A comprehensive review on biomethane production from biogas separation and its techno-economic assessments

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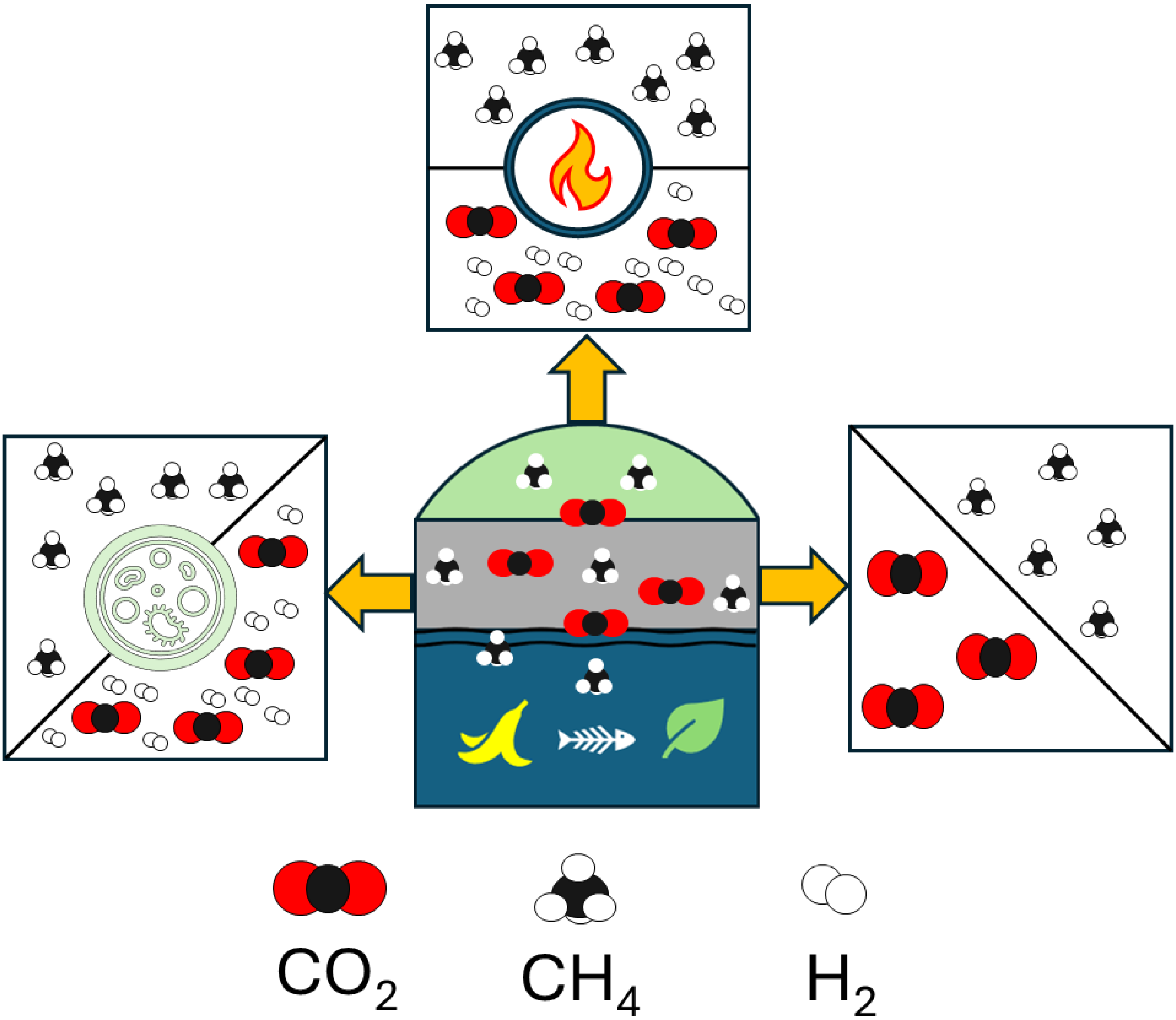

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Abstract: Biogas offers significant benefits as a renewable energy source, contributing to decarbonization, waste management, and economic development. This comprehensive review examines the historical, technological, economic, and global aspects of biomethane production, focusing on the key players such as China, the European Union, and North America, and associated opportunities and challenges as well as future prospects from an Australia perspective. The review begins with an introduction to biogas, detailing its composition, feedstock sources, historical development, and anaerobic digestion (AD) process. Subsequently, it delves into major biomethane production technologies, including physicochemical absorption, high-pressure water scrubbing (HPWS), amine scrubbing (AS), pressure swing adsorption (PSA), membrane permeation/separation (MP), and other technologies including organic solvent scrubbing and cryogenic separation. The study also discusses general guidelines of techno-economic assessments (TEAs) regarding biomethane production, outlining the methodologies, inventory analysis, environmental life cycle assessment (LCA), and estimated production costs. Challenges and opportunities of biogas utilization in Australia are explored, highlighting and referencing global projections, polarization in production approaches, circularity in waste management, and specific considerations for Australia. The review concludes discussing future perspectives for biomethane, emphasizing the importance of technological advancements, policy support, and investment in realizing its full potential for sustainable energy and waste management solutions.

1. Introduction

To meet climate targets within the next decade, global energy systems must undergo a fundamental shift towards carbon-neutral sources. Key to this transformation is the increased utilization of renewable energies alongside improvements in energy efficiency. Australia has emerged as a leader in global energy exports, leveraging its vast wind, solar, and hydro resources to produce renewable green fuels like green hydrogen [1]. Notably, Australia was grouped into the potential renewable energy "giants" in a 2018 article by Perner and Bothe [2], owing to its abundant resource availability, particularly its massive land areas paired with extensive renewable energy sources.

Renewable "green" energy (RGE), encompassing products such as hydrogen, methane, ammonia, and methanol, holds promise in replacing conventional hydrocarbon fuels and feedstocks [2]. Australia's transition to renewable energy, however, faces challenges. Despite efforts from climate activists and the growing commercial renewables industry, the nation is falling short of its carbon reduction targets. Carbon emissions surged by 0.8% in the 2022-23 fiscal year, contradicting Australia's commitment to a 43% reduction from 2005 levels by 2030 [3]. A critical aspect of Australia's energy transition is the exploration and adoption of alternative energy sources capable of driving decarbonization across pivotal sectors like transportation, industry, and agriculture. Among these alternatives, biogas methanation emerges as a promising technology to significantly contribute to Australia's renewable energy mix [1].

Biogas is a renewable resource owing to its circular production-and-use life cycle, and its net zero carbon dioxide generation. Biogas methanation involves the conversion of biogas – a mixture of methane (CH_4) and carbon dioxide (CO_2) produced from anaerobic digestion (AD) of organic waste – into synthetic methane through catalytic processes. Prospective bioenergy sources include various important products such as lignocellulosic agricultural biomass, organic acids, food additives, and enzymes. Conversion of agricultural wastes such as paddy and wheat straw, sugarcane bagasse, and corn stalks, into biogas which may serve an appropriate substitute to resolve a portion of global energy requirements [4]. Anaerobic digestion (AD) sometimes called bio-methanation is a mature industrial waste treatment technology that produces biogas (both methane and carbon dioxide) with the inclusion of some contaminants, where the carbon dioxide is generally seen as a waste by-product. AD has traditionally been used for power generation via combined heat and power technology (CHP) where both the combustion products of methane and carbon dioxide are vented to the atmosphere [5]. This process not only offers a renewable source of energy but also addresses pressing environmental concerns by providing a sustainable solution for organic waste management and reducing methane emissions from landfill sites and agricultural activities. In addition to its environmental benefits, biogas production holds immense economic potential, creating new opportunities for investment, job creation, and rural development.

Although biogas is known to the world since approximately 2000-3000 years ago [6], results on Scopus reveal a limited number of studies focused on "biogas methanation", with a total of 1062 hits. The earliest study in biogas methanation was published in 1981. In their study, Joassin and Matagn [7] theoretically demonstrated that the overall energy yield of a plant producing methane (CH_4) via anaerobic digestion (AD), from the input of refuse to the purification of the gas produced, is positive. Moreover, they found that the operation of such a plant is economically viable. Since 2008, substantial interest and research activity develop in the field of biogas methanation, reflecting its importance in the context of renewable energy production and waste management. Additionally, the same search yielded 38 results related to techno-economic aspects, suggesting a growing emphasis on evaluating the economic viability and feasibility of biogas methanation technologies in recently years. This intersection of research on both technical and economic aspects underscores the multidimensional nature of biogas methanation research, aiming to optimize both technological performance and economic sustainability. Figure 1 reports the literature on studying of biogas methanation since 2008 and biogas methanation AND techno-economic assessments (TEA).

Figure 1. Available literature distribution using key words "biogas methanation" AND "techno-economic" using Scopus database (13/03/2024).

Important biogas methanation studies in the literature include possible solutions for enhancing biogas production through advances in pretreatment strategies (particularly for lignin and silica removal), and the environmental aspects of the bio-methanation process and policy analysis. Dar et al [4] summarized related literature between 2010-2020 pertaining to agricultural waste based on anaerobe digestion (AD). These studies provide a clear understanding on various key aspects of AD technology, which help for future research scope in bio-methanation for more technologically sustainable, efficient and widely acceptable [4]. However, it is noted that very limited studies using techno-economic assessment (TEA) in agricultural waste based on anaerobe digestion (AD) biogas methane production [4].

Biogas methanation and its TEA assessments are still in their infancy. The successful implementation of biogas methanation projects in Australia requires a comprehensive understanding of their technical, economic, and regulatory aspects. Techno-economic assessments (TEAs) serve as valuable tools in this regard, enabling stakeholders to evaluate the feasibility and viability of biogas methanation systems across various scales and applications. Through detailed TEAs, researchers, policymakers, and industry stakeholders can assess the costs, benefits, and risks associated with biogas methanation projects, identify optimal deployment pathways, and inform strategic decision-making processes. A literature search on the combined keywords "biogas methanation" and "techno-economic" in the Scopus database yielded only 38 hits starting from 2011 as shown in Figure 1 (orange color). Zamalloa et al [8] pioneered a study estimating the levelized cost of energy using the process line "algae biomass – biogas – total energy module" to be in the range of €0.170–0.087 per kWh^{-1} (with €1 = \$1.65 as of March 14, 2024), taking into account a carbon credit of approximately €30 per ton of CO_2 equivalent.

A systematic search of the literature reveals a scarcity of studies on biogas methanation and techno-economic analysis (TEA) in Australia. Despite Australia's burgeoning biogas industry being poised for significant growth and innovation, this lack of research and investment hampers its ability to fully capitalize on the potential of biogas as a renewable energy source and impedes its competitiveness on the global stage. Further studies and investments in biogas methanation are crucial to unlocking efficiencies in biogas production processes, maximizing energy yields, and enhancing environmental sustainability. Similarly, a deeper exploration of techno-economic aspects is essential to assess the financial viability and economic feasibility of biogas projects, enabling informed decision-making and attracting investors. By prioritizing research and investment in these areas, Australia can accelerate the development of its biogas sector, drive innovation, and establish itself as a leader in sustainable energy production.

In this article, we explore the multifaceted realm of biogas cleaning, upgrading, methanation, and the related techno-economic assessments, focusing on global leaders and specifically in the context of Australia. Providing a historical overview of the biogas sector from its inception to recent advancements, we offer insights into opportunities for process optimization. Additionally, we encapsulate the current state-of-the-art and explore future perspectives concerning anaerobic digestion (AD) for biogas production as a renewable energy source. By examining existing research findings and policy frameworks, we aim to shed light on the potential of biogas upgrading to contribute to Australia's energy transition goals. Through detailed analysis and discussion, we strive to offer valuable insights into the feasibility, viability, and future prospects of biogas projects in Australia, ultimately facilitating informed decision-making and fostering advancements in sustainable energy solutions.

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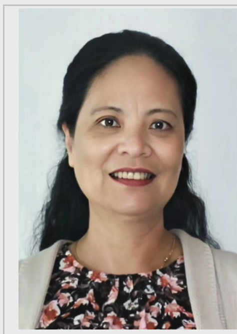


2. Biogas

2.1 Biogas and feedstock

Typically, biogas consists predominantly of methane (CH_4), ranging from 50% to 80%, with carbon dioxide (CO_2) emerging as the primary impurity, constituting approximately 19% to 50% of the gas mixture. While the presence of CO_2 does influence the energy content of biogas, other contaminants such as hydrogen sulfide (H_2S), water vapor (H_2O), ammonia (NH_3), oxygen (O_2), and siloxanes pose greater challenges [9]. The sources of organic matter utilized for biogas production are diverse. Feedstock for biogas typically encompasses agricultural waste, municipal solid waste, wastewater treatment plants, food processing waste, energy crops, and organic matter in landfills [10]. Agricultural waste, including crop residues, livestock manure, and organic residues from agricultural activities, stands as a common source of organic material for biogas production. Municipal solid waste, which comprises organic waste from households, restaurants, and urban areas, can undergo anaerobic digestion to yield biogas. Moreover, sewage sludge generated during wastewater treatment contains organic matter convertible into biogas. Food processing waste, such as byproducts and residues from food processing operations like fruit and vegetable peels, can also be harnessed for biogas production. Additionally, organic matter in landfills undergoes anaerobic decomposition, resulting in landfill gas, including methane, which can be captured and utilized for biogas production. Furthermore, energy crops cultivated specifically for energy purposes, such as maize, sorghum, and various grasses, offer biomass suitable for biogas production. Figure 2 illustrates the diverse feedstock for biogas production.

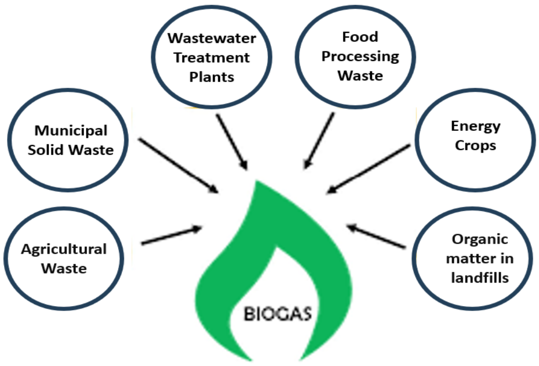


Figure 2. Sources of organic waste feedstock for biogas production.

Biogas is classified as carbon-neutral, or potentially even carbon-negative, stems from the renewable nature of its raw materials. The composition of biogas may vary depending on factors such as the feedstock used, the anaerobic digestion efficiency, and any subsequent gas purification or upgrading steps. Table 1 provides a typical composition of biogas, which typically consists of methane (CH_4) as the primary component, along with carbon dioxide (CO_2) as the secondary components, trace amounts of other gases such as hydrogen sulfide (H_2S), nitrogen (N_2), ammonia (NH_3) and moisture. Despite these variations, biogas remains an environmentally sustainable energy source that can contribute to mitigating climate change by reducing greenhouse gas emissions, and promoting a circular economy by converting organic waste into valuable energy [5].

Table 1. Composition (%) of biogas from different sources.*

Biomass source / Gas component	Agricultural wastes	Sewage sludge	Industrial wastes	Solid waste (Landfill)
Methane	50–80%	50–80%	50–70%	45–65%
Carbon dioxide	30–50%	20–50%	30–50%	34–55%
Water	Saturated	Saturated	Saturated	Saturated
Hydrogen	0–2%	0–5%	0–2%	0–1%
Hydrogen sulfide	100–7000 ppm	100 ppm	<0.5%	0.5–100 ppm
Ammonia	Trace	Trace	Trace	Trace
Carbon monoxide	0–1%	0–1%	0–1%	Trace
Nitrogen	0–1%	0–3%	0–1%	0–20%
Oxygen	0–1%	0–1%	0–1%	0–5%
Trace organics	Trace	Trace	Trace	5 ppm

*Ref [11]

2.2 Brief history of biogas development

The history of biogas production reflects a long trajectory of discovery, innovation, and adaptation, with its significance growing as societies increasingly prioritize renewable energy and environmental sustainability. It spans thousands of years and has evolved significantly over time, which approximately groups into six periods [12]: ancient roots (AR, 10th century B.C.), early modern development period (EMD, 17th -18th Centuries), industrial revolution (IR, 19th Centuries), world wars (WW, 1920-1945), post-war period (PWP, 1946-2000) and contemporary era (CE, 2001-present). The concept of biogas production has ancient origins in the AR period, with evidence suggesting its use in civilizations such as the Persians and Chinese potentially as far back as 2000-3000 years ago [6]. These early societies likely utilized anaerobic digestion to produce biogas from organic materials for heating and lighting purposes. In the 17th and 18th centuries (EMD), advancements in understanding the microbial processes involved in anaerobic digestion laid the foundation for more deliberate biogas production. Experiments of Alessandro Volta and Joseph Priestley helped elucidate the chemical reactions involved in biogas generation. Volta was believed the first to recognize that the conversion of organic matter contained in lakes and rivers' sediments resulted in the formation of "inflammable air" [13].

With the advent of the industrial revolution (IR) in the 19th century, biogas production gained traction as a means of providing energy for lighting and heating in urban areas. The AD process was systematically studied in the latter half of the 19th century in France, with the initial aim of suppressing the unpleasant odor exhaled by wastewater lagoons. Researches at that time, detected the presence of microorganisms, which today are known to be responsible for the AD process [14]. Biogas plants were established in Europe to process sewage and organic waste from cities, contributing to improved sanitation and energy provision. However, other well documented mid-nineteenth century attempts to harness the AD include when digesters were in constructed in New Zealand, India, and Exeter, UK where a sewage sludge digester built to fuel street lamps in the 1890s [12]. The scarcity of conventional fuels during World War I and World War II (WW) prompted further interest in biogas as an alternative energy source. Biogas plants were utilized to process agricultural residues and provide fuel for vehicles and machinery. After the World Wars (PWP), biogas production saw continued development, particularly in countries seeking energy independence and sustainable waste management solutions. Germany, for example, emerged as a leader in biogas technology, promoting its use for decentralized energy production. During the past decade and a half of the contemporary era (CE) biogas based power capacity has been growing rapidly, with global biogas electricity generation increasing from 65 GW in 2010 to 120 GW in 2019 representing a 90% growth in capacity [15]. Biogas is now recognized as a key component of renewable energy systems, contributing to efforts to mitigate climate change and transition to a more sustainable energy economy [12]. Advancements in biogas technology have expanded its applications and efficiency.

2.3 Anaerobic digestion (AD)

Biogas can be produced from several techniques and a myriad of biomass types, research into the best energy yields with optimal investment on time and costs has been ongoing since the 1980s [10]. Anaerobic degradation or digestion (AD) encompasses the biological processes by which complex molecules are converted into the simplest substances containing carbon, its most oxidized state (CO_2), and its most reduced form (CH_4). AD occurs in anoxic conditions in the presence of anaerobic microorganisms (bacteria and archaea) in a sequence of steps. This biological route is enzymatically catalyzed by a wide range of microorganisms acting synergistically [9]. The four successive stages of AD are hydrolysis, acidogenesis, acetogenesis, and methanogenesis [16]. The AD process is dependent on the interactions between the diverse microorganisms that can carry out the four aforementioned stages. Figure 3 illustrates the four stages of the AD process.

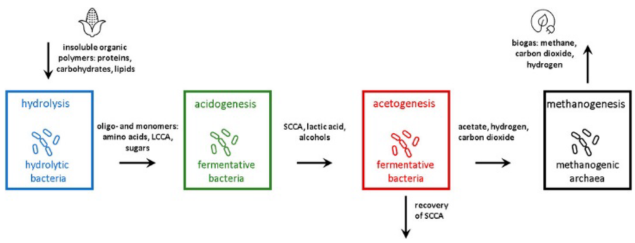


Figure 3. Four stages of the anaerobic digestion process [16]. Licensed under CC-BY 4.0 license.

The AD process initiates with hydrolysis, where complex proteins, fats, and carbohydrates are broken down by hydrolytic bacteria into simpler molecules like amino acids, long-chain fatty acids, glycerin, and sugars. These simpler molecules can then permeate the cell membrane of microorganisms, facilitating subsequent steps. Hydrolysis may act as a limiting step depending on the substrate type, with different groups of hydrolytic bacteria prevailing based on substrate quality. In acidogenesis, fermentative processes within bacterial cells convert amino acids, fatty acids, and sugars into intermediate compounds like short-chain organic acids, alcohols, ketones, and gases, which serve as substrates for acetogenic and methanogenic bacteria in subsequent steps [16]. Acidogenic bacteria are typically obligate anaerobes, while some facultative species can consume oxygen, preventing toxicity to methanogenic archaea. During acetogenesis, compounds produced by acidogenic bacteria are transformed into products assimilable by methanogenic archaea, including carbon dioxide, hydrogen, and acetic acid. This step requires the involvement of hydrogenotrophic and acetotrophic methanogenic archaea to create conditions conducive to acetogenic bacteria reactions. Finally, strict anaerobic archaea, including acetoclastic and hydrogenotrophic methanogens, produce methane from substrates resulting from previous steps [16]. Approximately 70% of methane is produced by acetoclastic methanogens and 30% by hydrogenotrophic methanogens, with the latter's hydrogen consumption facilitating acetogenesis. Notably, two distinct families of acetoclastic methanogens are prominent: metanosarcina, capable of metabolizing various compounds, and methanosaeta, which exclusively consume acetate [16].

Table 2 illustrates the principal reactions occurring in each phase of the biogas production process [17]. An example is the hydrolysis of cellulose ($C_6H_{10}O_5$), depicted in Eq (1), where water (H_2O) reacts to form glucose ($C_6H_{12}O_6$) and H_2. These chemical transformations take place within the fermenter or digester under the influence of bacterial activity. The subsequent phase, acidogenesis, involves the decomposition of compounds produced during hydrolysis into methanogenic substrates, including hydrogen, alcohols, carbon dioxide, carbon acids, and ammonia, as demonstrated by Eqs (2)-(4). Acetogenesis and methanogenesis often occur concurrently. Acetogenesis results in the formation of carbon dioxide, hydrogen, and acetic acid (Eqs 5-7), which serve as substrates for methanogenic bacteria. Methanogenesis then leads to the production of methane (CH_4) and carbon dioxide (CO_2). Eq (8) represents the conversion of acetic acid (CH_3COOH) into methane and carbon dioxide, while Eq (9) illustrates the reduction of CO_2 to CH_4 via hydrogen. Additionally, Eq (10) shows the generation of methane through the decarboxylation of ethanol (CH_3CH_2OH).

Table 2. Principal chemical reactions in the AD process.*

AD process	Substrate types	Chemical reactions	
Hydrolysis	Carbohydrates, proteins, lipids	$(C_6H_{10}O_5)_n + n\ H_2O \rightarrow n\ C_6H_{12}O_6 + n\ H_2$	(1)
Acidogenesis	Amino acids, alcohols, fatty acids	$C_6H_{12}O_6 \rightarrow 2\ CH_3CH_2COOH + 2\ CO_2$	(2)
		$C_6H_{12}O_6 + 2\ H_2 \rightarrow 2\ CH_3CH_2COOH + 2\ H_2O$	(3)
		$C_6H_{12}O_6 \rightarrow 3\ CH_3COOH$	(4)
Acetogenesis	Volatile fatty acid, acetate, propionate, ethanol, lactate	$CH_3CH_2COO^- + 3H_2O \rightarrow CH_3COO^- + H^+HCO^-$	(5)
		$C_6H_{12}O_6 + 2\ H_2O \rightarrow CH_3COOH + 2\ CO_2 + 4\ H_2$	(6)
		$CH_3CH_2OH + 2\ H_2O \rightarrow CH_3COO^- + 3\ H_2 + H^+$	(7)
Methanogenesis	Acetate, H2 and CO2	$CH_3COOH \rightarrow CH_4 + CO_2$	(8)
		$CO_2 + 4\ H_2 \rightarrow CH_4 + H_2O$	(9)
		$2\ CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2\ CH_3COOH$	(10)

*See Ref [18, 19].

This anaerobic digestion (AD) approach contributes to improved waste management while striving to achieve sustainable energy goals [20]. The AD processes typically span three to six weeks, influenced by factors such as material conversion efficiency and technology. Various methods such as pretreatment, co-digestion, and bioaugmentation can enhance biogas yield. Pretreatment techniques, such as substrate preparation and mechanical solubilization combined with low-temperature heat treatment, have been shown to increase biogas yield, particularly in AD processes involving wastewater sludge. However, waste with high lignin content, such as woody matter, may require longer processing times for optimal biogas production [20]. Table 3 outlines the advantages and disadvantages of waste recovery through the anaerobic digestion process.

Table 3. Advantages and disadvantages of waste recovery through the anaerobic digestion process.*

Advantages	Disadvantages
High quality soil fertilizer produced as by-product of energy production	Lower heat released compared to aerobic composting resulting in higher pathogen loads
Turning of waste for the purpose of oxygenation not required	unsuitable for low organic matter wastes
All produced gases contained within closed system available for use	Requirement for waste separation to improve decommissioning efficiency
Greenhouse gas monitoring	Pretreatment essential
No unwanted odors, rodents, or flies	Post-processing required
Smaller footprint due to modular construction and closed processes	2-4 Month start-up time
Net positive environmental gains	
Small scale implementation possible	
Low power requirements	
High fertilizer nutrient retention	
Long storage period of sludge possible	
Relatively low construction costs	
Low sludge production	
Low nutrient demand	
High organic removal	

*from reference [20].

Studies to improve the AD process, efficiency, biogas production, methane yield, and cost reductions for the disposal of the digested sludge have been conducted. Other production cost measures include dynamic operation to increase the potential of existing AD processes without extra investment costs for the installation of on-site gas storage. This can be achieved through feedstock volume variation or feedstock alternation. Other significant methods of other studies include feedstock pre-treatments[21], co-digestion [22, 23], optimization of AD control parameters [24], and biological hydrogen methanation (BHM) techniques [25, 26].

2.4 Applications and end uses

In addition to sustainable energy production, biogas finds diverse applications across various sectors. It also contributes to waste management, and environmental stewardship. In the energy sector, biogas serves as a renewable and clean alternative to fossil fuels, providing heat and electricity for residential, commercial, and industrial purposes. It can be utilized in combined heat and power (CHP) systems, cogeneration plants, and microgrids, offering decentralized energy solutions and reducing reliance on non-renewable resources. Biogas can also be upgraded to biomethane quality and injected into natural gas pipelines or used as a vehicle fuel in compressed natural gas (CNG) and liquefied natural gas (LNG) vehicles, further diversifying the transportation sector's energy sources and reducing emissions [1]. Beyond energy production, biogas facilities contribute to effective waste management by converting organic waste streams into valuable energy and biofertilizers, diverting materials from landfills and mitigating greenhouse gas emissions. Furthermore, biogas plants serve as key components of circular economy initiatives, promoting resource efficiency and environmental sustainability by closing the loop on organic waste utilization. Through these versatile applications, biogas plays a pivotal role in transitioning towards a more resilient, low-carbon, and circular economy. Figure 4 reports a circular economy framework produced from biogas AD process aiming at nutrient recycling, greenhouse gas (GHG) reduction, and biorefinery applications [5].

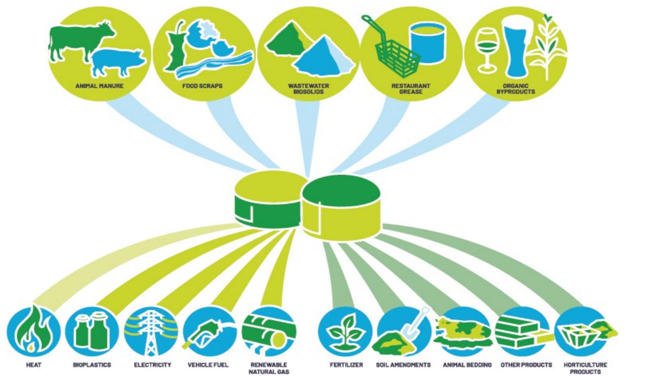


Figure 4. A circular economy framework produced from biogas [27]. Reproduced with permission of the American Biogas Council.

In the contemporary landscape, the biogas sector is experiencing rapid expansion, with innovative strides laying the groundwork for advanced bioenergy factories. Biogas is now regarded as a domestic energy source in many countries that can support energy security reduce and dependency on natural gas imports [5]. Biogas is considered a carbon neutral due to the renewable nature of the feedstocks. Occasionally biogas has been considered carbon negative due to the collection of CH_4 that would have ended up in the atmosphere. For AD of organic substrates to produce biogas, several physicochemical conditions must be met, without which the methane yield may be greatly impaired or not occur. The engineering involved in biogas production and use projects has been developed from a wide scope of knowledge, accumulated over the years, resulting in the experience in, and development of, the mature and low risk technology that it is today. Key considerations with biogas production includes production yield and cost balances to minimize cost while maximizing production, operation and maintenance parameters to maximize production lifetime while maintaining yield thresholds and production robustness, and ensuring production availability at a level that meets demands and needs for an energy project.

3 Biomethane production and purification technologies

Biogas enrichment processes also known as biogas upgrading, biogas purification or biogas refinement, and occasionally biogas methanation. These terms refer to the process of improving the quality and energy content of raw biogas by removing impurities and other contaminants. Raw biogas typically contains around 60% methane and 40% carbon dioxide as its primary constituents along with some contaminants which include water vapor (H_2O), hydrogen sulfide (H_2S), oxygen (O_2), nitrogen (N_2),and ammonia (NH_3) [28] as shown in Table 1 earlier. The presence of impurities such as H_2O, H_2S, and CO_2 in the biogas [29] increases the volume of gas transported through pipelines, reduces the heating value, and increases pipeline corrosion during transportation and distribution, and emits sulfur dioxide (SO_2) in the upon combustion.

The goal of biogas upgrading is to produce a higher-purity biogas, typically enriched in methane (CH_4) — called biomethane — which enhances its energy density and makes it suitable for various end uses, including injection into natural gas pipelines, vehicle fuel, and power generation as shown in Figure 4. The biogas should have more than 95% of CH_4 to upgrade biogas as biomethane [30]. In this study, "biogas" refers to raw biogas with CO_2 and other contaminants (see Table 1). Biomethane refers to processed biogas with more than 95% methane. Compressed natural gas (CNG) and compressed biomethane (bio-CNG) share significant similarities in use potential due to methane content [30]. There are several methods and technologies used for biogas upgrading, each with its own advantages and applications. A range of biogas treatments and bioreactors have been studied that appear to have the capacity to enhance biogas production. Many of these technologies are currently available companies that hold propriety or licensing rights [31]. The most commonly used methods of biogas enrichment globally include [30, 31] physicochemical absorption, (high pressure) water scrubbing (HPWS), amines scrubbing (AS), pressure swing adsorption (PSA), absorption in organic solvents, membrane permeation/separation (MP), cryogenic separation/distillation, biological upgrading technologies, and in recent years in situ methane enrichment have also been used for these purposes [32-34].

3.1 Physicochemical sorption

Physiochemical sorption includes the processes of adsorption and absorption. Adsorption is a selective separation process which includes preferential selection of certain gaseous molecules in the solvents or on the solid surface, known as the adsorbent. This process is governed by intermolecular forces such as Van der Waals forces and can be physical or chemical. Depending on the route followed by the reaction, adsorption can remove impurities such as carbon dioxide (CO_2), hydrogen sulfide (H_2S), moisture (water vapor), and others from biogas [18]. Physical absorption is based on the solubility variations of different gas fractions in a liquid scrubbing solution. The absorption upgrading process for biogas relies on either the physiochemical solubility differences or chemical reactivity of gaseous compounds with the absorber liquid, which is later regenerated [30]. At a given temperature, the solubility of methane (CH_4) and carbon dioxide (CO_2) in water/solvent is directly proportional to the partial pressure of methane or carbon dioxide above the water/solvent. This means that as the partial pressure of CH_4 or CO_2 increases, more of the gas will dissolve into the water until reaching equilibrium. Figure 5 reports the solubility of methane (CH_4) and carbon dioxide (CO_2) in biogas as functions of temperature.

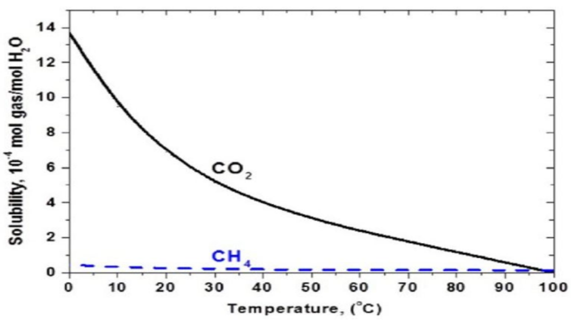


Figure 5. Solubility of solubility of methane (CH_4) and carbon dioxide (CO_2) in biogas in water [35]. Licensed under CC-BY 4.0.

3.2 High pressure water scrubbing (HPWS)

Water scrubbing has been the most common process used for large scale biogas upgrading to biomethane. Scrubbing is a process used to remove impurities, contaminants, or unwanted substances from gases or liquids. It involves passing the gas or liquid through a medium or solution that selectively absorbs or reacts with the impurities, thereby purifying the gas or liquid. Water scrubbing (WS) is a physical scrubbing which applies different solubilities of the gases in the biogas such as CO_2 and CH_4 with the solvent (water). It involves passing biogas through a column or tower filled with water (solvent). CO_2 and other impurities such as H_2S are more soluble in the water than CH_4. The solubility of CO_2 in room temperature (25 °C) water is approximately 26 times higher than CH_4 [36]. Figure 6a illustrates simplified diagram of regenerative pressurized water scrubbing [37]. As carbon dioxide from the biogas stream is absorbed into the water, weak carbonic acid (H_2CO_3) is formed. At the top gas outlet of the scrubber, CH_4 with a purity exceeding 96% can be obtained using this process [38]. The methane-rich gas is then collected at the top of the column, while the CO_2-enriched water is removed and treated separately.

An unconventional and novel sponge carrier water scrubber system which had improved hydraulic retention time for scrubbing water compared to conventional HPWS systems. This new type of water scrubber can achieve high purification of biogas purification while operating at atmospheric pressure conditions. The results showed an upgrading purity of biogas from 60% CH_4 to over 90% CH_4 with no traces of H_2S [39]. Parameters that affect the absorption of water scrubbing include the scrubbing pressure, the temperature of the absorption column, and feed flow rate [28]. WS can operate at low temperature [40] or low pressure [41]. Water scrubbing comprises 41% of the total biogas cleaning and upgrading systems globally [30]. High-pressure water scrubbing (HPWS) is the most commercially popular upgrading technique [42].

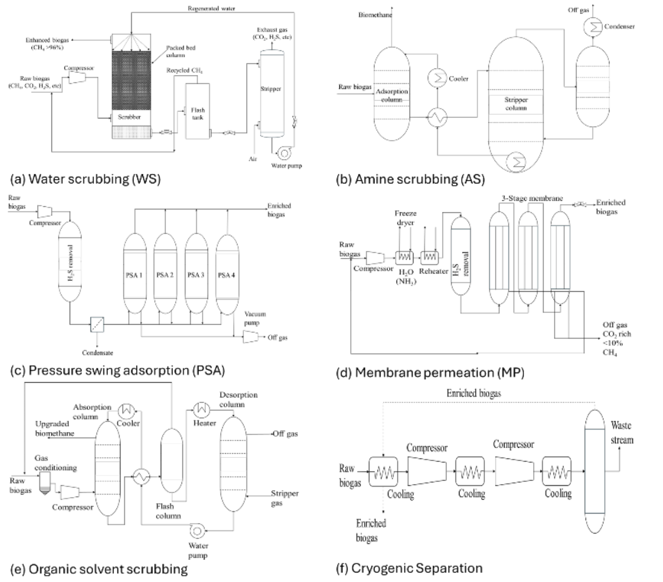


Figure 6. Simplified diagrams of regenerative pressurized water scrubbing (WS) (a) [37], amine scrubbing (AS) (b) [43], pressure swing adsorption (PSA) (c) [44], membranes (MP) (d) [45], organic solvent scrubbing (e) [43], and Cryogenic separation (f) [46].

3.3 Amine scrubbing (AS)

Amine scrubbing is also known as chemical absorption used in gas-liquid separation, particularly in gas scrubbing or gas purification applications. In these chemical absorptions, different types of primary and secondary amine compounds commonly used in biogas enrichment are such as mono ethanol amine (MEA), diethanol amine (DEA), methyl diethanol amine (MDEA), diisopropanol amine (DIPA), and amino-ethoxyethanol (DGA) [47]. Other solvents can also serve the purpose but the most commonly used solvents for biogas scrubbing are DEA, MEA, and MDEA. The most commonly applied amine is activated MDEA (aMDEA) which is a mixture of MDEA with piperazine (PZ) [43]. Figure 6c shows a flow diagram of the amine/alkali solution absorption process [30]. Amine solutions can ensure that the purity of CH_4 of between 99.5–99.9% due to methane's low solubility, and allows for plant availability of between 91–96% [30]. The amine solution can be regenerated via applying significant thermal energy to the solution – heating the solution to between 120-150 °C – the bonds between the amine and the acid components (CO_2 & H_2S) [43]. Amine scrubbers tend to have lower electricity requirements compared to other methods due to the lower pressures for absorption (1-2 bar) and desorption (1.5-3 bar), and low methane loss while simultaneously removing H_2S [43]. Issues with respect to this technique include possible corrosion, amine losses and foaming, which may contribute to the reduction of the global market share for upgrading biogas. Figure 6b presents a simplified diagram of chemical absorption by amine process [43].

3.4 Pressure swing adsorption (PSA)

Adsorption processes are classified into several categories, including pressure swing adsorption (PSA), vacuum swing adsorption (VSA), and temperature swing adsorption (TSA). These methods offer methane purity ranging from 50% to 99% and recovery rates between 75% and 99.4% [48-50]. As one of the most common biogas purification processes, PSA involves passing biogas through an adsorbent material through variations of pressure. The adsorbent selectively captures CO_2 molecules, allowing methane-rich gas to pass through. The pressure is then reduced, releasing the captured CO_2 and regenerating the adsorbent for reuse. The adsorbent solids used have high surface areas and porosity. Commercially carbon molecular sieves tend to be commonly utilized, less commonly zeolites, activated carbon, and titanosilocates are employed. The PSA system can separate nitrogen, oxygen, water and hydrogen sulfide gases in addition to CO_2, however, desulfurization is recommended prior to PSA as sulfur compounds can irreversibly contaminate some adsorbents. Zeolites are recommended for operation with dry biogas [51]. Figure 6c displays the simplified diagram of PSA. Methane losses in more sophisticated cycles are reduced by 3 to 12 % via pressure equalization steps. These steps occur between columns in different stages. A pressure equalization step can have a biomethane purity of 97.1% and can increase the methane recovery from 79.4% to 86.3%. Equalization steps, at the cost of increased equipment complexity and higher capital costs, increase biomethane production [51].

VSA is a gas separation method which is a variation of PSA but operates at close to ambient temperatures and pressures. Due to this it requires less power and has lower operating costs when compared to PSA. Another advantage of VSA is the low susceptibility to humid environments. However, it requires high adsorbent selectivity and its non-isothermal behavior [28]. TSA is another separation method through variation of the temperature periodically and often with amine sorbent. TSA combines an exothermic adsorption and an endothermic desorption process, hence, heat transfer is critical in TSA. This technique requires lower energy than PSA and is able to handle larger amount of CO_2, but has a slower adsorption rate and short regeneration rate which is not favorable [28].

3.5 Membrane permeation/separation (MP)

In recent years, membrane permeation (MP) or separation has emerged as a highly competitive technology compared to its counterparts [52]. Membranes find widespread applications ranging from wastewater treatment to potable water production and gas purification. Membrane separation operates on the basis of highly selective processes, exploiting differences in chemical species transport rates across the membrane interface [52]. Membrane processes demonstrate exceptionally high separation efficiency and typically yield high-purity retentate. Key parameters for porous membranes include pore size and shape, as well as transport flow through interphase layers, influenced by pore characteristics, layer porosity, and compound affinity for the layer walls [52]. Despite extensive research on various materials such as inorganic, polymeric, and composite membranes for gas separation over recent decades, the most commonly used membranes comprise polyimide, polyamide, and cellulose acetate [52]. Synthetic membranes, composed of polymers like cellulose acetate, polyamide, or ceramic materials, exhibit effective gas mixture separation in biogas upgrading systems. Table 4 compiles properties and materials of polymer membranes for biogas separation.

Table 4. Permeability and selectivity of polymeric membranes for biogas separation.[a]

Polymer	Selectivity CH_4/CO_2	Permeability at 30 °C (Barrer)[b] CH_4	CO_2	H_2	O_2	N_2	T_g [°C]
Cellulose acetate (CA)	30.0	0.21	6.30	2.69	0.59	0.21	80.0
Ethyl Cellulose (EC)	1.39	169	26.5	87.0	26.5	8.40	43.0
Polycarbonate (PC)	32.5	0.13	4.23		1.36	0.18	150
Polydimethyl-siloxane (PDMS)	3.38	800	2700	550	500	250	-123
Polyimide (PI)	42.8	0.25	10.7	28.1	2.13	0.32	317
Polymethylpentene (PMP)	5.75	14.9	84.6	125	27.0	6.70	30.0
Polyphenoloxide (PPO)	6.89	11.0	75.8	113	16.8	3.81	210
Polysulfone (PSf)	22.4	0.25	5.60	14.0	1.40	0.25	190

[a]Data from [29]. [b]Barrer = 10^{-10} cm^3 (STP) $cm \cdot cm^{-2} \cdot s^{-1} \cdot cmHg^{-1}$ = $10^{-10} \frac{cm^3_{STP(permeating\ substance)} \cdot cm_{material\ thickness}}{cm^2_{(material\ surface\ area)} \cdot s \cdot cmHg}$

Polymer membranes stand as the predominant materials in gas separation technologies, owing to their robust stability under higher pressures, straightforward production process, and cost-effectiveness. Common polymer materials include cellulose acetate, polysulfone, and polysiloxane [29]. Typically, polymeric membranes in commercial applications function based on the solution-diffusion mechanism [53]. The choice of the appropriate polymeric membrane material for a specific gas separation application generally hinges on various properties such as selectivity, permeability, processability, chemical, mechanical, and thermal stability, cost, material availability, glass transition temperature (Tg), and critical CO_2 pressure for plasticization [52].

The schematic arrangement of the membrane biogas purification process is illustrated in Figure 6d. These systems operate on the principle of different gas permeabilities through membrane fibers. As biogas flows through a dense polymer membrane, CO_2, H_2S, H_2O, and other impurities pass through to the permeate side, while CH_4 remains on the inlet side. However, pre-removal of impurities like H_2S, aerosols, oil droplets, and water from the raw biogas is essential as they can negatively impact membrane performance. With a single stage, raw biogas can be enriched to a maximum of 92% CH_4, while employing two or three stages can yield a gas with 96% or more CH_4. The off-gas, still containing 10–25% CH_4 content, can be flared or utilized in a steam boiler. Membrane separation, together with water scrubbing, are the most cost-effective techniques while chemical scrubbing offers relatively high biomethane purities with less CH_4 losses [30]. However, polymer membrane materials are very susceptible to moisture content; therefore, biogas drying should always be performed prior to membrane separation. The main drawback of membrane separation is low membrane resistance to aggressive compounds present in the separated medium [52].

3.6 Organic solvent scrubbing

The gas scrubbing process can be enhanced through the selection of a high CO_2 and hydrogen sulfide solubility, and low vapor pressure scrubbing liquid. The process of scrubbing and regeneration, which is the same as water scrubbing, is shown in Figure 6a. An organic solvent such as dimethyl ethers of polyethylene glycol and methanol can be used for this purpose. The commercial names of some common solvents are Genosorb™, Purisol™, Rectisol™, and Selexol™ [54]. Selexol™ is the solvent mixture of dimethyl ethers and polyethylene glycol, which offers affinity for CO_2 and H_2S five times greater than water [55]. The absorber volumes to be circulated are significantly smaller due to the higher solubility of H_2S and CO_2 in organic solvents which enables lower energy consumption when compared to water absorption systems. Figure 6e shows a simplified diagram of organic solvents process. As a result, organic solvent scrubbing systems tend to have smaller absorption columns, lower pumping requirements, and reduced absorbent losses to the product stream, which decreases the in investment and operating costs [56].

Most biomethane plants employ the Genosorb® 1753 absorber using this process, as there is no water consumption and only requires minor solvent replacement to compensate for losses due to product vaporization [43]. The absorption column is usually pressurized to about 8 bar and 50°C is required for desorption. Final product biomethane concentration has a range of 93-98%, and methane losses approximately 2%, which may require special off gas treatment. This technology is best suited for treating higher gas flow systems, however usage for selective H_2S removal has yet to be proven competitive. The global biogas upgrading market share of this technology is small at only 6% [57], this may be due to the fact that the use of air in biological desulfurization systems for biogas pretreatment should be carefully evaluated as nitrogen and oxygen are not removed by this process.

3.7 Cryogenic separation

Cryogenic separation is an innovative technology employed for the separation of gases by utilizing temperature differentials [30]. In this process, the unique boiling points of different gas components are exploited for efficient separation. For instance, methane (CH_4) has a boiling point of approximately −160 °C, while carbon dioxide (CO_2) boils at around −78°C under ambient pressure conditions. By lowering the temperature of the raw biogas and subjecting it to increased pressure, the various components within the biogas condense at different temperatures. This enables the isolation of specific gases, such as CO_2, which liquefies at these conditions. For instance, the raw biogas can be compressed to a pressure of 40 bar and cooled to −100°C to facilitate the liquefaction of CO_2. Through cryogenic separation, the distinct boiling points of gas components enable their efficient separation, resulting in enhanced biogas purity and usability. These phase differences can be utilized to separate the gaseous CH_4 from the liquid and solid phases of biogas that form at cryogenic conditions. Figure 6f illustrates the arrangement of cryogenic separation [46].

Cryogenic systems have high capital and operating costs due to the large range of equipment and instruments required, and have significant energy demands during high-pressure compression of raw biogas, equal to 5–10% of produced CH_4. Cryogenic separation has CH_4 losses of less than 1%. Analysis of cryogenic packed bed (CPB) indicates that only 5% combustion heat of CH_4 is used in the process, which is 22% less energy than vacuum pressure swing adsorption (VPSA), for the purification [58].

3.8 Other technologies

Biological biogas upgrading technologies have undergone experimental validation and are in the initial stages of pilot for practical implementation. A relatively new approach to biogas valorization involves biotechnology-based upgrading. In contrast to physico-chemical methods, which primarily focus on CO_2 removal, biological biogas upgrading technologies employ microorganisms to convert the carbon dioxide content of the biogas into methane (chemoautotrophic upgrading) or algal biomass (photoautotrophic upgrading) [59]. This biological upgrading approach represents a more progressive method compared to conventional techniques, as the total energy content of the resulting products is significantly higher than that of the feed gas. During the chemoautotrophic process, the methane content and energy content of the upgraded gas are considerably increased, whereas they may remain constant or even decrease with physico-chemical methods due to methane losses. Additionally, biotechnological upgrading methods may offer lower operational costs and reduced energy consumption compared to physico-chemical upgrading technologies, and they do not require expensive chemicals in general [59]. Furthermore, unlike conventional physico-chemical CO_2 removal methods, the volume flow of the gas remains unaffected by biological upgrading, meaning that the volume of incoming biogas and outgoing grid-scale gas will be almost the same.

Utilizing chemo-autotrophic methanogenic activity, such as that of methano-bacterium thermo-autotrophicum, along with uncoupled methods of methanogenesis, has proven effective in enhancing the methane (CH_4) content of biogas while simultaneously removing hydrogen sulfide (H_2S) from off-gases. Studies indicate that employing methano-bacterium thermo-autotrophicum can elevate the CH_4 content in biogas from 60 to 96%, with negligible levels of H_2 and H_2S observed. Alternatively, biogas can be upgraded using hydrogenotrophic methanogenesis, where continuous injection of hydrogen (H_2) into the biogas digester results in a CH_4 content of approximately 95%, alongside impurity concentrations ranging from 0.7 to 4.2% CO_2 and 2.3 to 7.0% H_2. This microbial transformation of CO_2 and H_2 into CH_4 occurs via an exothermic reaction, leveraging the ability of hydrogenotrophic methanogens to utilize CO_2 as a carbon source and electron acceptor, and H_2 as an electron donor.

Another method is in situ methane enrichment. It combines Power-to-Gas and biogas upgrading by converting electricity-derived H_2 and biogas-CO_2 to CH_4 in existing biogas reactors [60]. In this process, the digester sludge undergoes circulation within a desorption column before being returned to the digester. In this process, carbon dioxide (CO_2) is desorbed from the sludge in the desorption column by pumping air through it. This continuous process of CO_2 removal from the sludge leads to a higher content of methane (CH_4) in the biogas exiting the digester. Achieving enriched biogas with a CH_4 content of 95% is feasible while minimizing CH_4 loss to below 2%. Moreover, simultaneous removal of hydrogen sulfide (H_2S) is achievable through in situ enrichment processes. Studies have indicated that the cost of enrichment can be significantly lower, up to one-third, compared to conventional methods, particularly for biogas flow rates of less than 100 Nm^3/h. Pilot plant testing has been conducted using a 15 m^3 digester capacity and a 140 dm^3 bubble column to validate the effectiveness of this method. In situ biomethanation offers a sustainable and cost-effective solution for enhancing biogas quality while optimizing the efficiency of biogas production processes. Its advantages make it an attractive option for biogas plant operators looking to improve performance and reduce environmental impact [60]. Table 5 compares the advantages and disadvantages of the most important biological biogas upgrading technologies [59].

Table 5. Comparison of the advantages and disadvantages of the most important biological biogas upgrading technologies*

Technology (working principle)	Typical final CH4 conc. (Vol%)	Advantages	Disadvantages
Ex-situ chemoautotrophic (methanogenesis)	>90-95	High CH4 recovery Upgraded biogas CH4 content is appropriate for gas grid injection or CNG fuel Simple microbiological or biochemical process	High investment and operational costs Separate biomethanation reactor is required High electric energy requirement for hydrogen generation Requires separate H2S removal pH increase, H2 dissolution nuisances
In-situ chemoautotrophic (methanogenesis)	70-90	Relatively low investment costs integrated with anaerobic digestion No additional bioreactor required CO_2 capture	Generally lower CH4 content in the upgraded biogas than required for gas grid injection High electric energy requirement for hydrogen generation pH increase, H2 dissolution nuisances
Photoautotrophic (photosynthesis)	>90-97	High CH_4 recovery CO_2 valorization in form of algal biomass Simultaneous H2S removal Simultaneous wastewater treatment possibility	High investment costs and energy demand High risk of biological contamination

*Ref [59].

3.9 Comparison of biogas pre-treatment and separation technologies

Biogas enrichment processes play a critical role in maximizing the energy potential and environmental benefits of biogas production. These processes aim to enhance the quality of biogas by increasing its methane content while reducing impurities such as carbon dioxide and hydrogen sulfide. Figure 7 summaries the physicochemical and biological methods for biogas upgrading [61]. The specific applications require different levels of treatment. The biogas upgrading market is currently dominated by physiochemical upgrading methods based on adsorption, absorption, chemical reaction, cryogenic and membrane separations. Each differing in price, energy requirements and efficiency [28].

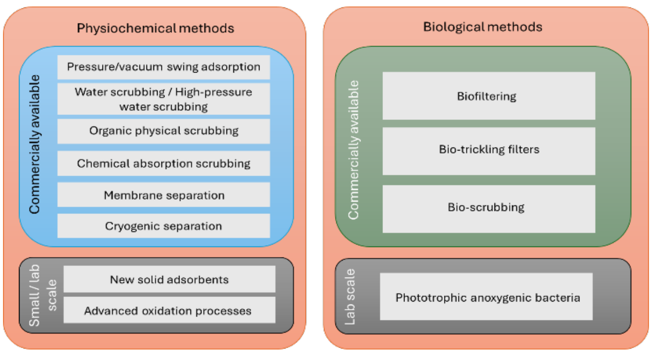


Figure 7. Summary of the physicochemical and biological methods for biogas upgrading [61].

These technologies are classified into two main categories based on the biogas enrichment processes involved: physicochemical and biological methods. The first category encompasses innovative techniques that either improve existing methods or are adapted from other fields for potential use in biogas upgrading (see Figure 7). Physicochemical methods, which require high amounts of energy and chemicals, are still the most commonly used methods for biogas upgrading. [61]. In contrast, the second category focuses on biological methods, particularly emphasizing conversion of CO_2 and the removal of hydrogen sulfide (H_2S). Notably, there is a heightened interest in phototrophic bacteria [59], which have historically been utilized for H_2S removal from wastewater. Their application in biogas treatment presents novel opportunities and revitalizes an area that has received comparatively less attention. Table 6 presents a comparative analysis of the major technologies used for biogas enrichment.

Table 6. Comparison of the major biogas upgrading techniques.*

Technology	Parameters	Advantages
Pressure Swing adsorption	Operation pressure (MPa): 0.4-1 Outlet pressure (MPa): 0.4-0.5 Temperature range: 50-56 °C Power demand (€/m): 0.25 CH_4 losses: <4% CH_4 Purity: 96-98%	Quality of gas is high Low energy demand CH_4 losses are low No use of chemicals, minimizing post processing Suitable for modest volumes of biogas Tolerant of impurities
Temperature swing adsorption	CO_2 adsorption temperature: 293 K CO_2 desorption temperature: 348 K CO_2 partial pressure (adsorption): 0.15 bar CO_2 partial pressure (desorption): 0.4 bar	Low energy requirements Continuous process Supports higher capacity of CO_2 Suitable for adsorbates of moderate volatility
Vacuum swing adsorption	Feed pressure: 200 kPa Feed time: 20-40 s Vacuum pressure: 6-20 kPa Operating temperature: 313.15 K Feed gas composition: 50% CH_4 50% CO_2	System is less sensitive to humidity compared to PSA Lower operating costs Low energy demand
Physical scrubbing	Operation pressure (MPa): 0.4-1 Outlet pressure (MPa): 0.7-1 Temperature: 70 C Power demand (€/m):0.25 CH_4 losses: <2% CH_4 purity: 96-98%	Simple process High CH_4 purity Low CH_4 losses Absorbed CH_4 can be recovered with heating Temperature and pressure can change absorption capacity
Chemical scrubbing	Operation pressure (MPa): 0.4-1 Outlet pressure (MPa): 0.4-0.5 Temperature: up to 180 C Power demand (€/m): 0.42 CH_4 losses: <1% CH_4 purity: >99%	High CO_2 absorption per unit of volume High efficiency for CH_4 recovery Low CH_4 losses Faster than physical scrubbing Biogas compression not required Can work in low pressure environments
Membrane separation	Operation pressure (MPa): 0.5-0.8 Outlet pressure (MPa): 0.4-0.6 Temperature: ambient Power demand (€/m): 0.5 CH_4 losses: <1% CH_4 purity: 92-96%	Environmentally friendly Low energy consumption Reduced cost Straightforward process Design, installation, and operation are all simple and compact Can be used for low gas flow rates
Cryogenic separation	Operating pressure (Ma): 1-8 Outlet pressure (MPa): 0.8-1 Temperature range: -25 ~ -110 °C Power demand (€/m): 5 CH_4 losses: <2% CH_4 purity: 97-98%	High quality gas Low methane losses Environmentally friendly

*From references [31, 38, 62].

Different applications necessitate varying levels of treatment, prompting the dominance of physicochemical methods in the biogas upgrading market. These methods, which include absorption, adsorption, chemical reaction, cryogenic and membrane separations, which vary in cost, energy requirements, and overall efficiency (see Table 6). Water scrubbing and in situ techniques are offer higher economic viability, while chemical absorption techniques and cryogenic separation offer higher efficiency and cost. Complete cost related data is not yet available for the various emerging techniques such as biological upgrading, cryogenic separation, and in situ methane enrichment. Water scrubbing is a commonly used technique that relies on the solubility of impurities in water to remove them from biogas. It is cost-effective and relatively simple to implement, making it suitable for smaller-scale applications. Chemical absorption involves the use of chemical solvents to selectively capture impurities from biogas. While it offers high efficiency in impurity removal, it often comes with higher operational costs and requires careful handling of chemicals. Membrane separation utilizes selective permeation through membranes to separate different gas components. Although it requires a higher initial investment, it can offer long-term cost savings and is suitable for a wide range of biogas volumes. Cryogenic separation employs temperature differentials to condense impurities, allowing for their removal from biogas. While it offers high efficiency and purity, it typically involves higher capital and maintenance costs, making it more suitable for larger-scale operations. Biological up-gradation, including in situ biomethanation, involves leveraging microbial processes to enhance biogas quality. This approach offers environmental benefits and can be integrated into existing anaerobic digestion systems, but its efficiency and cost-effectiveness may vary depending on the specific microbial strains and operational conditions [61].

Typically, the major biomethane production technologies prioritize the removal of carbon dioxide (CO_2) as the primary contaminant to elevate the energy value of produced biomethane [61]. Many of these methods necessitate the removal of contaminants, predominantly hydrogen sulfide, from biogas, or at least greatly recommend doing so. The technological readiness level (TRL) of physicochemical techniques when compared to biological approaches is often higher as most physiochemical techniques are readily deployable, whereas biological approaches are still considered novel and have not yet reached commercialization. Biological approaches, nevertheless, show promise in terms of technological simplicity, potential, and feasibility [28] and in terms of chemical or energy requirements are more competitive [59].

4 Techno-economic analyses (TEAs) of biogas pre-treatment and separation technologies

The term "promising technology" does not represent a systematic evaluation on commercial and environmental viability but reflects a subjective opinion [63]. For years, designers and contractors have prioritized cost minimization in their projects, while researchers continuously strive to develop reliable economic evaluation methods to aid in product development. Clear and standardized frameworks are essential to enhance the effectiveness of these methods. In the realm of technological innovation, two commonly used methodologies are techno-economic analysis (TEA) and life cycle cost analysis (LCCA). Despite their widespread acceptance, these tools lack clear guidelines and comprehensive documentation of their features, leading to significant ambiguity [64]. In addition, uncertainty analysis emerges as a critical element in both methods, offering valuable insights into the consequences of assumptions and underlying model structures. By assessing uncertainty, analysts gain a measure of model quality and robustness, ultimately providing insight into the reliability of the outcomes [65].

Techno-economic analysis (TEA) provides a methodological framework for the the technical and economic performance analysis of a process [63]. It is a method used to evaluate the economic feasibility and viability of a technological process or project. It involves assessing both the technical aspects (such as technology performance, energy efficiency, and process optimization) and the economic factors (such as capital investment, operational costs, revenue streams, and financial metrics) associated with the implementation of the technology. TEA aims to provide decision-makers with insights into the potential costs, benefits, risks, and returns associated with adopting a particular technology or undertaking a specific project. By systematically analyzing the technical and economic aspects, TEA helps stakeholders make informed decisions regarding investments, resource allocation, and project planning. TEA can serve as practical tools to ensure that resources are allocated appropriately and efficiently based on the technological assessment scopes [64, 65].

Techno-economic analysis (TEA) plays a crucial role in assessing the feasibility and viability of biogas methanation processes, offering valuable insights into the economic performance and potential of these renewable energy initiatives. In this section, we delve into the methodology, key factors considered, case studies, challenges, and future directions of biomethanation TEA, aiming to shed light on its significance in guiding sustainable energy solutions. Through a comprehensive exploration of TEA in the context of biomethanation, we seek to provide valuable insights for stakeholders and researchers involved in the development and implementation of biogas-to-energy projects. Although there have been some techno-economic analyses over the past few decades, a systematic discussion of its methodological approach was arguably initiated recently [65, 66].

4.1 Overview of techno-economic analysis (TEA)

Techno-economic analysis (TEA) includes studies on the development, demonstration and deployment of technologies, economic impact of research, uncovering the cost of manufacturing and market opportunities [63]. TEA is structured into distinct phases: goal and scope, inventory, calculation of indicators, and interpretation, as depicted in Figure 8. The goal phase sets the overarching objectives of the study, while the scope phase defines the included aspects and the comparison methodology. The inventory phase involves collecting all relevant data, and the calculation of indicators generates the results. Throughout each phase, the consistency and robustness of outcomes are assessed, with any necessary modifications recommended during the parallel interpretation phase. TEA is an iterative process, allowing practitioners to revisit prior phases to adjust assessments based on interpretation recommendations.

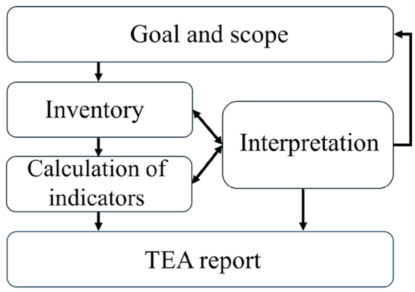


Figure 8. Phases of techno-economic analysis [67]

As TEA is still in its early stages, the literature lacks a purely theoretical discourse on the methodological framework for TEA [66]. Much of the information must be gathered through industry-specific reviews and dedicated studies focusing on particular technological domains. This deficiency necessitates the development of the method's conceptual framework primarily through sector-specific guidelines, resulting in a considerable orientation toward specific industrial nuances. Giacomella outlined the primary methodology of TEA, typically involving the following key steps [64, 66]:

- Definition of technology readiness levels (TRL),
- Identification of system elements and boundaries,
- Study of economic feasibility, costs and market conditions,
- Profitability analysis,
- Risk and uncertainty analysis through sensitivity and scenario forecasting,
- Recommendations,

which can be outlined as two major steps as goal and scope, and inventory analysis. By following these steps, TEA provides a structured approach to evaluating the economic aspects of technological processes or projects, helping stakeholders make informed decisions and optimize resource allocation.

Assessment and decision-making are distinct steps that should be treated separately. The outcomes of TEA play a crucial role in guiding the next steps in technology development, identifying business opportunities, and informing decision-making processes across various domains including research, product development, investment, policy, and regulation. TEA can offer decision support for individual products or combinations thereof, with a focus on providing recommendations based on economic and technical considerations. While TEA is closely linked with technical development activities such as chemical process design, it does not directly involve technical development efforts but rather relies on information provided by process design to inform its analysis [63]. It's important to recognize that TEA results are context-specific, influenced by factors such as location, time horizon, and availability of information. Moreover, TEA primarily addresses questions related to technology and economics, often excluding considerations of environmental and social impacts. While TEA can aid decision-making in project-specific and economic contexts, applying its results on a broader scale, such as in global policy-making, may have limitations and requires careful consideration.

4.2 TEA of the selected biogas pre-treatment and separation technologies

The techno-scientific literature highlights the environmental benefits of biomethane production, showcasing its potential to reduce greenhouse gas (GHG) emissions compared to both natural gas production [68] and electricity generation from natural gas [69]. Studies indicate that biogas-to-biomethane systems generally exhibit superior environmental performance compared to biogas-to-power systems [70], although there are variations in findings [71]. Some research suggests that cogeneration may yield higher environmental benefits, while others emphasize the economic feasibility of biogas-to-biomethane systems, which appear to be more profitable when compared to cogeneration and other energy processes [72]. Selected biogas upgrading techniques considered for the present analysis include pressure swing absorption (PSA), membrane permeation (MP), chemical absorption by amines (or amine scrubbing) (AS), and high-pressure water scrubbing (HPWS). This section briefly discusses the phases of goal and scope definition, inventory analysis, the impact assessment, the conventional economic analysis through net present value (NPV) indicator is performed based on the assumed classical cost data.

4.2.1 Goal and scope

An economic analysis comparing four prominent biogas-to-biomethane upgrading technologies—PSA, MP, AS, and HPWS—considered the most relevant in the market, is discussed [64]. The system boundaries of these analyzed technologies are depicted in Figure 9, emphasizing the upgrading processes involved. These systems include biogas pre-treatments, such as H2S removal using activated carbon, and primary upgrading processes for CO2 separation. Additionally, the system encompasses steps for compressing biomethane for injection into the national gas grid, as well as managing the transportation and disposal of solid and liquid wastes generated during these processes. These wastes primarily consist of exhausted activated carbon and condensate from biogas, intended for disposal in landfills, wastewater treatment plants (WWTP), and source-sorted organic fraction of municipal solid waste (SS-OFMSW), respectively [64]. The economic analysis incorporates the cost of biogas production, ensuring that both the AD plant and other associated processes are considered within the system.

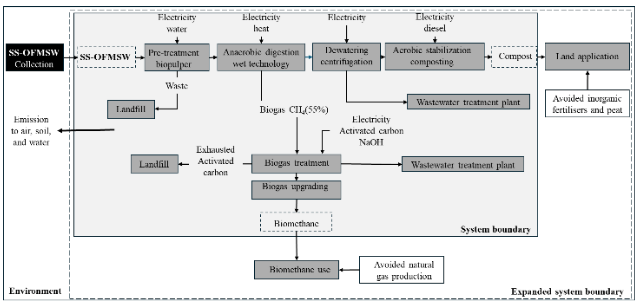


Figure 9. System boundaries (light grey fill) of the considered biogas-to-biomethane plant. The system is composed by biogas production section and the upgrading section [64].

Focusing solely on the upgrading aspect, a theoretical integrated process involving AD of SS-OFMSW, followed by the composting of resulting digestate, was simulated and incorporated within the system boundaries. These boundaries encompass the production stages of fuels, materials, chemicals, and utilities. Carbon dioxide (CO_2) emissions from biogas upgrading (off-gas stream) and composting originate from the biological breakdown of biomass, categorizing them as biogenic emissions, thus their contribution to global warming potential (GWP) was not considered [64]. Plant construction and equipment assembly were excluded from the system boundary for environmental evaluation purposes. The functional unit of analysis is the upgrading of 1 normal cubic meter (Nm3) of raw biogas from SS-OFMSW, sourced from typical Italian scenarios, consisting of organic waste (79%), paper and cardboard (11%), glass and inert materials (5%), and plastic waste (5%) [64]. The system expansion method was applied to incorporate the avoided production of energy and materials resulting from system by-products, such as energy and recovered materials (e.g., biomethane and compost), which substitute natural gas production, chemical fertilizer generation, and peat production, as outlined in the inventory.

4.2.2 Inventory analysis

During the inventory phase, quantitative data regarding inputs and outputs of material and energy flows to and from the system were gathered, along with economic data. Foreground data for the wet AD and subsequent composting processes were obtained from literature sources. Additionally, foreground data for the upgrading techniques were obtained through personal communications with companies providing upgrading plants and confirmed through literature review [64]. "Biomethane Calculator,"[73] was utilized to expand the economic database for these major biogas-to-biomethane technologies under consideration [64]. The subsequent sections describe and inventory the AD and composting processes, which are common to all compared systems, followed by descriptions and inventories of these upgrading processes. To offer a comprehensive overview of the conversion system and its ramifications, the biogas production processes originating from SS-OFMSW need to be integrated in the assessment. For economic indicators, it's imperative to incorporate the cost of biogas production. Therefore, the TEA encompass within the system not only the AD plant but also other associated processes [42, 64].

Wet AD and aerobic stabilization: In the initial composition, biogas feedstock is initially pre-treated to remove undesirable fractions. These undesirable fractions contain substances like inert components, plastics, and paper which are then landfilled. However, up to 10% of the rejected materials contain organic material that could be used in AD. Table 7 lists the assumptions for the AD facility in the assessment [64].

High-pressure water scrubbing (HPWS): High-pressure water scrubbing (HPWS) (refer to Figure 6a) is commercially the most common upgrading technique [64]. This technology, compared to others, is affected by a higher consumption of water. The pressure of the biomethane as it leaves the absorption column tends to be between 6-10 bar [64]. The desorption column reduces the pressure to atmospheric to regenerate the absorption solution, via the injection of air to release the CO_2-rich gas through the off-gas outlet at the top. Table 8 collects the parameters of HPWS for the TEA, together with other biomethane production technologies.

Amine scrubbing (AS): Amine scrubbing is also known as chemical absorption by amines (refer to Figure 6b). The cleaning and upgrading system utilizes aqueous solutions of mono-, di-, or tri-ethanolamine, owing to their CO_2 selectivity and absorption affinity [64]. The limited losses of CH_4 are a distinguishing aspect of AS technology. Aqueous amine solutions have extremely limited affinity for the absorption of N_2 and O_2. The separated biomethane exits the absorption column with a lower pressure (1-2 bar) and electricity requirements compared to HPWS systems [64]. More details of the parameters of the SA in the TEA are compared in Table 8 with other bi biomethane production technologies.

Pressure swing adsorption (PSA): This renowned upgrading technique relies on the ability of a molecular sieve, contained in an adsorption fixed bed, to selectively retain CO_2 based on its size relative to CH_4. Figure 6c gives the simplified diagram of PSA. While the PSA technique yields biomethane of lower purity, the molecular sieve can partially retain N_2 and O_2, although H_2S removal is necessary in the pre-treatment stage using activated carbon due to its irreversible adsorption [64]. The resulting biomethane exits the adsorption system at a pressure of 3-6 bar. Notably, no water, chemicals, or thermal energy are required for this technology. Table 8 summarize the parameters of the technology.

Table 7. Assumptions for the anaerobic digestion (AD) facility.*

Parameters	Values	Unit of measures
Pretreatment - specific consumption/production per t SS-OFMSW		
Electricity consumption	26.5	kWh/t
Water consumption	0.4	m^3/t
Waste production	0.23	t/t
AD - specific consumption/production per t SS-OFMSW		
Electricity consumption	23	kWh/t
Heat consumption	82	kWh/t
Specific biogas production	120	Nm^3/t
Biogas treatment for H2S removal by activated carbon		
Activated carbon bed capacity	140	kg H_2S/Nm^3 raw biogas
Activated carbon bulk density	570	kg/Nm^3 raw biogas
NaOH impregnation	5	wt. %
Activated carbon consumption	1.85	g/Nm^3 raw biogas
Dewatering - specific consumption/production per t SS-OFMSW		
Electricity consumption	2.5	kWh/t
Liquid waste production	0.52	m^3/t
Composting		
Specific compost production	0.39	t/t solid digestate
Electricity consumption	38	kWh/t solid digestate
TS of compost	50	%
CH_4 emission	0.025	kg/t solid digestate
N_2O emission	0.1	kg/t solid digestate

* The data sources refer to references in Ref [64]. The unit mass 1t SS-OFMSW refers to the entering mass flow at the pre-treatment stage, as received, thus with its initial moisture.

Membrane permeation (MP): The MP upgrading technique operates on the principle of polymeric membranes' selective retention of CO_2 and, to some extent, other components like O_2, under high pressure conditions (10-15 bar), while N_2 is not retained. Figure 6d provides a simplified diagram of the MP technique. A pre-treatment step for H_2S is typically necessary to prevent membrane pore blockage and extend membrane lifespan. To achieve high biomethane purity and minimize CH_4 losses, the three-stage configuration is commonly employed. However, this setup demands significant energy consumption, particularly during the compression stage [64]. The resulting biomethane exits the system at a pressure of approximately 10-15 bar, and no water, chemicals, or thermal energy are required for this process. For comparison to other major bio biomethane production processes, please refer to Table 8.

Table 8. Characteristic parameters of the considered upgrading technologies.*

Assumed Value	AS	HPWS	MP	PSA
Biomethane purity [%]	97	99	96	97
EE consumption [kWh/Nm^3]	0.28	0.14	0.23	0.3
TE consumption [kWh/Nm^3]	-	0.55	-	-
EE consumption (compression phase) kWh/kg CH_4	0.08	0.13	0.15	0.05
Outlet pressure of biomethane (bar)	7	4	3	10
Water consumption [l/Nm^3]	0.1	-	-	-
CH_4 losses [%]	2	0.1	3	1

*Data from [64]. Specific consumptions are expressed with reference to the unit of volume (1Nm^3) of raw biogas entering the upgrading stage. (EE = electric energy; TE = thermal energy). Averaged values are taken. More details see ref [64].

4.3 Environmental life cycle and life cycle cost assessment

Environmental life cycle assessment (LCA) for bio biomethane production involves evaluating the environmental impacts associated with the entire life cycle of biogas production, including its conversion to methane. Life cycle assessment (LCA) and life cycle costing (LCC) are two assessment tools, widely recognised as among the most objective and reliable to analyze and quantify the environmental and economic performances of goods, processes and services [74]. Life cycle costing (LCC) is a method used to evaluate the total cost of a product or system over its entire lifecycle. When applied to biogas upgrading processes, LCC assesses all costs associated with the production, operation, maintenance, and disposal of the system [74]. This includes upfront capital investment, operational expenses, maintenance costs, and decommissioning or disposal expenses. By considering costs over the entire lifecycle, LCC provides a comprehensive view of the financial implications of biomethane. This method helps decision-makers compare different options, identify cost-saving opportunities, and make informed choices that optimize economic efficiency. Additionally, LCC can factor in external costs such as environmental impacts, allowing for a more holistic assessment of biomethane production technologies. The steps of LCA/LCC are similar to TEA but the former include additional environmental LCA/LCC steps in the assessment loop. Recently, Ardolino et al provided a comprehensive review of life cycle for biogas-to-biomethane upgrading [74]. The structure of the methodological approach in the LCA/LCC is summarized in Figure 10.

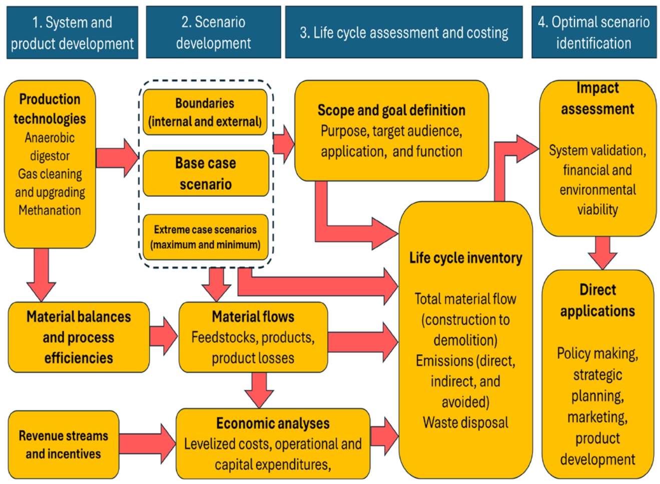


Figure 10. Structure of the methodological approach, with the indication of each step and related inputs/outputs and links [75, 76].

As the present study concentrate on biomethane production and its TEA assessment, we do not intend to dive into the LCA and LCC processes. However, they help identify environmental hotspots, assess the sustainability of biogas production systems, and inform decision-making to minimize environmental burdens throughout the life cycle. Several parameters need to be considered to comprehensively evaluate the environmental and economic aspects of a product or process. In LCA, the key general parameters needed to consider include:

- Input Materials: Assess the types and quantities of raw materials used throughout the life cycle,
- Energy Consumption: Evaluate energy usage during all stages, including production, operation, and disposal,
- Emissions: Quantify emissions to air, water, and soil, including greenhouse gases, pollutants, and waste,
- Resource Depletion: Determine the depletion of natural resources, such as minerals, water, and fossil fuels,
- Waste Generation: Analyze the generation of waste materials and their impact on the environment,
- Transportation: Consider the energy and emissions associated with transporting materials and products,

- End-of-Life Treatment: Assess the environmental impact of disposal methods, such as recycling, landfilling, or incineration,

which lead to up to 11 parameters such as Abiotic depletion (AbD); Abiotic depletion fuel (AbfD); Global warming potential (GWP); Ozone layer depletion (OLD); Human toxicity (HT); Fresh water aquatic ecotoxicity (FWAET); Marine aquatic ecotoxicity (MAET); Terrestrial ecotoxicity (TET); Photochemical oxidation (PO); Acidification (A) and Eutrophication (E) [64]. The LCA results show that among the four systems considered, the AS system presented with the overall best performance primarily due to limited CH_4 emissions and the lower EE requirements compared to the other technologies [64]. When considering only the upgrading contribution AS has the lowest indicators for GWP contribution, whereas PSA shows the lowest impacts on human toxicity (HT) indicator among the compared technologies [64].

The LCC analysis is conducted to evaluate the financial costs of the studied systems by calculating the present value of the monetary costs outlined in the inventory. The LCC can be performed by combining the calculation of the environmental external costs with a conventional economic analysis for the net present value (NPV) indicator (time horizon equal to 20 years) [64]. Later in the process external costs analyses are incorporated into the financial LCC. The LCC and LCA evaluations can be combined [64]. the key general costs needed to be considered are:

- Capital Costs: Include initial investment costs for equipment, infrastructure, and facilities,
- Operating Costs: Account for ongoing expenses, such as labor, maintenance, utilities, and raw materials,
- Maintenance Costs: Evaluate costs associated with repairing and replacing equipment over its lifespan,
- Disposal Costs: Consider expenses related to the disposal or decommissioning of assets at the end of their life cycle,
- Revenue: Factor in any potential revenue streams generated by the product or process,
- Discount Rate: Apply an appropriate discount rate to calculate the present value of future costs and benefits,
- Inflation Rate: Consider the impact of inflation on future costs and revenues.

The net cash flow (NCF) for a given system can be determined by considering both active and passive costs stated in the inventory, assuming a one-year time period. Key indicators such as net present value (NPV), payback time (PT), and internal rate of return (IRR) are then calculated to assess the economic viability of the systems [64]. Typically, a project is considered economically sustainable if its NPV value is higher than zero.

Unlike LCA inventory data, which focuses on upgrading consumptions and performances, LCC focuses on the specific costs of the AD and composting plants, as well as the upgrading processes, which may vary depending on the plant size [64, 74]. Generally, increasing plant size decreases specific costs. Therefore, plant size will introduce variation into the analysis of NPV, IRR, and PT. The IRR, PT, and NPV (in V/Nm^3 of raw biogas) of the four considered systems (including biogas production and upgrading) are reported in Table 9 according to different plant sizes described in terms of biogas production. Across the 20 years considered for the plant life of the analyses, plants of all considered sizes were economically sustainable. There were, however, no substantial differences among the different technologies when comparing plants of the same size across the key parameters of NPV, PT, IRR. The larger plant sizes improved economic indicators due to the higher revenue from increased biomethane production [64].

When increasing the size of the plant from 350 Nm^3/h to 2000 Nm^3/h of raw biogas the PT reduced from 10 years to 3.5 respectively (Table 9). The technology that was determined to be more cost effective for small plants was HPWS, though, this was only a slight difference over other technologies (Table 9). However, for large scale raw biogas plants (~2000 Nm^3/h), NPV is highest for HPWS (€ 6.51 /Nm^3 in Table 9) due to the higher revenue from biomethane sales. Moreover, MP is less economically favorable for large plant sizes, due to the high EE consumptions (0.38 kWh/Nm^3 Table 8). For small plant sizes, MP has a lower EE costs for grid injection (0.003 €/Nm^3 Table 10) compared to AS (0.008 €/Nm^3 Table 10). The IRR results reflect those of the NPV; in particular, when increasing plant size, the interest rate required to zero the NPV, increases from about 5.5% to 28.5% [64].

Table 9. Various costs of system for different plant sizes (biogas production and upgrading).*

	Size [Nm^3/h]	NPV [€/Nm^3]	IRR [%]	PT [y]	CFR [%]
AS	350	1.528	5.34	10	1.29
	500	2.899	9.45	8	1.22
	1000	4.978	18.15	5	1.12
	2000	6.487	28.68	3.5	1.06
HPWS	350	1.717	5.82	10	2.47
	500	3.034	9.83	8	2.33
	1000	5.042	18.36	5	2.15
	2000	6.510	28.69	3.5	2.04
MP	350	1.599	5.55	10	1.95
	500	2.920	9.55	8	1.84
	1000	4.942	17.98	5	1.70
	2000	6.427	28.10	3.5	1.60
PSA	350	1.609	5.51	10	2.91
	500	2.941	9.49	8	2.75
	1000	4.974	17.94	5	2.53
	2000	6.462	28.13	3.5	2.39

*Data from [64]. Here NPV for net present value, IRR for net present value, PT for payback time and CFR for cash flow reduction. Excluding the PCS results as PCS is not discussed in this article.

4.4 Estimated costs for biomethane production

The trends of the NPV over time are reported for various systems, considering a size of 500 Nm^3/h of raw biogas. The results indicate that high pressure water scrubbing (HPWS) and pressure swing adsorption (PSA) technologies tend to be slightly more cost-effective compared to amine scrubbing (AS) and membrane permeation/separation (MP), particularly for smaller plants [64]. However, if TE can be locally recovered, thus reducing costs, AS would potentially yield higher NPV than HPWS and PSA. Despite variations, all considered systems remain economically sustainable over a 20-year period for all sizes. However, compared to the reference case without CO_2 recovery, NPV values decrease due to lower revenues from liquid CO_2 sales compared to the additional costs of EE required for liquefaction. To achieve higher economic performance, liquid CO_2 should ideally be sold at least at 40 V/t. In a direct comparison of upgrading technologies, excluding biogas production steps, cash flows reveal differences primarily attributed to EE and TE demand as shown in Table 10. Among the upgrading units, PSA demonstrates the lowest total costs, respectively 2%, 15%, and 13% lower than HPWS, AS, and MP. Despite variations, biomethane revenue remains relatively consistent across all scenarios.

Table 10. Comparison of cash flows (for the first 10 years) of the considered technologies for 500 Nm^3/h of raw biogas.*

Parameters	Values (€/Nm³)			
Biogas production (AD and composting plant)				
Costs	0.588			
Revenues	0.792			
Upgrading	AS	HPWS	MP	PSA
Water		4.03E-10 (0.00%)		
Activated carbon	0.01 (14.05%)	0.01 (16.21%)	0.01 (14.37%)	0.01 (16.43%)
Upgrading EE	0.021 (28.94%)	0.042 (66.80%)	0.045 (63.46%)	0.035 (55.62%)
Injection EE	0.008 (10.54%)	0.005 (7.34%)	0.003 (4.11%)	0.009 (13.81%)
NaOH	3.24E-05 (0.04%)	3.24E-05 (0.05%)	3.24E-05 (0.05%)	3.24E-05 (0.05%)
MEA solution K2C03 solution	7.03E-03 (9.69%)			
Waste transport	9.26E-5 (0.13%)	9.26E05 (0.15%)	9.26E-05 (0.13%)	9.26E-05 (0.15%)
Solid waste to landfill	1.76E-04 (0.24%)	1.76E-04 (0.28%)	1.76E-04 (0.25%)	1.76E-04 (0.28%)
TE from natural gas	0.016 (21.98%)			
Maintenance costs	0.010 (14.39%)	0.006 (9.17%)	0.012 (17.63%)	0.008 (13.65%)
Total costs upgrading	0.073	0.063	0.071	0.062
Biomethane revenue	0.456	0.448	0.452	0.443
Aggregated results and net cash flows calculation (Biogas production + upgrading part)				
	AS	HPWS	MP	PSA
Total costs	0.66	0.651	0.659	0.65
Total revenues	1.248	1.239	1.244	1.235
Net cash flows	0.587	0.588	0.585	0.585

* Data from [64]. The contributions of the biogas production plant and the upgrading plant are reported separately. Specific costs and revenues are expressed in €/Nm³ of raw biogas and the percent contributions of the costs for the upgrading systems are pointed out in the brackets (%).

The cost of producing biomethane is determined by the combined expenses of biogas production and the additional costs associated with upgrading [64]. Currently, the average global cost of producing biomethane through biogas upgrading is estimated at approximately $USD 19 per MBtu. The bulk of this expense comes from biogas production, while the upgrading process typically incurs additional costs ranging from $USD 2 to $USD 4 per MBtu for facilities processing around 3.5 million m^3 of biogas annually [5]. Upgrading costs can vary significantly based on facility size and geographic location. For instance, in North America, economies of scale from larger unit sizes contribute to lower upgrading costs. Connecting to the gas grid represents an additional expense, particularly if biomethane is to be injected into gas networks rather than used locally. Proximity to the gas network is crucial for cost-effectiveness, with typical network connection costs averaging around USD 3 per MBtu. In developing economies in Asia, where a significant expansion of the gas network is anticipated alongside increased natural gas demand, more feedstock is expected to be geographically accessible to the gas grid. Despite growing interest in biomass gasification as a means of scaling up biomethane production, few successful plants have been developed to date. Gasification currently remains the more expensive production method globally, with average costs around USD 25 per MBtu. This approach's potential is also constrained by the availability of cost-effective feedstock, such as forestry management and wood processing residues, as well as municipal solid wastes and agricultural residues. Looking ahead to 2040, it is projected that the global biomethane potential will increase by over 40%, primarily driven by the increased availability of biogas, while the potential for biomass gasification is expected to grow at a slower pace. Figure 11 Comparison of cost of using the least expensive biomethane to meet 10% of gas demand and natural gas prices in selected regions in 2018 [5]. Biomethane with higher costs pose a limitation, rendering biomethane from biogas less competitive compared to natural gas.

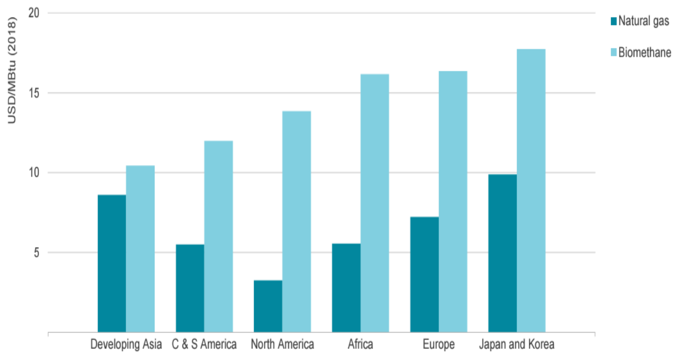


Figure 11. Comparison of cost of using the least expensive biomethane to meet 10% of gas demand and natural gas prices in selected regions in 2018 [77]. Here C & S America = Central and South America; Developing Asia = People's Republic of China, India, the Association of Southeast Asian Nations (ASEAN) and other developing economies in Asia Pacific. 1 MBtu = 0.29 MWh = 1.055 GJ Licensed under CC-BY 4.0.

5 Global status of biogas and biomethane

5.1. Current global status and key players

As of 2023, the global biogas and biomethane production has demonstrated significant growth, reaching over 1.6 exajoules (EJ) by 2022, marking a notable 17% increase since 2017. Despite the pandemic and its impact on supply chains and fuel demand in the transportation sector, the RNG sector has been resilient. Global RNG production was up 20% in 2020 to 5 billion cubic meters (bcm). It has more than doubled since 2015. There were 1,161 biogas upgrading facilities operating in the world at the end of 2020, with a production capacity of 800,000 Nm^3/h (or 6.7 bcm/y), ensuring healthy growth going forward [78]. Europe stands as a dominant player in this sector, contributing almost half of the global production, with Germany alone accounting for nearly 20% of the total consumption. Other key contributors include China (21%), the United States (12%), and India (9%) [5]. However, variations across regions and countries can be substantial, influenced by diverse energy system characteristics and government support policies. Notably, the Chinese government initiated a transition within its biogas industry since 2019, focusing on large-scale bio-natural gas (BNG) or biomethane projects exceeding 10 million cubic meters per year. These projects integrate rural and urban waste feedstocks to generate electricity and gas for grid injection. Ambitious targets set by the Chinese government aim to achieve 10 billion cubic meters by 2025 and 20 billion cubic meters by 2030 [5].

Despite slower-than-expected production expansion from 2010 to 2020, recent years have seen the introduction of new regulations supporting biogas deployment, including subsidies and national standards for plant construction. This renewed focus also extends to incorporating urban organic waste as a feedstock, further diversifying the sources of biogas and biomethane production [5]. Figure 12 reports the main uses of biogases for selected countries and regions in 2021 [5](a) and main biogases productions for countries and regions in 2021 (b).

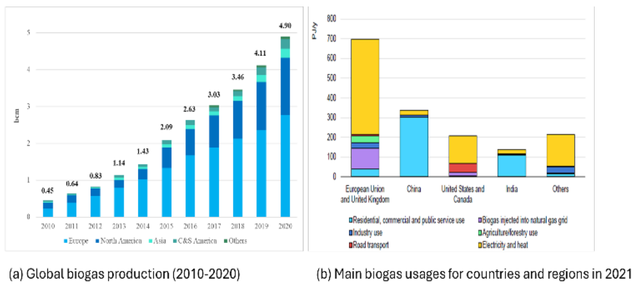


Figure 12. (a) Global biogas production (2010-2020)[79]. (b) Main biogases productions for countries and regions in 2021 (Source IEA Renewables 2023 report) [5]. Figure 11b licensed under CC-BY 4.0.

The global biogas plant market comprised at a total of 67,690 in 2018. Projections indicate a continued positive trajectory from 2019 to 2027, with a compound annual growth rate (CAGR) of 6.3%. By the conclusion of 2027, the market volume is anticipated to reach 110,354 biogas plants, suggesting an addition of over 40,000 installations during the forecast period. the global bioenergy market size is anticipated to exceed $USD 258.7 Billion by 2033, growing at a compound annual growth rate (CAGR) of 7.5% from 2023 to 2033. The largest manufacturers of biogas plant market worldwide are present across all parts of the values chain. Some of the players that have led the global biogas plant market till 2018. The key players include [79].

- IES BIOGAS (250 biogas plants throughout Europe)
- Bosch KWK System GmbH (Supplier of CHP systems based in Germany)
- Bio-En Power Inc. (110,000 tonnes of waste processing R&D facility in Canada)
- 2G Energy AG (Supplier of CHP systems based in Europe)
- DMT Environmental Technology BV (Biogas conditioning and upgrading systems based in Europe)
- Ameresco, Inc. (Renewable energy systems including biogas CHP, based in Canada)
- Air Liquide (Biomethane production on three continents)
- DVO, Inc. (Producer of AD, based in the USA)
- WELTEC BIOPOWER GmbH (Biogas plant design and construction, based in Germany)
- EnviTec Biogas (AD and upgrading system supplier, based in Germany)
- Wärtsilä (Large scale energy production with focus on renewable, based out of Finland)
- Agrinz Technologies GmbH (Large scale AD including WWTP, based out of Austria)
- Exxonmobil (Large investments in biofuels including biogas)
- Biokraft (formerly Scandinavian Biogas) (AD systems, optimization, and R&D, based in Sweden)
- SP Renewable Energy Sources Pty. Ltd. (Biogas production systems, based in India)
- PlanET Biogas International (biogas production and upgrading systems, based out of Germany)
- GAsum International (formerly Swedish Biogas International AB) (Major biogas producer in Sweden, Norway, and Finland)
- Quadrogen (Biogas cleaning and upgrading systems, based out of Canada)
- Lusakert Biogas Plant (Poultry manure bigas plant that 7 GWh of electricity annually, based in Armenia)

5.2 China

China emerges as a dominant force, accounting for a remarkable 98.4% of biogas generation among non-OECD countries [80]. The development and utilization of biogas in this region are significantly influenced by robust infrastructural advancements and favorable socioeconomic conditions. China is recognised as the global leader with the largest number of plants for the production of biogas from waste [20]. The development of household digestors, in China, began decades ago, to help supply clean energy for residential heating and cooking, which has accounted for approximately 300,000 TJ of biogas annually. This impressive energy production was facilitated by the investment support of the Chinese Rural Household Biogas State Debt Project, which began in 2003, and over the first twelve year (2015) of operation had installed almost 42 million household digesters [5]. During the period of 2015-2019, a governmental policy shift towards combined heat and power generation via engineered plants, with which feed-in tariffs and capital aid were offered. Figure 12 displays biogas production and consumption from 2005 to 2018 [81]. Since 2019, the Chinese government has embarked on a significant transition within the biogas industry, particularly investing in large-scale biogas projects exceeding 10 million cubic meters per year. These projects utilize a combination of rural and urban waste feedstocks to generate electricity and gas for grid injection. The "Guiding Opinions on Promoting the Industrialization of biogas" introduced in 2019 set ambitious targets of reaching 10 billion cubic meters by 2025 and 20 billion cubic meters by 2030 [5, 20].

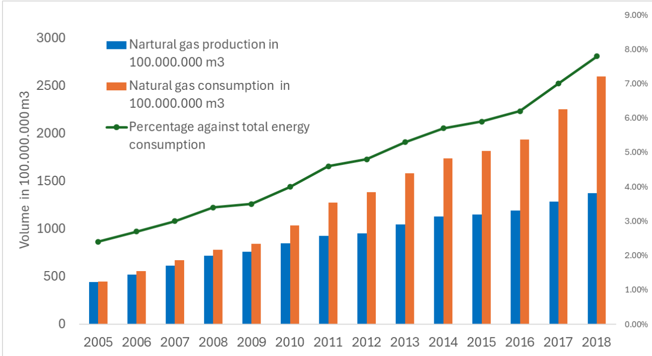


Figure 13. China's biogas production and consumption from 2005 to 2018 [81, 82].

While production expansion progressed slower than anticipated from 2010 to 2020, recent years have seen the implementation of new regulations aimed at supporting biogas deployment. Notably, China's 14th Five-Year Plan for Renewable Energy Development (2021-2025) prioritizes large-scale projects for grid injection to broaden applications, with ongoing discussions regarding subsidies. Additionally, a new national standard for plant construction was issued in 2022 [81]. Although much of China's biogas and biomethane originates from manure, there is a growing interest in incorporating urban organic waste as a feedstock in large rural facilities. Preliminary estimations suggest that leveraging animal manure and straw for biogas production could yield approximately 63 bcm of biomethane annually [81]. Furthermore, the identification of 300 potential biomethane production locations across China presents the opportunity to generate an additional 18 bcm annually [81].

In the landscape of Asia's biogas production, notably, countries like India and Bangladesh have made significant strides in the deployment of small-scale and household biogas systems. Research indicates that developing nations possess ample resources for biogas production once key barriers such as socioeconomic factors, climatic conditions, and the availability of suitable technology are effectively addressed. Encouragingly, both China and India have witnessed the establishment of numerous biogas plants ranging from medium to large scale, showcasing a concerted effort towards sustainable energy development in the region [80].

5.3 European countries

The European Union (EU) here broadly means European countries including the UK. The recorded use of bioenergy in the EU has been increasing, which may be due less to the use of solid biomass and more the use of biogas. In 2017, 8.3% (394.5 PJ) of the total bioenergy utilized was from biogas used for cooking, heating, and electricity production, which represents a five-times increase on 2005 production and utilization. Of the biogas produced almost 60% was used for electricity generation [83]. The capacity of installed biogas plants has significantly increased since 2005, nearly tripling in size by 2017. The leading countries in EU are Germany (44%), UK (17%), Italy (12%) and France (5%). Figure 13 reports the related shares in biogas production in European countries.

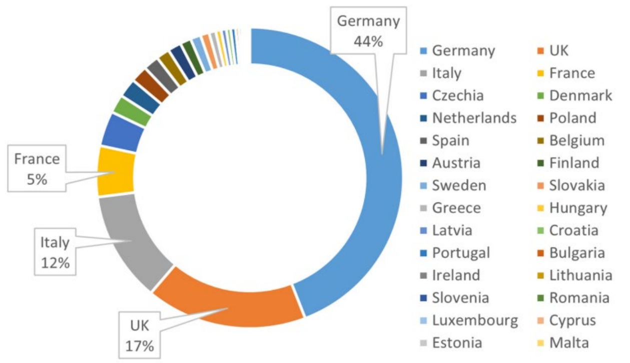


Figure 14. Related shares in biogas production in European countries (2020) [83]. Licensed under CC-BY 4.0.

The growth in the total number of biogas and biomethane plants across the EU over the past decade. From just under 182 plants in 2011, the number rose to almost 1,222 in 2022. Figure 14 exhibits the total number of biogas and biomethane facilities in the EU in the period 2011–2022, according to the Biomethane Map 2023, published by the European Biogas Association (EBA) and Gas Infrastructure Europe (GIE) [84]. This surge in facilities corresponds with a notable increase in biogas production. The European Union (EU) generated 16.8 million tonnes of oil equivalent (Mtoe) of biogas in 2018. Although suffering from the UK's withdrawal from the EU, biogas production in the remaining EU 27 countries amounted to 13.8 Mtoe in the same year [83] and steady increase since 2018 and reached 1,222 in 2022.

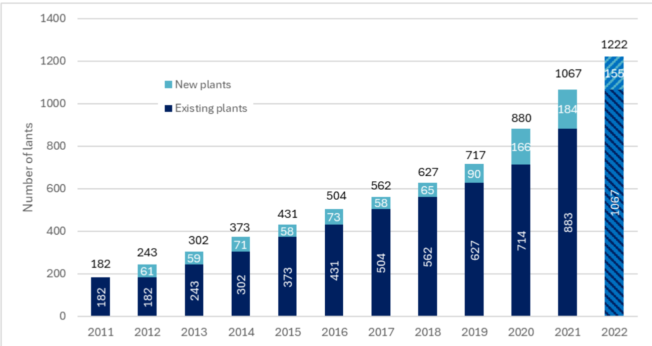


Figure 15. Number of biomethane plants in EU during 2011-2022 [84].

The Biomethane Map 2023, published by the European Biogas Association (EBA) and Gas Infrastructure Europe (GIE) [84], provides valuable insights into the infrastructure for biomethane production across Europe. Analysis of substrate utilization reveals that the majority of plants in the EU rely on agricultural substrates, including residues, manure, and plant residues, which serve as feedstock for 28% of facilities. Energy crops account for 25% of biomethane production, while sewage sludge and waste, as well as bio and municipal waste, contribute to 14% and 12% of total biomethane facilities, respectively [84]. Figure 15 Total number of newly installed biomethane plants in Europe, overall and per feedstock type. Notably, significant biomethane production is observed in non-EU member states, such as the UK and Norway. In the UK, 80 biomethane facilities primarily utilize energy crops for production (60%) [83].

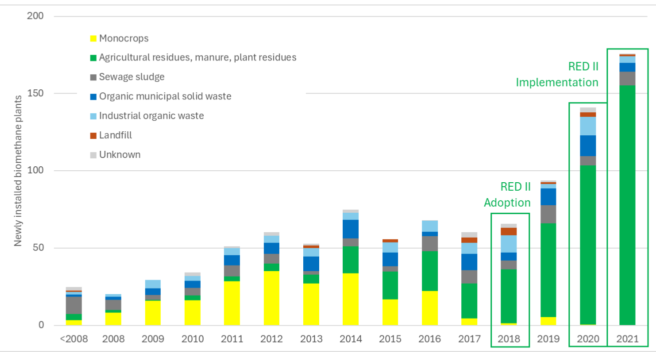


Figure 16. Total number of newly installed biomethane plants in Europe, overall and per feedstock type [84]

While the production of biogas is on the rise in European nations, its primary application remains in heat and electricity generation. However, the full potential of biogas can be realized by purifying and commercializing it as fuel, thereby curbing greenhouse gas emissions and fostering emission reductions through fossil fuel displacement and methane emission avoidance from organic waste [83]. These benefits collectively contribute to a negative carbon footprint. Despite these advantages, the market value of biogas often does not reflect its full range of benefits, resulting in a higher price compared to fossil natural gas. To address this disparity, ongoing advancements in biogas upgrading technologies are imperative. Recent geopolitical shifts, particularly in the natural gas market, have underscored the importance of diversifying energy sources, potentially catalyzing greater integration of biogas and biomethane into the energy mix. Achieving decarbonization goals in Europe necessitates robust policy and regulatory frameworks to promote biomethane production and ensure clarity in market regulations, thereby facilitating the transition towards renewable and low-carbon energy sources [83].

5.4 North America (US and Canada)

In the United States (US), the biogas industry is flourishing with over 2,200 operational biogas plants, including 250 anaerobic digesters on farms, 1,269 wastewater recovery plants utilizing anaerobic digestion, and 66 independent plants processing food waste, along with 652 landfill gas projects in 2021 [80]. The immense potential for further industry growth, estimating a potential power generation of 103 trillion kWh per year nationwide. California leads the way in biogas production potential, followed closely by Texas, with power generation estimates of 9,731 million kWh and 6,574 million kWh, respectively. The numbers of the biogas industry in the US in March 2024 become more than 2,400 sites producing biogas in all 50 states: 473 anaerobic digesters on farms, 1,269 water resource recovery facilities using an anaerobic digester, 102 stand-alone systems that digest food waste, and 566 landfill gas projects, according to the American Biogas Council [85].

Meanwhile, in Canada, bioenergy constitutes approximately 26.7% of the country's entire renewable energy market. Solid biomass burning accounts for the largest share at 23.1%, followed by liquid biofuels at 2.4%, and biogas at 1.2% [80]. Canada boasts around 150 installed biogas production plants, with landfill sites accounting for 30%, the agriculture sector 24.7%, and wastewater treatment plants 20.7%. As of 2018, these facilities generated approximately 195 MW of electricity and 400,000 GJ of biogas. Biogas is utilized for various purposes, including providing heat and electricity, delivering through pipelines, converting to electricity connected to the grid, or refined into biogas based on site conditions and energy demands. About 50% of produced biogas is converted to power, with the remainder allocated to combined heat and power (CHP), heat, biogas, or electricity and biogas applications.

5.5 Australia

The biogas industry in Australia is emerging, with significant potential for growth and contribution to the country's energy landscape. In the fiscal year 2016-17, electricity generation from biogas reached approximately 1,200 gigawatt-hours (GWh), accounting for 0.5% of the nation's total electricity generation [86]. There were 242 biogas plants in operation across the country in 2017, with half of them located in landfills and collecting landfill gas. However, a substantial portion of landfill gas remained unused and was instead flared. Figure 16 presents the estimated number of biogas plants in Australia by feedstock type [86].

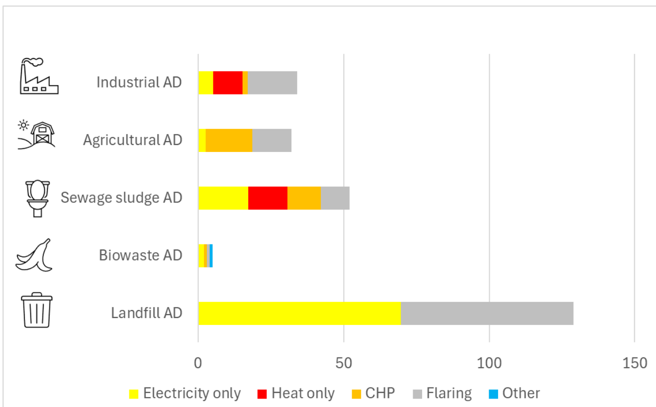


Figure 17. Estimated number of biogas plants in Australia by feedstock type (data 2016-2017) [86, 87].

The Australian biogas industry is slated to grow. Australia is a much smaller producer – in 2017 there were 242 biogas plants [5]and half of which were landfills. In 2021 the first large-scale biogas plant, converting cow manure and other organic waste, was announced for Nowra, NSW, Australia's total estimated to produce up to 2.2 megawatts of power [88]. Australia's total estimated biogas potential is significant, standing at 103 terawatt-hours (TWh), which represents nearly 9% of the country's total energy consumption. This energy potential, considering the average size of biogas units in Australia, could translate to up to 90,000 biogas units. Additionally, there is an estimated at \$3.5 to 5.0 billion (AUD), worth of investment opportunities in new bioenergy and energy-from-waste projects, with the annual potential to avoid CO_2 equivalent emissions of up to 9 million tonnes [89]. Estimates on the number of operational biogas facilities in Australia range from 135 [90] to 242 [86]. Figure 17 is the map of operational biogas facilities in Australia.

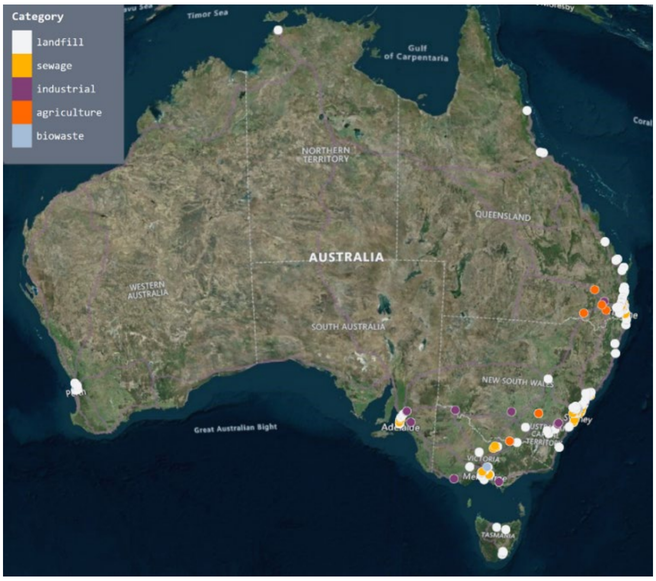


Figure 18. Operational biogas facilities. Image adapted from the Australian interactive National Map 2023 [90].

Environment Protection Authority Victoria (EPA Victoria) funded a A\$27 million Yarra Valley Water's waste-to-energy plant, ReWaste, came into commercial operation in 2017 [86]. It has reached a significant milestone by converting more than 45,000 tonnes of food waste into 10,000 MWh (megawatt hours) of clean energy since its inception in 2017 [86]. This substantial clean energy output is ample to power over 2000 households, underscoring the plant's dual success in waste management and renewable energy generation. Commercial food waste producers, such as markets or food manufacturers, deliver 33,000 tonnes of food waste to the Wollert facility each year.

6 Challenges and opportunities of biogas pre-treatment and separation

6.1 Global biogas pre-treatment and separation projection

The World Energy Outlook 2023 published by the International Energy Agency (IEA), for the first time, dedicated a special section for biogas and biomethane in the renewable energy market report series, due to a strong surge in the past two years in 2021-2022 [5]. Market conditions are stimulating biogas use, alongside targeted policies. According to the projection of IEA, a notable increase in the share of biomethane within the total biogas demand is expected. This growth trajectory is primarily fueled by the recognition of biomethane's inherent advantages, particularly its flexibility and on-demand availability as an energy source. Biomethane's capacity to seamlessly substitute conventional natural gas, coupled with its dispatchable characteristics, positions it as a pivotal solution for decarbonizing gas supplies across diverse sectors [86]. Moreover, leveraging existing gas infrastructure underscores biomethane's potential to expedite the transition towards cleaner energy alternatives on a significant scale. organic waste, including various types of biomass such as agricultural residues, food waste, sewage sludge, and animal manure, holds significant potential for mitigating greenhouse gas (GHG) emissions on a global scale. The decomposition of organic waste in landfills or its open-air storage often results in the release of methane, a potent GHG with a much higher warming potential than CO_2 over a specific timeframe. Figure 19 reports potential of global organic wastes to reduce GHG emissions [86]. By capturing and properly managing organic waste through anaerobic digestion, biogas production, and subsequent methane utilization or mitigation, substantial reductions in GHG emissions can be achieved.

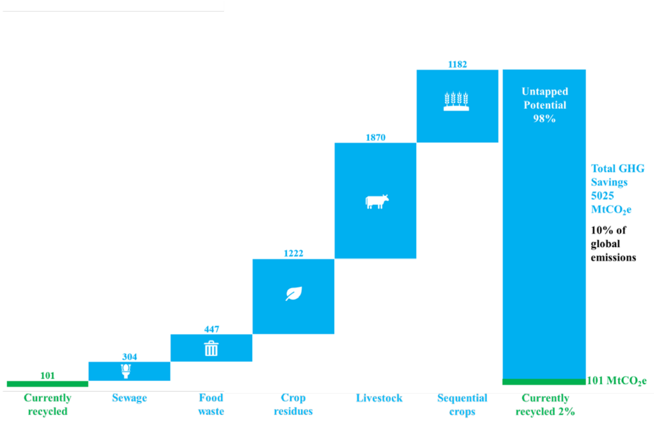


Figure 19. Potential of global organic wastes to reduce GHG emissions [86].

The future growth of the global biogas plant market is anticipated to be fueled by escalating support from government and private sectors. This support is exemplified through financial incentives and favorable regulations for biogas plant operators. Furthermore, the market is spurred by the positive environmental outcomes associated with functional biogas plants, which play a crucial role in reducing landfill waste and serving as sustainable alternatives to conventional fuels. Compared to the period from 2017 to 2022, there is an anticipated acceleration in global biogas production growth from 2023 to 2028. This growth is attributed to the implementation of impactful new policies in more than 13 countries during 2022-2023. Europe and North America are expected to experience the most significant growth, benefiting from established infrastructure and prior experience. Previous policies have facilitated rapid deployment within a five-year timeframe. While China and India also have ambitious expansion plans, their growth potential in the next five years is limited by infrastructure constraints. However, due to substantial biogas production potential, increasing energy demand, and ambitious decarbonization objectives, both countries are poised for accelerated growth beyond 2028 [5]. Figure 20 provides a trajectory of the biogas production history from 2011 and projection into 2028.

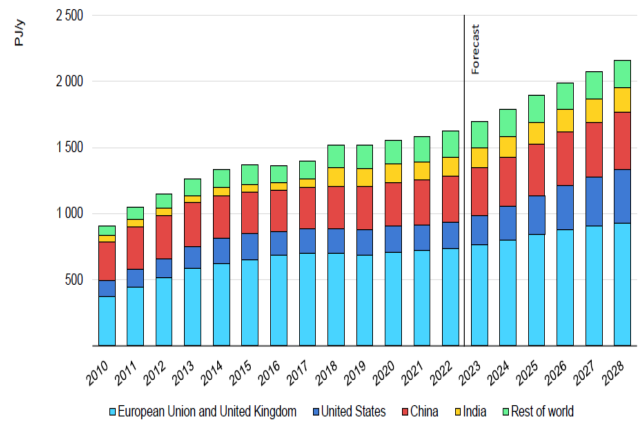


Figure 20. Global historical production and forecast of biogases, 2010-2028 [5]. Licensed under CC-BY 4.0

However, the growth trajectory has been hampered by ineffective waste segregation processes and equipment. As a result, the availability of biogas feedstock is constrained, dissuading potential new entrants from joining the market. The current growth rate is further impeded by the absence of viable waste segregation systems, limiting feedstock access for biogas plants and discouraging new players from entering the competitive arena [79].

6.2 Polarizations in the spectrum of biomethane production

Despite being generally welcomed as an environmentally friendly domestic energy solution, there is a presence of polarizations in the discourse surrounding biogas [91]. While these polarizations may seem like clear-cut binaries, they often exist along a spectrum of views and are interconnected rather than isolated. This creates a complex landscape of knowledge, values, and opinions, with different aspects of reality being emphasized or downplayed. Lyytimäki et al [91] conducted a recent review discussing biogas debate in Finland presenting dynamic and reflects, reproduces, and challenges in various societal dichotomies. These include divisions between producers and consumers, rural and urban communities, local and national interests, domestic and foreign interests, centralized and distributed, food and energy, environment and economy, traditional and innovative, long-term and short-term, and private and public [91]. Some of such divisions are shared by other areas and issues in the energy field, but others are quite unique to biomethane production. Nevertheless, these diverse and deeply ingrained dichotomies shape societal debates and perceptions. While they can stimulate critical thinking and discussion, they may also pose challenges to transforming current energy behaviors and systems, as well as centralized and distributed energy systems [91]. Building societal capabilities to bridge these interconnected yet distinct dichotomies is essential for fostering sustainable energy transitions. By fostering understanding and collaboration across these divides, societies can navigate complex energy challenges more effectively and pave the way moving beyond binary thinking for a more sustainable future.

6.3 Circularity in waste management and resource utilization

Before delving into energy recovery through biomethane production, it's imperative to prioritize the principles of use, reuse, and recycling to enhance resource efficiency and mitigate waste generation. Initially, efforts should focus on maximizing the utilization of organic materials through methods like composting or direct application in agriculture, extracting value from waste streams before they undergo AD for biogas production. Furthermore, exploring opportunities for reuse, such as repurposing organic waste for animal feed or industrial processes, can prolong resource lifespan and decrease reliance on energy-intensive production of new materials. Additionally, implementing robust recycling initiatives to reclaim valuable nutrients and materials from organic waste streams can help close the loop on resource consumption and foster a circular economy model. By prioritizing these strategies, we can minimize waste generation, reduce environmental impact, and optimize the sustainability benefits of biomethane production as an energy recovery solution [92]. The adoption of a circular economy model globally aligns with these principles, emphasizing waste minimization, pollution prevention, and the efficient utilization of resources to address resource depletion and environmental concerns, ultimately contributing to climate change mitigation [93]. This approach contrasts with the linear economy model of "take, use, and dispose," which perpetuates resource depletion and pollution without regard for sustainability, underscoring the importance of transitioning towards circularity in waste management and resource utilization. Figure 21 presents the waste hierarchy.

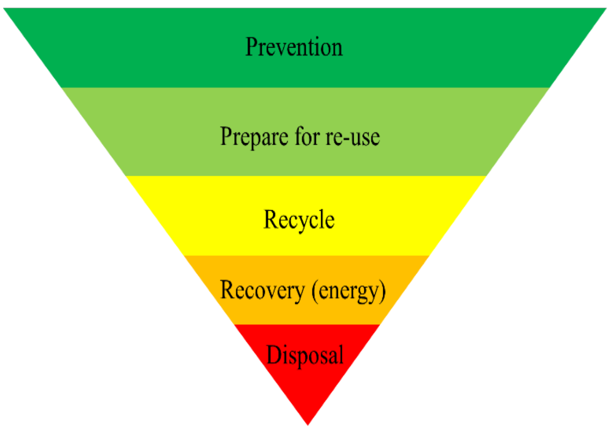
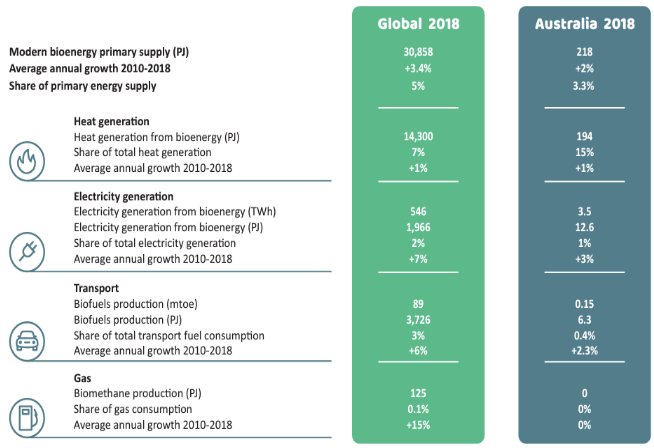


Figure 21. Waste prevention, re-use, recycle and recovery hierarchy [94]

6.4 Opportunities of biomethane production in Australia

In the Australian context, biogas emerges as a vital renewable energy source crucial for steering the decarbonization efforts of the economy. Australia, known as an energy exporter with abundant biomass resources [1], stands to benefit significantly from biogas utilization, as it presents a secure, continuous, and dispatchable energy option that holds significant potential for bolstering the nation's energy supply. Through the transformation of biogas into biomethane, Australia gains access to a renewable gas alternative capable of replacing natural gas in various applications. Biomethane's versatility extends to household use for cooking, heating, and hot water, as well as serving as a fuel for gas vehicles. This transition presents an opportune moment for the Australian gas and transport sectors to play a more substantial role in facilitating the country's energy transition. Additionally, biogas offers an alternative pathway for waste treatment, aligning with Australia's goals of reducing landfill waste. Furthermore, the growth of the biogas industry in Australia holds promise for bolstering local economies and regional communities, creating job opportunities, and providing new income sources, particularly beneficial for farmers. Figure 22 compares the global and Australian bioenergy production per market in 2018, indicating a vast potential for Australian biomethane production to grow.



	Global 2018	Australia 2018
Modern bioenergy primary supply (PJ)	30,858	218
Average annual growth 2010-2018	+3.4%	+2%
Share of primary energy supply	5%	3.3%
Heat generation		
Heat generation from bioenergy (PJ)	14,300	194
Share of total heat generation	7%	15%
Average annual growth 2010-2018	+1%	+1%
Electricity generation		
Electricity generation from bioenergy (TWh)	546	3.5
Electricity generation from bioenergy (PJ)	1,966	12.6
Share of total electricity generation	2%	1%
Average annual growth 2010-2018	+7%	+3%
Transport		
Biofuels production (mtoe)	89	0.15
Biofuels production (PJ)	3,726	6.3
Share of total transport fuel consumption	3%	0.4%
Average annual growth 2010-2018	+6%	+2.3%
Gas		
Biomethane production (PJ)	125	0
Share of gas consumption	0.1%	0%
Average annual growth 2010-2018	+15%	0%

Figure 22. Comparison of global and Australian bioenergy production per market in 2018 [89]. Licensed under CC-BY 3.0.

While there are challenges to overcome, the biogas and biomethane sectors in Australia holds significant promise for addressing energy and environmental needs, driving economic development, and contributing to the transition to a more sustainable energy future. The opportunities exist in Australian biomethane production to develop, including:

- Abundant biomass resources: Australia is rich in biomass resources, including agricultural waste, organic residues, and municipal solid waste. These abundant feedstocks offer ample opportunities for biogas production and purification, providing a sustainable energy source while addressing waste management challenges.
- Learning from international experience: Despite starting later, Australia can learn from the experiences of early adopters of biogas technology in other countries. By leveraging international best practices and lessons learned, Australia can accelerate its biogas development and avoid common pitfalls.
- Tailored solutions: Australia's unique environmental conditions and biomass resources present opportunities for the development of tailored biogas solutions. Customized approaches that consider local factors such as climate, feedstock availability, and infrastructure can optimize the efficiency and effectiveness of biomethane projects.
- Economic diversification: The biogas industry has the potential to support local economies and regional communities in Australia by creating jobs and offering new income sources, particularly for farmers and rural areas. Biogas projects can contribute to economic diversification and resilience, especially in regions reliant on traditional industries.

6.5 Challenges of biomethane production in Australia

Many of the opportunities of biomethane production are shared among many countries, but they vary depending on the particular country. Despite the promising opportunities and outlook, there are several barriers hindering the maximization of the biogas sector's potential in Australia. These barriers include regulatory, financial, and technological challenges. To address these hurdles and advance the biogas sector, Bioenergy Australia of Australian Renewable Energy Agency (ARENA) commissioned consultation by Enea Consulting and Deloitte examining the benefits of biogas and the current challenges faced by the industry [86]. Despite being a significant renewable energy source in Australia, bioenergy's contribution remains relatively small. For instance, in 2019-2020, bioenergy production accounted for approximately 47% of Australia's renewable energy output (inclusive of hydropower, wind, and solar) [95]. However, bioenergy only represented around 3.3% of Australia's total primary energy supply [86]. The challenges face biogas industry in Australia include

- Geographical isolation: Australia's geographical distance from major technology hubs and markets increases transportation costs as an energy exporter [1] and can hinder access to global expertise and resources in biogas technology. This isolation adds complexity and expense to importing specialized equipment and knowledge required for biogas projects.
- High labor costs: Australia's relatively high labor costs compared to some other regions can impact the competitiveness of biogas projects. Labor-intensive aspects of biogas production, such as feedstock collection, processing, and plant operation, may be more expensive, potentially affecting project economics and viability.
- Policy fragmentation: The division of regulatory authority between state and federal governments in Australia can result in fragmented policy frameworks for biogas projects. Inconsistent regulations and approval processes may create barriers and uncertainties for project developers.
- Late start: Australia began adopting biogas technology relatively late compared to some other countries. This delayed start means that Australia may lag behind in terms of infrastructure development, technological innovation, and expertise in biomethane production.
- Technological development: The pace of technological development in biogas enrichment in Australia may be behind that of other countries. This could limit the efficiency and competitiveness of biogas projects and request investment for upgrading.

6.6 Future perspectives for biomethane production in Australia

Future perspectives for biogas upgrading in Australia are promising despite facing significant challenges and barriers. Australia's Table 11 shows Bioenergy Roadmap [86], which demonstrates that there is significant potential for bioenergy to contribute to the economy, particularly in regional areas.

Table 11. Key findings of bioenergy projections in Australia.*

	Possible contribution	
Benefits	**2030**	**2050**
Waste recovery: per cent of 2019 landfill waste diverted	6%	7%
Liquid fuel security: extra days of consumption cover from 2019 levels	27 days	63 days
Jobs	26,200	35,300
GDP impact: additional annual GDP	\$10 billion (AUD)	\$14 billion (AUD)

*From ref. [86]

By addressing these hurdles and leveraging opportunities, Australia can unlock the full potential of biomethane, contributing to energy security, environmental sustainability, and economic development. Key challenges include high upfront infrastructure costs, volatile natural gas prices, inadequate market access mechanisms, limited feedstock resources, regulatory gaps, and technological deficiencies. To overcome these obstacles, Australia can learn from the experiences of developed nations, optimize subsidy programs, improve transparency and oversight, prioritize digestate management, elevate project standards, and intensify research and development efforts. Additionally, further research into CO_2 methanation from biogas, focusing on lowering costs and energy requirements, holds promise for reducing net carbon emissions from hard-to-abate sectors. Environmental and social license considerations are paramount, influencing project acceptance and longevity. By designing biogas facilities tailored to local conditions and researching lower-energy methanation systems, Australia can enhance the viability and sustainability of biogas methanation, positioning itself as a leader in renewable energy innovation with the recommendations:

- Technological advancements: Continued research and development efforts are needed to advance biogas upgrading technologies in Australia. Innovations in anaerobic digestion processes, gas purification techniques, and methane upgrading methods can improve efficiency, lower costs, and enhance the overall viability of biogas production.
- Integration with existing infrastructure: Integrating biogas production facilities with existing agricultural, industrial, and waste management infrastructure can maximize resource utilization and minimize environmental impact. This integration requires careful planning and collaboration between stakeholders to optimize synergies and minimize conflicts.
- Policy support and regulatory frameworks: Clear and consistent policies at both the state and federal levels are essential to support the growth of biogas sector in Australia. Governments can incentivize investment in biogas projects through financial incentives, regulatory certainty, and streamlined permitting processes, thereby fostering a conducive environment for industry growth.
- Market development and value chain optimization: Developing robust markets for biomethane and biogas-derived products is crucial for the long-term success of biogas in Australia. This involves establishing reliable off-take agreements, expanding distribution networks, and creating market incentives for renewable energy sources. Additionally, optimizing the value chain from feedstock supply to end-user consumption can enhance the economic viability of biogas projects.
- Community engagement and social acceptance: Building public awareness and garnering community support for biogas projects is essential for their successful implementation. Engaging stakeholders through transparent communication, consultation, and education initiatives can address concerns, build trust, and foster social acceptance of biogas facilities in local communities.
- Environmental sustainability and carbon neutrality: Biogas and biomethane play a significant role in reducing greenhouse gas emissions and mitigating climate change. By converting organic waste into renewable energy and bio-based products, biogas facilities contribute to a circular economy and support Australia's transition to a low-carbon future. Emphasizing environmental sustainability and carbon neutrality in biogas projects can enhance their social and environmental benefits while aligning with national and international climate goals.

7. Conclusions

In conclusion, biogas and biomethane production hold immense promise as sustainable solutions for waste management and energy generation through anaerobic digestion (AD) processes. Global production figures for biogas and biomethane reveal a growing trend, with significant contributions from regions like China, Europe and the USA. The review also includes the biogas development and status at home in Australia. However, challenges persist, particularly in enhancing the caloric value of biogas through major upgrading technologies like water scrubbing (WS), amine scrubbing (AS), pressure swing adsorption (PSA) and membrane separation (MP). These major upgrading technologies exhibit advantages and disadvantages under various conditions. From economical point of view, they yield very close total costs although levelized costs vary at different steps. Methanation presents a promising avenue for further increasing the biomethane content, offering potential benefits for energy production. Despite the promising prospects, the production cost of biomethane via methanation remains a concern, influenced by various factors including capital and operational expenditures, feedstock costs, and utility expenses. Addressing these challenges requires comprehensive techno-economic assessments (TEA), exploration of alternative methane enrichment systems, and comparative analyses of gas separation technologies. Additionally, further research into the optimization of operational processes, renewable energy integration, and potential revenue streams from by-products is essential to enhance the economic viability and sustainability of biomethane systems. By advancing research and innovation in this field, Australia can unlock the full potential of biogas upgrading and utilisation, contributing to its energy security, environmental sustainability, and economic development in the years to come.

8. Nomenclature

A	Acidification
AbD	Abiotic depletion
AbfD	Abiotic depletion fuel
Ad	Anaerobic digestion
aMDEA	Activated MDEA
AR	Ancient roots
ARENA	Australian Renewable Energy Agency
AS	Amine scrubbing
ASEAN	Association of Southeast Asian Nations
bcm	Billion cubic meters
BNG	Bio-natural gas
C & S America	Central and South America
C6H12O5	Cellulose
$C_6H_{12}O_6$	Glucose
CA	Cellulose acetate
CAGR	Compound annual growth rate
CE	Contemporary era
CH_3CH_2OH	Ethanol
CH_3COOH	Acetic acid
CH_3OH	Methanol
CH_4	Methane
CHP	Combined heat and power
CNG	Compressed natural gas
CO_2	Carbon dioxide
CPB	Cryogenic packed bed
DEA	Diethanol amine
DGA	Amino-ethoxyethanol
DIPA	Di-isopropanol amine
E	Eutrophication
EBA	European Biogas Association
EC	Ethyl cellulose
EE	Electrical energy
EJ	Exajoules
EMD	Early modern development
EPA	Victoria Environmental Protection Agency Victoria
EU	European Union
FWAET	Fresh water aquatic ecotoxicity
GHG	Greenhous gases
GIE	Gas Infrastructure Europe
GJ	Gigajoule
GWh	Gigawatt hours
GWP	Global warming potential
H2	Hydrogen
H2O	Water
H2S	Hydrogen sulfide
HPWS	High pressure water scrubbing
HT	Human toxicity
IEA	International Energy Agency
IR	Industrial revolution
IRR	Internal rate of return
LCA	Life-cycle assessment
LCC	Lifecycle costing
LCIA	Lifecycle inventory analysis
LLCA	Life-cycle cost analysis
LNG	Liquified natural; gas
MAET	Marine aquatic ecotoxicity
Mbtu	Mega British thermal units
MDEA	Methyl diethanol amine
MP	Membrane permeation/separation
Mtoe	Million tonnes of oil equivalent
MW	Megawatt
MWh	Mega watt hours
N2	Nitrogen
NCf	Net cash flow
NH3	Ammonia
NPV	Net present value
O_2	Oxygen
OECD	Organization of Economic Co-operation and Development
OFMSW	Organic fraction of municipal solid waste
OLD	Ozone layer depletion
PC	Polycarbonate
PDMS	Polydimethylsiloxane
PI	Polyimide
PMP	Polymethyl pentene
PO	Photochemical oxidization
PPO	Polyphenol oxide
PSA	Pressure swing adsorption
PSf	Polysulfone
PT	Payback time
PWP	Post world war period
PZ	Piperazine
RES	Renewable energy source(s)
RGF	Renewable "Green" Fuels
SO_2	Sulfur dioxide
SS-OFMSW	Source sorted organic fraction of municipal solid waste
STP	Standard temperature and pressure
TEA	Tecno-economic analysis/assessment
TEA	Thermal energy
TET	Terrestrial ecotoxicity
Tg	Glass transition temperature
TJ	Terajoule
TRL	Technological readiness level
TSA	Temperature swing adsorption
TWh	Terawatt hours
USA/US	United States of America
VPSA	Vacuum pressure swing adsorption
VSA	Vacuum swing adsorption
WW	World wars
WWTP	Wastewater treatment plant

Declaration of competing interest

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

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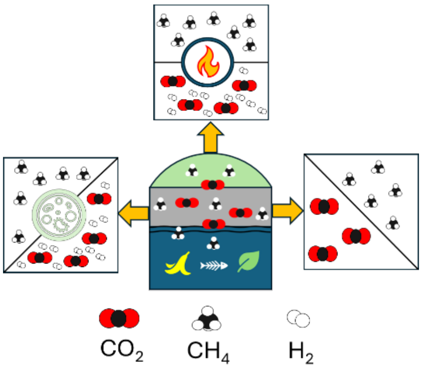
Keywords: Biogas • Biomethane separation• Techno-economic assessment • Lifecycle analysis • Methanation

References

1. Wang, F., R. Swinbourn, and C.e. Li, *Shipping Australian sunshine: Liquid renewable green fuel export.* International Journal of Hydrogen Energy, 2023.
2. Perner, J. and D. Bothe, *International aspects of a power-to-X roadmap.* Frontier Economics, 2018. **156**.
3. Riely, W. *What is the future of gas-powered generation in Australia?* 2024 [cited 2024 April 05]; Available from: https://blog.energy-insights.com.au/what-is-the-future-of-gas-powered-generation-in-australia.
4. Dar, R., et al., *Biomethanation of agricultural residues: Potential, limitations and possible solutions.* Renewable and sustainable energy reviews, 2021. **135**: p. 110217.
5. IEA, *Renewables 2023*, in *Renewables*. 2024: Paris.
6. He, P.J., *Anaerobic digestion: An intriguing long history in China.* Waste management, 2010. **30**(4): p. 549-550.
7. Joassin, L. and D. Matagne, *Methanation of urban refuse: theoretical study of energy balance and economic aspects.* Stud. Environ. Sci.;(Netherlands), 1981. **9**.
8. Zamalloa, C., et al., *The techno-economic potential of renewable energy through the anaerobic digestion of microalgae.* Bioresource technology, 2011. **102**(2): p. 1149-1158.
9. Kougias, P.G. and I. Angelidaki, *Biogas and its opportunities—A review.* Frontiers of Environmental Science & Engineering, 2018. **12**: p. 1-12.
10. Pérez-Chávez, A.M., L. Mayer, and E. Albertó, *Mushroom cultivation and biogas production: A sustainable reuse of organic resources.* Energy for Sustainable Development, 2019. **50**: p. 50-60.
11. Coombs, J. and Y. Coombs, *Recovery of energy from municipal solid waste in fabricated digesters*, in *Studies in Environmental Science*. 1991, Elsevier. p. 305-316.
12. Bond, T. and M.R. Templeton, *History and future of domestic biogas plants in the developing world.* Energy for Sustainable Development, 2011. **15**(4): p. 347-354.
13. Khanal, S.K., *Anaerobic biotechnology for bioenergy production.* Principles and Application Willey and Blackwell, 2008: p. 161-86.
14. Deublein, D. and A. Steinhauser, *Biogas from waste and renewable resources: an introduction*. 2011: John Wiley & Sons.
15. Kabeyi, M.J.B. and O.A. Olanrewaju, *Biogas production and applications in the sustainable energy transition.* Journal of Energy, 2022. **2022**: p. 1-43.
16. Janesch, E., et al., *Phase separation in anaerobic digestion: a potential for easier process combination?* Frontiers in Chemical Engineering, 2021. **3**: p. 711971.
17. Anukam, A.I., et al., *Improving the understanding of the bonding mechanism of primary components of biomass pellets through the use of advanced analytical instruments.* Journal of wood chemistry and technology, 2020. **40**(1): p. 15-32.
18. Anukam, A., et al., *A review of the chemistry of anaerobic digestion: Methods of accelerating and optimizing process efficiency.* Processes, 2019. **7**(8): p. 504.
19. Goswami, R., et al., *An overview of physico-chemical mechanisms of biogas production by microbial communities: a step towards sustainable waste management.* 3 Biotech, 2016. **6**: p. 1-12.
20. Zupančič, M., et al., *Current status and review of waste-to-biogas conversion for selected European countries and worldwide.* Sustainability, 2022. **14**(3): p. 1823.
21. He, P.J., *Anaerobic digestion: An intriguing long history in China.* Waste Manag, 2010. **30**(4): p. 549-50.
22. Nguyen, L.N., et al., *Biomethane production from anaerobic co-digestion at wastewater treatment plants: A critical review on development and innovations in biogas upgrading techniques.* Sci Total Environ, 2021. **765**: p. 142753.
23. Angelidaki, I., et al., *Biogas upgrading and utilization: Current status and perspectives.* Biotechnol Adv, 2018. **36**(2): p. 452-466.
24. Lima, D., G. Appleby, and L. Li, *A Scoping Review of Options for Increasing Biogas Production from Sewage Sludge: Challenges and Opportunities for Enhancing Energy Self-Sufficiency in Wastewater Treatment Plants.* Energies, 2023. **16**(5).
25. Antukh, T., et al., *Hydrogenotrophs-Based Biological Biogas Upgrading Technologies.* Front Bioeng Biotechnol, 2022. **10**: p. 833482.
26. Rafrafi, Y., L. Laguillaumie, and C. Dumas, *Biological Methanation of H and CO with Mixed Cultures: Current Advances, Hurdles and Challenges.* Waste and Biomass Valorization, 2021. **12**(10): p. 5259-5282.
27. American Biogas Council. *Harness the Benefits of Biogas*. 2024 [cited 2024 14 March]; Available from: https://americanbiogascouncil.org/resources/why-biogas/.
28. Karne, H., et al., *A review on biogas upgradation systems.* Materials Today: Proceedings, 2023. **72**: p. 775-786.
29. Basu, S., et al., *Membrane-based technologies for biogas separations.* Chemical Society Reviews, 2010. **39**(2): p. 750-768.
30. Katariya, H. and H. Patolia, *Advances in biogas cleaning, enrichment, and utilization technologies: a way forward.* Biomass Conversion and Biorefinery, 2021: p. 1-17.
31. Kwaśny, J. and W. Balcerzak, *Sorbents used for biogas desulfurization in the adsorption process.* Polish Journal of Environmental Studies, 2016. **25**(1).
32. Deschamps, L., et al., *In-situ biogas upgrading by bio-methanation with an innovative membrane bioreactor combining sludge filtration and H(2) injection.* Bioresour Technol, 2021. **337**: p. 125444.
33. Luo, G. and I. Angelidaki, *Integrated biogas upgrading and hydrogen utilization in an anaerobic reactor containing enriched hydrogenotrophic methanogenic culture.* Biotechnol Bioeng, 2012. **109**(11): p. 2729-36.
34. Zhao, J., Y. Li, and R. Dong, *Recent progress towards in-situ biogas upgrading technologies.* Sci Total Environ, 2021. **800**: p. 149667.
35. Yentekakis, I.V. and G. Goula, *Biogas management: advanced utilization for production of renewable energy and added-value chemicals.* Frontiers in Environmental Science, 2017. **5**: p. 7.
36. Läntelä, J., et al., *Landfill gas upgrading with pilot-scale water scrubber: Performance assessment with absorption water recycling.* Applied Energy, 2012. **92**: p. 307-314.
37. Yang, L., et al., *Progress and perspectives in converting biogas to transportation fuels.* Renewable and Sustainable Energy Reviews, 2014. **40**: p. 1133-1152.
38. Adnan, A.I., et al., *Technologies for Biogas Upgrading to Biomethane: A Review.* Bioengineering (Basel), 2019. **6**(4): p. 92.
39. Demirbas, A., *Global renewable energy projections.* Energy Sources, Part B, 2009. **4**(2): p. 212-224.
40. Pirolaa, C., et al., *Biogas upgrading by physical water washing in a micro-pilot absorption column conducted at low temperature and pressure.* CHEMICAL ENGINEERING, 2015. **43**.
41. Huang, L., et al., *Experimental study for biogas upgrading by water scrubbing under low pressure.* The Open Chemical Engineering Journal, 2015. **9**(1).
42. Khoshnevisan, B., et al., *Life cycle assessment of different strategies for energy and nutrient recovery from source sorted organic fraction of household waste.* Journal of Cleaner Production, 2018. **180**: p. 360-374.
43. Bauer, F., et al., *Biogas upgrading-Review of commercial technologies.* 2013.
44. López, M.E., et al., *Biogas technologies and cleaning techniques.* Environmental Chemistry for a Sustainable World: Volume 2: Remediation of Air and Water Pollution, 2012: p. 347-377.
45. Kadam, R. and N. Panwar, *Recent advancement in biogas enrichment and its applications.* Renewable and Sustainable Energy Reviews, 2017. **73**: p. 892-903.
46. Biernat, K., W. Gis, and I. Samson-Bręk, *Review of technology for cleaning biogas to natural gas quality.* Silniki spalinowe, 2012. **51**.
47. Chen, X.Y., et al., *Membrane gas separation technologies for biogas upgrading.* RSC advances, 2015. **5**(31): p. 24399-24448.
48. Hosseini, S.S. and J.F. Denayer, *Biogas upgrading by adsorption processes: Mathematical modeling, simulation and optimization approach–A review.* Journal of Environmental Chemical Engineering, 2022. **10**(3): p. 107483.
49. Canevesi, R.L., et al., *Pressure swing adsorption for biogas upgrading with carbon molecular sieve.* Industrial & Engineering Chemistry Research, 2018. **57**(23): p. 8057-8067.
50. Álvarez-Gutiérrez, N., et al., *Adsorption performance indicators for the CO2/CH4 separation: Application to biomass-based activated carbons.* Fuel Processing Technology, 2016. **142**: p. 361-369.
51. Grande, C.A., *Biogas upgrading by pressure swing adsorption.* Biofuel's Engineering Process Technology, 2011: p. 65-84.

52. Vrbova, V. and K. Ciahotny, *Upgrading biogas to biomethane using membrane separation.* Energy & Fuels, 2017. **31**(9): p. 9393-9401.
53. Koros, W.J. and G. Fleming, *Membrane-based gas separation.* Journal of membrane science, 1993. **83**(1): p. 1-80.
54. Miltner, M., A. Makaruk, and M. Harasek, *Review on available biogas upgrading technologies and innovations towards advanced solutions.* Journal of Cleaner Production, 2017. **161**: p. 1329-1337.
55. Tock, L., M. Gassner, and F. Maréchal, *Thermochemical production of liquid fuels from biomass: Thermo-economic modeling, process design and process integration analysis.* Biomass and bioenergy, 2010. **34**(12): p. 1838-1854.
56. Ryckebosch, E., M. Drouillon, and H. Vervaeren, *Techniques for transformation of biogas to biomethane.* Biomass and bioenergy, 2011. **35**(5): p. 1633-1645.
57. Muñoz, R., et al., *A review on the state-of-the-art of physical/chemical and biological technologies for biogas upgrading.* Reviews in Environmental Science and Bio/Technology, 2015. **14**: p. 727-759.
58. Tuinier, M.J. and M. van Sint Annaland, *Biogas purification using cryogenic packed-bed technology.* Industrial & engineering chemistry research, 2012. **51**(15): p. 5552-5558.
59. Lóránt, B. and G.M. Tardy, *Current status of biological biogas upgrading technologies.* Periodica Polytechnica Chemical Engineering, 2022. **66**(3): p. 465-481.
60. Jensen, M.B., et al., *Integrating H2 injection and reactor mixing for low-cost H2 gas-liquid mass transfer in full-scale in situ biomethanation.* Biochemical Engineering Journal, 2021. **166**: p. 107869.
61. Struk, M., I. Kushkevych, and M. Vítězová, *Biogas upgrading methods: recent advancements and emerging technologies.* Reviews in Environmental Science and Bio/Technology, 2020. **19**(3): p. 651-671.
62. Sahota, S., et al., *Review of trends in biogas upgradation technologies and future perspectives.* Bioresource Technology Reports, 2018. **1**: p. 79-88.
63. Zimmermann, A., et al., *Techno-economic assessment & life-cycle assessment guidelines for CO2 utilization*. 2018.
64. Lombardi, L. and G. Francini, *Techno-economic and environmental assessment of the main biogas upgrading technologies.* Renewable Energy, 2020. **156**: p. 440-458.
65. Barahmand, Z. and M.S. Eikeland, *Techno-Economic and Life Cycle Cost Analysis through the Lens of Uncertainty: A Scoping Review.* Sustainability, 2022. **14**(19): p. 12191.
66. Giacomella, L., *Techno-economic assessment (TEA) and life cycle costing analysis (LCCA): Discussing methodological steps and integrability.* Insights into Regional Development, 2021. **3**(2): p. 176-197.
67. Zimmermann, A.W., et al., *Techno-economic assessment guidelines for CO2 utilization.* Frontiers in Energy Research, 2020. **8**: p. 5.
68. Adelt, M., D. Wolf, and A. Vogel, *LCA of biomethane.* Journal of Natural Gas Science and Engineering, 2011. **3**(5): p. 646-650.
69. Pertl, A., P. Mostbauer, and G. Obersteiner, *Climate balance of biogas upgrading systems.* Waste Management, 2010. **30**(1): p. 92-99.
70. Ardolino, F., F. Parrillo, and U. Arena, *Biowaste-to-biomethane or biowaste-to-energy? An LCA study on anaerobic digestion of organic waste.* Journal of Cleaner Production, 2018. **174**: p. 462-476.
71. Florio, C., et al. *A Life Cycle Assessment of Biomethane Production from Waste Feedstock Through Different Upgrading Technologies*. Energies, 2019. **12**, DOI: 10.3390/en12040718.
72. Lee, D.-H., *Evaluation the financial feasibility of biogas upgrading to biomethane, heat, CHP and AwR.* International Journal of Hydrogen Energy, 2017. **42**(45): p. 27718-27731.
73. NNFCC. *BIOMETHANE & BIOGAS CARBON CALCULATOR*. 2015 [cited 2024; Available from: https://www.nnfcc.co.uk/publications/tool-biomethane-carbon-calculator.
74. Ardolino, F., et al., *Biogas-to-biomethane upgrading: A comparative review and assessment in a life cycle perspective.* Renewable and Sustainable Energy Reviews, 2021. **139**: p. 110588.
75. Arvanitoyannis, I.S., *ISO 14040: life cycle assessment (LCA)–principles and guidelines.* Waste management for the food industries, 2008: p. 97-132.
76. Kun, M. and I. Atsushi, *Life Cycle Assessment: Best Practices of ISO 14040 series.* 2004.
77. IEA, *Outlook for biogas and biomethane*. 2020, International Energy Agency: France.
78. Losson, L. *GLOBAL BIOMETHANE MARKET 2022 ASSESSMENT + DATABASE*. Biogas – Biomethane – Green Gas 2022 2 May 2022 [cited 2024 March 18]; Available from: https://www.cedigaz.org/global-biomethane-market-2022-assessment/.
79. Transparency Market Research. *Biogas Plant Market*. 2024 [cited 2024 March 18]; Available from: https://www.transparencymarketresearch.com/biogas-plant-market.html.
80. Abanades, S., et al., *A critical review of biogas production and usage with legislations framework across the globe.* Int J Environ Sci Technol (Tehran), 2022. **19**(4): p. 3377-3400.
81. Zheng, L., et al., *Bio-natural gas industry in China: Current status and development.* Renewable and Sustainable Energy Reviews, 2020. **128**: p. 109925.
82. China, N.B.o.S.o. *China Statistical Yearbook 2019*. 2019 [cited 2024 March 25]; Available from: https://www.stats.gov.cn/sj/ndsj/2019/indexeh.htm.
83. Pavičić, J., et al., *Biogas and biomethane production and usage: technology development, advantages and challenges in Europe.* Energies, 2022. **15**(8): p. 2940.
84. GIE. *Euopean Biomethane Map 2023*. 2023 [cited 2024 March 18]; Available from: https://www.gie.eu/publications/maps/european-biomethane-map/.
85. American Biogas Council. *American Biogas Council*. 2024 [cited 2024 March 18]; Available from: https://americanbiogascouncil.org/.
86. Carlu, E., T. Truong, and M. Kundevsk, *Biogas opportunities for Australia.* 2019.
87. Kaparaju, P., et al., *B5: Opportunity Assessment Anaerobic digestion for electricity, transport and gas Final Report*, in *Race to 2023*. 2023, Australian Government | Departmentt of Industry, Science, Energy and Resources: AusIndustry Cooperative Research Centres Program. p. 192.
88. Finkel, A., *Quarterly Essay 81 Getting to Zero: Australia's Energy Transition*. Vol. 81. 2021: Black Inc.
89. Enea and Deloitte for ARENA. *Australia's Bioenergy Roadmap | Appendix: Market Activity and Opportunities*. 2021 [cited 2024 March 18]; Available from: https://arena.gov.au/assets/2021/11/appendix-market-activity-and-opportunities-australias-bioenergy-roadmap.pdf.
90. AREMI. *National Map | Biogas facilities*. 2023 2023 [cited 2023 17 August]; Available from: https://www.nationalmap.gov.au/renewables.
91. Lyytimäki, J., et al., *Two sides of biogas: Review of ten dichotomous argumentation lines of sustainable energy systems.* Renewable and Sustainable Energy Reviews, 2021. **141**: p. 110769.
92. Tshemese, Z., et al., *An Overview of Biogas Production from Anaerobic Digestion and the Possibility of Using Sugarcane Wastewater and Municipal Solid Waste in a South African Context.* Applied System Innovation, 2023. **6**(1): p. 13.
93. Guohui, S. and L. Yunfeng, *The effect of reinforcing the concept of circular economy in west china environmental protection and economic development.* Procedia Environmental Sciences, 2012. **12**: p. 785-792.
94. Kwapinska, M., et al., *Valorisation of Composted Organic Fines and Sewage Sludge Using Pyrolysis (OF-PYR).* Environmenta l Protection Agency, Johnstown Castle, Co. Wexford, Ireland, 2020.
95. Statistics, A.E., *Australian energy update.* Department of the Environment and Energy; Commonwealth of Australia Canberra: Canberra, Australia, 2019: p. 36.

Entry for the Table of Contents



This review examines the multifaceted realm of biogas and biomethane production, covering historical, technological, economic, and global perspectives. It details production methods, including physicochemical absorption and membrane permeation, and discusses challenges and opportunities in Australia. Concluding with future prospects, it highlights the importance of technological advancements and policy support for sustainable energy and waste management.