the close spatial arrangement of microorganisms, resulting from higher microbial density, combined with the intrinsic properties of biochar, promotes synergistic microbial interactions. These interactions contribute to enhanced process stability and productivity by facilitating interspecies electron transfer and optimizing metabolic cooperation.

- Environmental effects

Biochar currently represents one of the most promising alternatives for carbon emission reduction, due to its high calorific value and long-term carbon sequestration capacity. However, its beneficial effects in the context of anaerobic digestion are not primarily linked to its role as a substitute for fossil-based materials, but rather to its ability to retain microbial biomass and enhance in-situ biogas upgrading processes through the direct conversion of carbon dioxide into methane.

The improvement in methane yield facilitated by biochar leads to a direct reduction of carbon emissions via the off-gas stream. Additionally, the decreased CO_2 concentration in the biogas mixture increases the calorific value of the gas produced, while simultaneously simplifying the handling and valorization of biogenic CO_2. This aspect is particularly relevant, as it allows for greater overall energy efficiency in the process and reduces reliance on complex and costly upgrading technologies.

Another important environmental advantage of using biochar in anaerobic digestion lies in its potential post-process application as a soil amendment. The residual biochar can be applied to agricultural land, where it improves soil properties, reduces the demand for synthetic fertilizers, and promotes sustainable agricultural practices. This integrated approach contributes to closing the carbon loop and supports the development of a circular, low-impact bioeconomy.

- Nutrient retention

The use of digestate as an agricultural soil amendment is already widely recognized for its nutritional value and organic matter content, both of which offer significant agronomic benefits. However, this practice is not without environmental concerns, notably the leaching of residual ammonia and methane. These compounds can infiltrate the soil and contaminate groundwater, posing a major challenge to the long-term sustainability of digestate application.

In this context, biochar presents a promising solution due to its exceptional nutrient retention and immobilization properties. As previously described, its high specific surface area, porosity, and cation exchange capacity enable biochar to effectively retain nutrients within the digestate, reducing their mobility and minimizing the risk of leaching into the environment. Furthermore, biochar contributes to the immobilization of organic nitrogen, thereby enhancing the nutritional quality of the digestate and prolonging nutrient availability for plant uptake.

Biochar is also a cost-effective material, which implies that it does not require recovery after the anaerobic digestion process. This makes it a strategic component for optimizing circular economy models in organic waste treatment. Integrating biochar into anaerobic digestion not only mitigates the environmental risks associated with nutrient leaching but also contributes to the overall sustainability of the process, enhancing system efficiency and delivering economic advantages.

- Rules and regulations on the use of biochar in anaerobic digestion and digestate management

The use of biochar in anaerobic digestion and digestate management is governed by a set of regulatory frameworks designed to ensure environmental safety and the quality of the final products. In the European context, the Waste Framework Directive (2008/98/EC) establishes criteria for the safe handling of materials involved in waste treatment processes, including organic waste. This implies that biochar used in anaerobic treatment must meet specific quality and origin standards to prevent the introduction of hazardous contaminants.

Moreover, when biochar is intended to come into contact with waste or be used as an additive in anaerobic digesters, it must comply with Regulation (EC) No. 1069/2009 on animal by-products and derived products, which defines environmental and health safety requirements.

With regard to digestate derived from anaerobic digestion, its application as an organic fertilizer is subject to Regulation (EU) 2019/1009, which sets out the safety parameters and quality requirements for organic fertilizers and soil improvers. These regulations ensure that materials applied to agricultural land do not pose risks to soil health or groundwater quality.

Biochar, due to its nutrient retention properties and its ability to enhance the overall quality of digestate, plays a key role in reducing nitrogen and phosphorus losses. Additionally, it can significantly mitigate the environmental risks linked to nutrient leaching and groundwater contamination caused by poor nutrient management practices. Its compliance with existing EU regulatory standards makes it a viable and strategic tool for improving the sustainability of anaerobic digestion systems.

8.2. CO_2 recovery and valorisation

When producing biomethane, a permeate containing carbon dioxide is inevitably generated from the upgrading process. In the case of the La Falchetta plant, the membrane upgrading system is specifically designed to separate the methane and carbon dioxide flows, as the molecules of CH_4 and CO_2 differ in size. This results in a retentate rich in methane, known as biomethane, and a permeate rich in CO_2, referred to as biogenic carbon dioxide. The CO_2 produced from biomass is termed as *biogenic* CO_2 and is part of *the natural short carbon cycle*. This concept presents an excellent opportunity to meet the growing demand for CO_2 from the food and beverage industry, as well as fertilizer production.

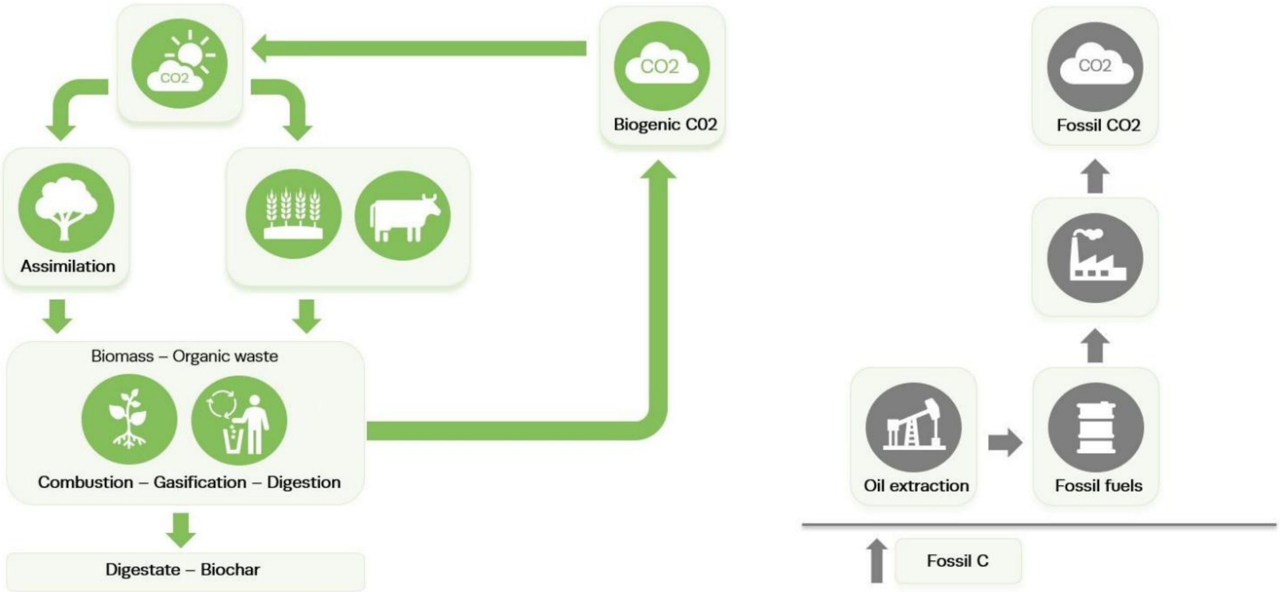

Figure 43 - Natural short carbon cycle (left) and fossil carbon release (right). (36)

The recovery of the biogenic CO_2 provides an ideal opportunity to optimize the utilization and efficiency of all components involved in the biomethane production process. In this way, the off gas is no longer treated as a waste product (subject to GHG reduction limits); rather, it becomes a valuable resource that can be utilized for profit generation. At the same time, this approach contributes to the further reduction of emissions by gradually phasing out traditional CO_2 extraction methods from fossil sources. The integration of biogenic CO_2 into industrial processes not only reduces environmental impact but also enhances the economic viability of the biomethane production system, aligning with sustainability goals and addressing both market growing demand and regulatory requirements.

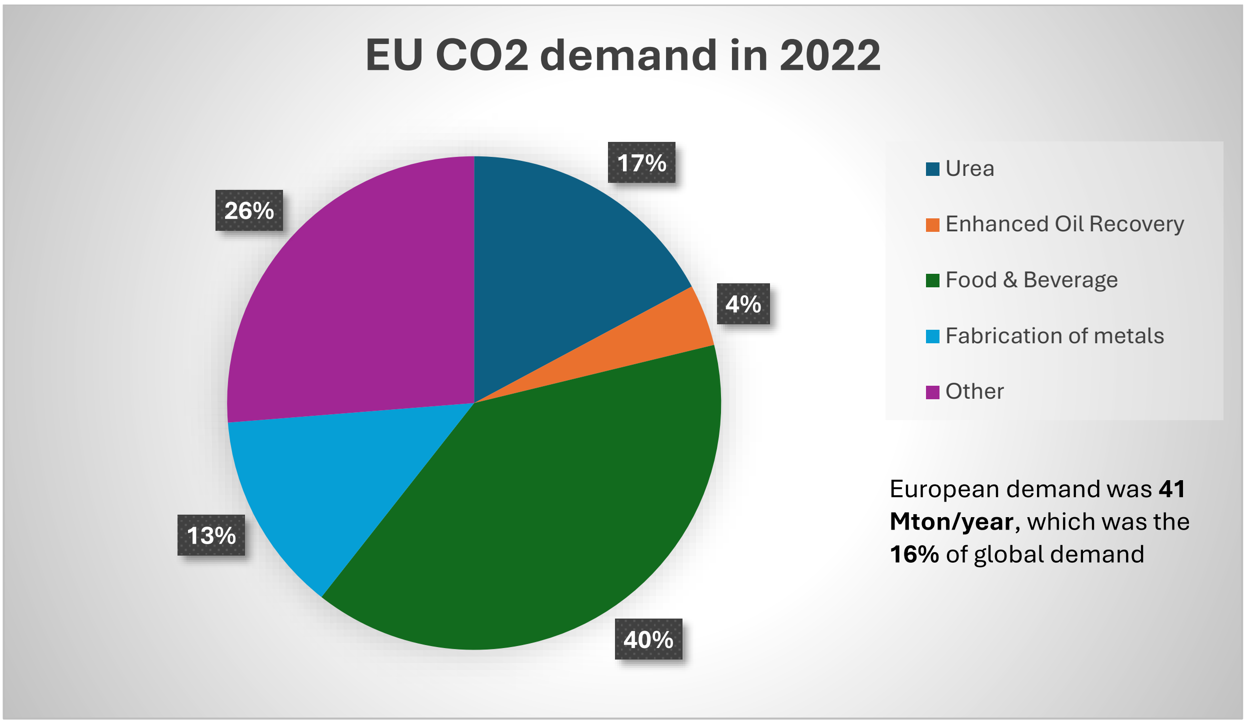

Figure 44 - CO2 demand in Europe, per sector, 2022. (37)

Additionally, the possibility to recover and store CO_2 also presents the opportunity to produce even more biomethane through a synthesis process between CO_2 and H_2, known as methanation. The most convenient way to obtain hydrogen to be used in the methanation phase is to subject water to electrolysis, so as to break it down into its components.

Methanation process has not yet reached a sufficiently high TRL (Technology Readiness Level) to allow for low CAPEX and OPEX. However, technological advancements, growing interest aimed at meeting market demand, and the potential for integration into a broader production process combined with other products, contribute to fostering confidence in the development of such techniques. As the technology matures and economies of scale are achieved, it is expected that the cost-efficiency of methanation processes will improve, making them a viable option for enhancing biomethane production.

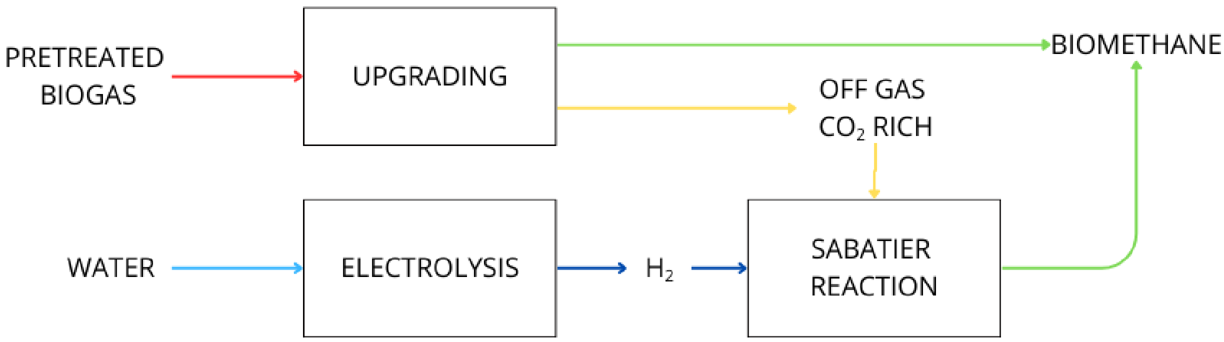

Figure 45 - Fluxes scheme.

8.2.1. Methanation

It is a Power-to-Gas technology that involves the synthesis of CH_4 from CO_2 and H_2 through the Sabatier reaction. In our process, we have a CO_2-rich stream, specifically the offgas, while the hydrogen required must be supplied externally. The most widely used technology for hydrogen production today is electrolysis, which involves the splitting of water molecules into oxygen and hydrogen by passing an electric current through an appropriate electrolyte. This is an endothermic reaction that requires an energy input.

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2H_2O$$

Equation 12 - Sabatier reaction.

There are several catalytic and biological methods for methanation that have been developed at a demonstration scale in recent years. For example, the Biological Methanation involves methanogenic microorganisms acting as biocatalysts to convert CO_2 into CH_4. The reaction occurs in a liquid solution, typically at temperatures ranging from 40 to 70°C. This method has the advantage of being highly tolerant to pollutants, which facilitates purification processes.

Another promising example is the Catalytic Methanation that takes place at temperatures between 300 and 400°C, with pressures ranging from 1 to 30 bar, typically using nickel or ruthenium-based catalysts. The reaction is highly exothermic, which necessitates careful temperature control. The excess heat generated during the process can be recycled to maintain optimal conditions.

As these technologies evolve, their integration into existing biomethane production facilities could represent a pivotal step toward the establishment of closed-loop carbon systems. In particular, the coupling of membrane-based CO_2 separation with methanation units powered by renewable electricity (green hydrogen) aligns with the principles of Power-to-Gas and sector coupling strategies promoted by the European Union.

Moreover, the valorisation of CO_2 through methanation has the potential to enhance the overall energy yield of the plant while contributing to grid balancing by storing surplus renewable electricity in chemical form. Although still at a pre-commercial stage, these synergistic processes exemplify the future direction of biomethane systems, transforming them from standalone bioenergy units into integrated platforms capable of producing carbon-neutral or even carbon-negative fuels. Therefore, ongoing investment in research, demonstration projects, and supportive regulatory frameworks will be essential to accelerate the deployment of CO_2 valorisation technologies in the biomethane sector.

9. Conclusions

The transition from electricity generation to biomethane production in agricultural biogas plants represents a significant opportunity for advancing the decarbonisation of the energy system while enhancing the sustainability and economic viability of agricultural operations. The case study of the "La Falchetta" plant demonstrates that such conversion is not only technically feasible but also environmentally and financially sound, when supported by coherent regulatory frameworks and targeted incentive schemes. It is also important to highlight that the opportunity to convert existing biogas plants to biomethane offers the possibility of extending their operational lifespan. This would help ensure a leading role for a sector that would otherwise be vulnerable without concrete external support. A key advantage lies in the shift from producing a non-storable good such as electricity to a much more versatile energy carrier like biomethane, which can be stored and produced either continuously or on demand. From a technical standpoint, the adoption of a membrane-based upgrading system offers high levels of biomethane purity and flexibility, making it well-suited for medium-scale agricultural installations. The process design, including the integration of co-digestion strategies and advanced monitoring of key parameters ensures the stability and efficiency of anaerobic digestion. The comprehensive mass and energy balance confirms that the plant can achieve a biomethane output of 300 Sm^3/h, while maintaining high energy recovery and minimizing operational costs.

Environmentally, the reconversion enables a marked reduction in greenhouse gas emissions, both through the substitution of fossil fuels with renewable gas and the optimal reuse of agricultural byproducts. The digestate produced remains a valuable co-product, contributing to soil fertility and reducing reliance on synthetic fertilizers. Furthermore, the potential implementation of biochar production and CO_2 capture and reuse technologies presents additional pathways to enhance the sustainability and circularity of the system.

Economically, the viability of the project is underpinned by Italy's current incentive schemes, which provides both capital contributions and premium tariffs. These measures significantly reduce investment risk and promote the reconversion of biogas plants nearing the end of their incentive periods. Looking forward, the biomethane sector in Italy and the EU holds considerable growth potential, driven by ambitious policy targets, including the European REPowerEU plan. To fully unlock this potential, it is essential to streamline administrative procedures, ensure long-term regulatory stability, and foster innovation in upgrading technologies and digestate valorisation.

In conclusion, the reconversion of biogas plants to biomethane production constitutes a technically robust and strategically relevant pathway for the agricultural sector. It aligns with national and European climate goals, promotes rural development, and contributes to energy diversification. Continued investment in this direction, supported by clear policy frameworks and technological innovation, will be crucial for scaling up sustainable biomethane production across Europe.

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List of figures

List of tables

List of equations