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REVIEW ARTICLE

Biogas Purification Technologies: A Comparative Review of Methods and Accessibility for Sustainable Energy Applications

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ABSTRACT

Biogas, a renewable energy source, is generated through anaerobic digestion and consists of methane (CH4) and carbon dioxide (CO_2) as main components, together with small amounts of hydrogen sulfide (H_2S), ammonia (NH_3), siloxanes and water vapour. The contaminants reduce heating capacity of biogas and cause operational issues and equipment deterioration in downstream applications. The study evaluated contemporary purification methods used to generate highly pure biomethane. The priority was to achieve necessary guidelines for energy manufacturing, automotive fuel and grid entry standards alongside cost-effective operations and environmentally friendly solutions. The analysis focused on four widespread upgrading techniques: membrane separation (MS), cryogenic upgrading, pressure swing adsorption (PSA) and water scrubbing. The evaluation process of each method depends on operational effectiveness combined with CH_4 output rates alongside development capacities and industrial pricing factors. The analysis demonstrated that one purification solution does not fit all cases, and therefore, proper approach selection requires an evaluation based on gas composition together with specific use targets. The combination of MS and PSA permits scalable operation and produces significant CH_4 yields, yet cryogenic and water scrubbing processes yield high purity at the cost of initial expense and energy consumption requirements. Technical performance must remain balanced against investment costs, together with environmental considerations, according to the study findings. Specific purification methods improve the sustainability potential of biogas as an alternative power source. The review demands specific solutions for each application to attain maximum operational efficiency and reduce expenses. This study will assist developers in making informed technological choices and support ongoing research by guiding efforts toward the global integration of biogas systems within renewable energy markets.

***Keywords**: Anaerobic digestion, Adsorption, Cryogenic purification, Membrane separation, Environmental sustainability*

INTRODUCTION

Biomethane, an improved and purified form of biogas, is the primary focus of this study. This study covers the fundamentals of biogas manufacturing and the primary and secondary systems, and the equipment required to purify raw biogas. Biomass energy is a form of stored solar energy. Solar power is utilized by biomass, or dwelling green plants, to absorb CO_2 from the environment and convert it into an herbal compound *via* the process of photosynthesis. Here, the molecule referred to as chlorophyll is responsible for absorbing solar energy, and the use of it to transform CO_2 and water into carbohydrates. Carbohydrates are a major class of natural compounds that is represented through a collection of CH_2O; for example, $C_6H_{12}O_6$ represents glucose. Solar energy provides the 470 kJ (112 kCal) of power needed to convert one gram mole of carbon into a carbohydrate (Ek *et al.*, 2011). The anticipated variety for biomass's performance of incident sun radiation is 8–15%; however, in actual international conditions, it is much less than 2%. Plants store diverse kinds of carbohydrates that are produced, such as starches and greens. These could then be staple meals for primitive animals. This solar energy is captured and moves with losses along the food chain. The by-products or useless bodies of those producers and clients in the food chain can be classified as biomass products. As a result, biogas that is created while biomass is broken down anaerobically is a form of solar power. Anaerobic digestion, additionally called biogas production, is the process used to explain the mixture of different gases produced when a group of bacteria breaks down biomass, or organic matter, without the presence of oxygen. Methane (CH_4) and carbon dioxide (CO_2) make up the majority of the biogas, with smaller quantities of different gases (Table 1). Generally, there are three primary lessons into which biogas derived from biomass may be divided (Hejnfelt and Angelidaki, 2009):

1. Farm-derived substrates, including liquid manure, feed waste, harvest waste, and energy plants.
2. Trash from both non-public homes and public areas, including the natural part of MSW, marketplace waste (from fish and vegetable markets, for instance), expired food, or meal waste (from grocery shops, motels, and so on).
3. Industrial by-products, inclusive of glycerin, leftovers from fat separators, waste, or by-products of food processing (dairy, meat, etc.).

Using biogas is one way to reduce greenhouse gas emissions, which include CO_2. When the whole biogas manufacturing cycle is taken into consideration, there are almost no net carbon emissions to the surroundings.

Table 1: Typical composition of raw biogas produced *via* anaerobic digestion

Component	Composition (%)
Methane (CH_4)	55–65
Carbon dioxide (CO_2)	35–45
Hydrogen sulfide (H_2S)	0–1
Nitrogen (N_2)	0–3
Hydrogen (H_2)	0–1
Oxygen (O_2)	0–2
Ammonia (NH_4)	0–1

Source : IPCC Guidelines for National Greenhouse Gas Inventories (2006)

Biogas emerges as a renewable power source because microorganisms break down organic substances under anaerobic conditions to create it. Methane makes up the majority (55–65%) of biogas components while determining its energy content. The second main component after CH_4 makes up 35–45% and reduces the overall heating potential of biogas. The trace gases H_2S, N_2, H_2, O_2 and NH_4 found in small quantities influence both biogas quality and the downstream processes that use it. Engine and grid injection operations require H_2S removal because this substance has corrosive properties. Monitoring feedstock along with digester operating conditions affects which feedstock materials end up in biogas generation (Al-Wahaibi *et al.*, 2020).

Promoting renewable energy sources worldwide has made biogas emerge as a fundamental element for building sustainable energy systems. Biogas acts as a renewable fuel which serves two important functions through reducing fossil fuel dependency while simultaneously mitigating the climate change. Raw biogas avoids its maximum utility potential as biomethane because it contains various impurities. The purification of biogas requires effective methods as regulatory standards need to be followed in order to obtain improved efficiency and expanded application opportunities. As biogas contains CH_4 alongside CO_2 and H_2S and various trace gases, it requires state-of-the-art purification systems which enhance CH_4 levels while preserving other valuable elements. The global energy market requires cost-efficient scalable purification systems to increase biogas's market potential. The purification methods like pressure swing adsorption (PSA), water scrubbing and membrane separation configure different strengths and weaknesses according to feedstock changes, system capacity and end-product demands. Waste management systems gain dual benefits through the integration of biogas purification techniques, because they create renewable energy while recovering waste resources that convert into industrial materials. The study aims to address missing information through research that evaluates operational efficiencies and economic potential of diverse biogas purification systems across different operational parameters. This research investigates all stages of biogas purification technology optimization for small-scale and industrial-level use that helps build a low-carbon circular economy structure (Wellinger and Lindberg, 2001). Systematic experimentation as well as data analytical methods will investigate new approaches for improving biogas purification through studies of CH_4 output alongside energy conservation and environmental conservation measures. The research findings will deliver essential knowledge to optimize biogas systems because they present applicable solutions that boost biomethane's entry into worldwide energy systems.

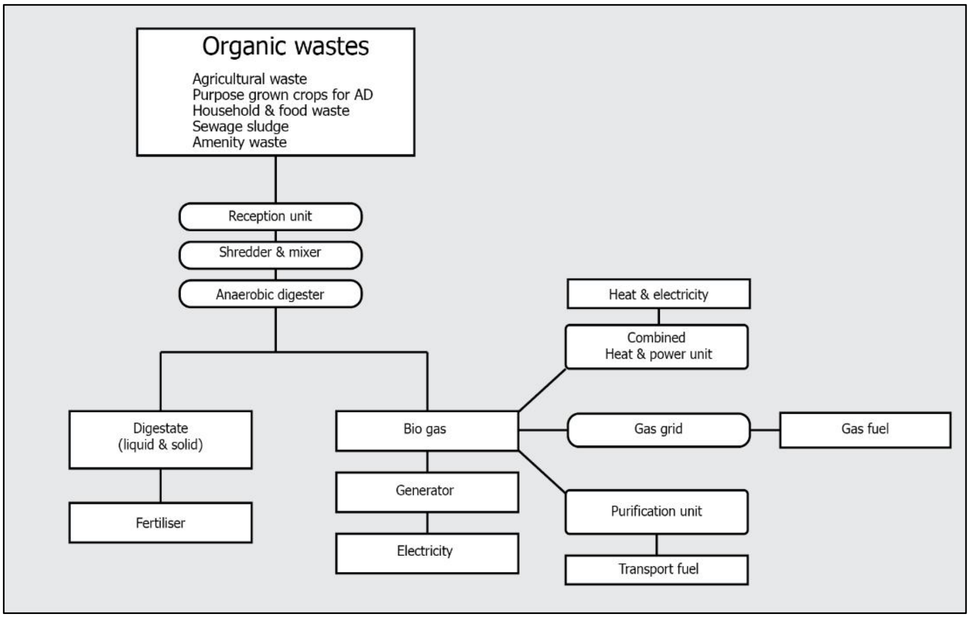

Figure 1: Process flow of Anearobic digestion plant

Figure 1 displays a process flow that illustrates the practical methods for turning organic waste into meaningful energy and beneficial by-products while building upon theoretical biogas manufacturing concepts. Organic waste sources consisting of agricultural residues, household and food waste, purpose-grown energy crops as well as sewage sludge and amenity waste arrive at a reception unit first. The material moves through a shredder with a mixer that combines particles to guarantee proper environments for microbial breakdown. The substrate moves to an anaerobic digester after preparing to experience microbial decomposition without O_2 while biogas and digestate form as a result. The liquid and solid fractions of digestate form a nutrient-rich by-product that producers can turn into organic fertilizer through additional processing steps before closing the nutrient cycle. Biogas generated from this process contains CH_4 and CO_2 which allow power generators to create electricity or feed into combined heat and power (CHP) units for electricity and heat operations (Weiland *et al.*, 2010). The removal of distracting gases including H_2S and N_2 with water vapor, makes biogas preparation possible for broader applications and better efficiency. The cleaned biomethane may then be pursued via three avenues: 1: injection into the natural gas grid, 2: production of transportation fuel through such products as bio-CNG or bio-LNG, and 3: direct use as a compressed gas fuel by eitherindustry or the home. The joint system demonstrates how anaerobic digestion provides both renewable power production along with sustainable waste management which establishes it as vital technology for achieving a circular low-carbon economy.

Literature

Impurities and biogas purification methods

There are two steps in the manufacturing system, including biogas cleaning and upgrading, whilst Biomethane necessities are met. Numerous techniques are to be had for both cleansing and upgrading, however, the most effective techniques depend on the composition of the biogas output. This stage of the biogas cleansing process involves removing several contaminants, which include water vapour, hydrogen sulphide, organic silicates (like siloxane), and small impurities (particles, and so on) (Table 2). However, the upgrading stage of biogas includes casting off carbon dioxide and enhancing the purity of the methane content. Because of their strong interdependencies, biogas cleansing and upgrading strategies are commonly included (Karthikeyan and Visvanathan, 2013).

CH_4 is separated from CO_2 at some stage in biogas upgrading, which results in a growth in the quantity of CH_4 in the handled biogas mixture. To accomplish that, the gas's volumetric energy content material cloth is raised. The steps within the biogas cleaning process are at once impacted by the biogas upgrading system. As turned into mentioned previously, a few additives should be eliminated both for the duration of the cleansing method and in the course of the upgrading steps. However, some components are damaging to particular upgrading processes. Thus, more research ought to be completed before selecting an upgrading approach for biogas (Papacz, 2011).

Figure 2 presents multiple biogas upgrading methods to transform raw biogas into biomethane, which functions as a renewable, high-purity fuel for vehicle applications and grid connection. The systemic overview shows multi-step processes which integrate PSA alongside water scrubbing, chemical scrubbing, cryogenic separation and membrane separation. Important pre-treatment functions are required before the biogas may be upgraded, and these include the primary removal of sulphur as well as the sophisticated desulphurisation steps, and further on, the process of compression entrenched with gas cooling and drying methods. These steps are critical for the effective removal of hydrogen sulfide , moisture, and carbon dioxide contaminants. Three types of biomethane production paths(ex- upgraded biogas from anaerobic digestion,Thermochemical gasification followed by methanation,Power to gas via hydrogenation of CO_2) exist due to the way different technologies intersect with operational factors. They are creating combinations that optimise methane recovery while fulfilling strict quality requirements.

Table 2: Common biogas impurities and their impacts

Impurities	**Drawback**
Carbon dioxide (CO_2)	• CO_2 is regarded as an impurity if a high volumetric strength content is wanted (for vehicle gas or when injected into the herbal gasoline grid). • When condensed water in the gas aggregate is available, carbonic acid is formed.
Water (H_2O)	• Water in biogas leads to the formation of acids (like carbonic acid) due to the fact that impurities are soluble in it. These water vapor' purpose corrosion in the pipelines can be downstream of the Digester. • The presence of water within the generated biogas lowers its power content.
Hydrogen sulfide (H_2S)	• H_2S is chargeable for pipe line corrosion (by using forming sulphuric acid). • In the event that the concentration of the hydrogen sulfide contained in the biogas produced is too high, the combustion process may result to the production of sulfuric acid which will in turn result in corrosion of the combustion system and equipment.
Oxygen (O_2) and nitrogen (N_2)	• Oxygen availability needs to be managed because methane manufacturing can result in the formation of a flammable mixture. • The presence of Nitrogen suggests that there is an air leak at the Digester.
Ammonia (NH_4)	• Methane production at the Digester can be inhibited by way of high ammonia levels.
Volatile organic compounds	• Certain unstable natural compounds present within the generated BM aggregate, which include Siloxanes, halogenated hydrocarbons, and alkanes, can be unsafe whilst used with certain devices (ex- Gas turbines,). When certain compounds burn in engines, they produce oxides (like siloxane oxide) that have a strong propensity to deposit on machinery. • During combustion, positive compounds with corrosive chemical contents are formed. (Halogenated hydrocarbons, for example, are formed while the generated BM mixture burns, generating acids like hydrochloric acid.)
Particles	• Because of its abrasive features, the presence of debris in the generated BM aggregate has a big carrying effect on distribution pipe lines and end-user gadgets.

Source: Biomethane from Dairy Waste: A Sourcebook for the Production and Use of Renewable Natural Gas in California

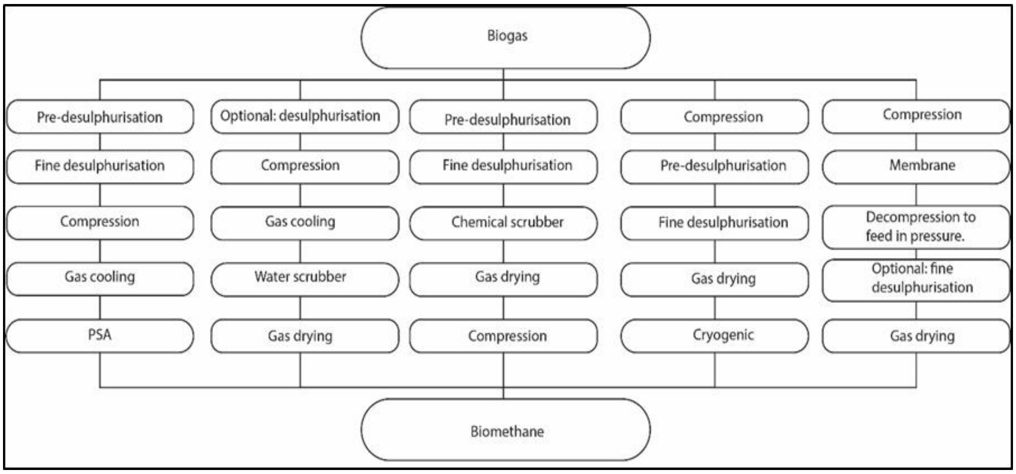

Figure 2: Schematic representation for biogas cleaning and upgrading

Table 3 shows both the common contaminant levels within raw biogas and the necessary purity requirements needed to create refined fuel products. To efficiently use biogas for energy production, engineers raise the CH_4 content beyond raw levels (55–60%) up to minimal levels of 95–97% (Abbassi-Guendouz *et al.*, 2012). CO_2 makes up 35–40% of raw biogas but needs to be reduced below 2% to optimise the fuel's energy potential. Minimal water levels in biogas must be maintained under 50 ppm because this threshold protects the equipment used in upgrading systems.

Table 3: Biogas composition and optimal threshold limits for effective utilisation and system performance

Impurity	Raw biogas typical concentration	Threshold limit for upgrading
Methane (CH_4)	55-60%	95-97% (final product)
Carbon dioxide (CO_2)	35-40%	<2% (final product)
Water (H_2O)	Trace (ppm level)	<50 ppm (for most upgrading systems)
Hydrogen sulfide (H_2S)	Trace (ppm level)	<1-5 ppm
Oxygen (O_2)	2-3%	<0.5%
Nitrogen (N_2)	2-3%	<1%
Ammonia (NH_3)	Trace (ppm level)	<10 ppm
Volatile Organic Compounds (VOCs)	Trace (ppm level)	<1 ppm for siloxanes, halogenated hydrocarbons
Particles	Trace (ppm level)	<1 mg/m^3

Source: Techniques for transformation of biogas to biomethane. Biomass and Bioenergy

The conversion of raw biogas H_2S into near-trace amounts less than 1–5 ppm is necessary because this substance damages equipment. The removal of O_2, N_2 and NH_3 from raw biogas down to concentrations under 0.5%, 1% and 10 ppm, respectively, is necessary for enhanced biogas purity and operational system safety (Priadi *et al.*, 2014).

Pressure swing adsorption

Gases are separated into the usage of an adsorptive medium within the pressure swing adsorption method (Figure 3). In this manner, a floor of solids (adsorbents) is penetrated with the aid of a gas combination (adsorbates), and the size of the molecular sieve traps undesirable impurities.

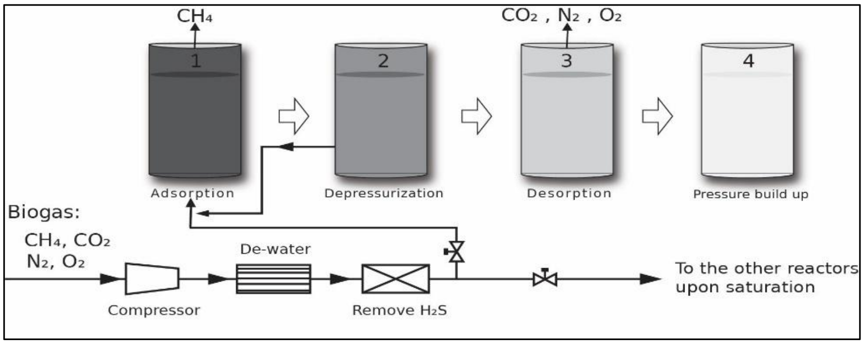

Figure 3: Pressure swing adsorption for biogas purification

Adsorbents consisting of carbon molecular sieves, activated carbon, and zeolites can be used. The adsorption rate is more suitable for nominally excessive pressure (4–7 bar) and a low temperature range (5–35°C). CO_2 is likewise co-adsorbed with H_2S, NH_3, and H_2O. H_2S and H_2O are separated in programs prior to the gasoline combination getting into the adsorption columns (Riadi *et al.*, 2020). CO_2 also partly absorbs N_2 and O_2. CH_4 are better adsorbed in small amounts for the duration of this method. However, maximum CH_4 passes through adsorbents without the present process of adsorption. Typically, the upgraded gasoline biomethane is constantly released from the adsorption tower. By freeing the stress at the adsorption columns, the desorption process is completed. CH_4 within the output gasoline product (BM) is more than 96% natural (Xu *et al.*, 2018).

The Pressure Swing Adsorption (PSA) method demonstrates high purification efficiency in biogas upgrading by selectively adsorbing specific gas components. It functions through the constituents of the feed gas and adsorption properties of an individual constituent and it allows testing characteristics of biogas to have been upgraded as a result of treatment.CH_4 successfully moves through the PSA process because adsorption occurs minimally, thus producing upgraded biogas with a CH_4 concentration exceeding 96%. The PSA process reduces CO_2 concentrations below 2% alongside N_2 and O_2, as well as trace impurities H_2S, NH_3 and H_2O to below 1 ppm (Chua *et al.*, 2013). The PSA method proves efficiency in biogas quality enhancement since it removes unwanted gases while purifying the stream (Table 4).

Table 4: Effectiveness of pressure swing adsorption purification method

Component	Feed gas composition	Adsorption process impact	Upgraded biogas (BM) composition
Methane (CH_4)	55–60%	Minimal adsorption (most CH_4 passes through)	>96%
Carbon dioxide (CO_2)	35–40%	Adsorbed along with other impurities (H_2S, NH_3, H_2O)	<2% (removed in process)
Nitrogen (N_2)	2–3%	Partially adsorbed, but with minimal effect	<1% (if adsorbed)
Oxygen (O_2)	2–3%	Partially adsorbed, but with minimal effect	<1% (if adsorbed)
Hydrogen sulfide (H_2S)	Trace (ppm level)	Removed in pre-treatment stage before PSA	<1 ppm (removed in pre-treatment)
Ammonia (NH_3)	Trace (ppm level)	Removed in pre-treatment stage before PSA	<1 ppm (removed in pre-treatment)
Water (H_2O)	Trace (ppm level)	Removed in pre-treatment stage before PSA	<1 ppm (removed in pre-treatment)

Source: Techniques for transformation of biogas to biomethane. Biomass and Bioenergy

Water scrubber

Water acts as an absorptive agent to dissolve any gasoline or vapour in it at the same time as it is being scrubbed. Reducing the temperature and increasing the stress of the gas aggregate coming into the absorption tower will boost the absorption rate. This approach can take away the gasoline aggregate's CO_2, H_2S, and NH_3. However, previously, water and other particulates ought to be removed. Following the separation of water and particulate count number, it undergoes two passes of compression to reach a maximum strain of 4–8 bar. Every degree of compression has fuel coolers working to keep the temperature between 5 and 10°C. The uncooked biogas supply to the bottom of the absorption column is compressed and at a low temperature. The top of the column is where the consistent pressurised water glide is coming down from. The raw biogas or the uncooked bio-gas mingled with water by the counterblow movement gets saturated with the flavours of CO_2, H_2S, and NH_3 when dissolved in water. A 'flash column' seems to get the release of the enhanced gasoline that fumes out of the apex of the column for adsorption drying, along with saturated water solution that has only a few volumes of CH_4 (Mohan and Jagadeesan, 2022). The stress of the water presure is lowered to 2–4 bar on the Flash Column. The 1st and 2nd compression tiers are then reached utilising the desorbed gas on the flash column.

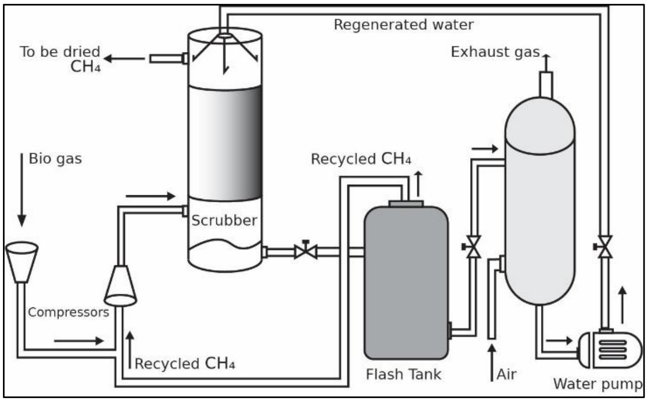

Figure 4: Water scrubber for biogas purification

The residual water solution is eventually introduced into the Desorption Tower, wherein an air glide is introduced at the base of the tower to facilitate the number one degassing of CO_2 and H_2S. After that, the water solution expands to the atmospheric strain level. Regenerated water is produced after this manner and may be carried out in the cleaning procedure. Before being launched into the environment, the dissolved off-gas discharge from the column has to first go through additional treatment to get rid of H_2S and trapped CH_4 (Figure 4). Methane with a purity of over 96% is the retention inside the Absorption Tower's output gas product (BM) (Petersson and Wellinger, 2009).

Table 5 demonstrates the water scrubber purification technique that delivers powerful biogas upgrading results. This reveals how biogas components transform during absorption while presenting the chemical makeup of processed biogas after enhancement. The water scrubber purification method dissolves CO_2, H_2S and NH_3 into water to reach CO_2 levels lower than 2% and H_2S and NH_3 concentrations less than 1 ppm in the upgraded biogas (Kumar and Singh, 2022). The absorption process leaves the CH_4 concentration unchanged at greater than 95% levels. Upgraded biogas consists predominantly of CH_4, exceeding 95% but nearly all N_2 along with O_2 remain at 1% or below (Angelidaki and Ellegaard, 2003). The scrubber absorbs H_2O from raw biogas and simultaneously eliminates minor contamination with other impurities.

Through this purification method, scientists eliminate contaminants to improve biogas quality and maintain high CH_4 concentrations.

Table 5: Effectiveness of water scrubber purification method

Component	Raw biogas composition	Absorption process impact	Upgraded biogas (methane) composition
Methane (CH_4)	55–60%	Minimal absorption; mostly passes through	>95%
Carbon dioxide (CO_2)	35–40%	Dissolved in water (removed)	<2% (removed in process)
Nitrogen (N_2)	2–3%	Minimal effect	<1% (minimal adsorption)
Oxygen (O_2)	2–3%	Minimal effect	<1% (minimal adsorption)
Hydrogen sulfide (H_2S)	Trace (ppm level)	Dissolved in water (removed)	<1 ppm (removed in process)
Ammonia (NH_3)	Trace (ppm level)	Dissolved in water (removed)	<1 ppm (removed in process)
Water (H_2O)	Trace (ppm level)	Absorbed by water scrubbing process	Trace (removed with impurities)

Source: Techniques for transformation of biogas to biomethane, Biomass and Bioenergy

Membrane separation

The one-of-a-kind permeability of gasoline combos *via* polymer membranes functions as the foundation for the ideas of fuel permeation and membrane separation processes (Figure 5). Three distinct flows may be identified using this technology: the feed, the permeate (CO_2 and other gases), and the retentate (primarily CH_4) (Li *et al.*, 2024).

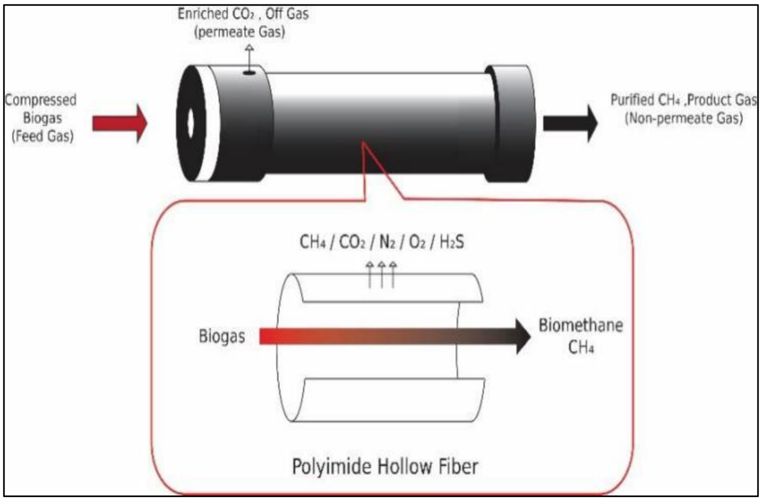

Figure 5: Membrane separation for biogas purification

Different partial pressures are applied on the membrane between the feed and permeate facets to create a driving force for the device, which results in off evolved the excessive flux. Membranes on the whole use aromatic polyamides and cellulose acetate as polymers. Compared to CH_4, the permeability traits of CO_2, H_2O, NH_3, and H_2S are higher (Liu *et al.*, 2019). N_2 and O_2 show off low permeability homes as well. Consequently, entering N_2 and O_2 ranges should be kept below management whilst generating biogas. New information indicates that the employed membranes demonstrate the CO_2/CH_4 selectivity factor at about 70. Also, the level of CH_4 within the upgraded biogas is slightly lower than 97% (Weiland *et al.*, 2010). As a result, before getting to membranes, raw biogas has to go through a drying and desulfurising phase. As shown in Table 6, membrane separation significantly impacts the composition of upgraded biogas, and this effectiveness along with membrane durability, should be considered at a key stage of the process cycle.

Membrane separation functions as a critical method to transform raw biogas through selective partitioning operations that enhance CH_4 levels for energy generation purposes. Membrane processing allows the raw biogas CH_4 content of 55 to 60% to remain in the retentate because the membranes are highly selective, which produces a CH_4 concentration of 97% in the retentate. Typical biogas impurity CO_2 exhibits high membrane permeability, thereby decreasing its concentration in upgraded biogas below 2%. Membranes selectively pass N_2 and O_2 because of their low permeability, yet their presence remains minimal in the retentate while final gas composition stays below 1% (Appels *et al.*, 2008).

Table 6: Effectiveness of membrane separation

Component	Raw biogas composition	Membrane separation process impact	Upgraded biogas (Methane) composition
Methane (CH_4)	55–60%	High selectivity for methane; retained in the retentate	97%
Carbon dioxide (CO_2)	35–40%	High permeability; CO_2 passes through the membrane, removed in the permeate	<2% (removed)
Nitrogen (N_2)	2–3%	Low permeability; remains in the retentate, but has minimal impact	<1% (controlled)
Oxygen (O_2)	2–3%	Low permeability; remains in the retentate, with minimal impact	<1% (controlled)
Hydrogen sulfide (H_2S)	Trace (ppm level)	Removed during pre-treatment (desulfurization)	<1 ppm (removed)
Ammonia (NH_3)	Trace (ppm level)	Removed during pre-treatment (drying/desulfurization)	<1 ppm (removed)
Water (H_2O)	Trace (ppm level)	Removed during pre-treatment (drying)	Trace (minimal presence after separation)

Source: Techniques for transformation of biogas to biomethane. Biomass and Bioenergy

The cleanup methods of desulfurization and drying effectively eliminate trace gases like H_2S and NH_3 from biogas streams before upgrading them. Pre-treatment drying methods successfully reduce water vapour content to detectable levels in the upgraded biogas. Through membrane separation, biogas quality improves substantially *via* enhanced CH_4 enrichment and complete unwanted impurity removal, which prepares it as a reliable, clean and efficient energy source.

Cryogenic upgrading

In order to benefit from separation, certainly one-of-a-kind gas boiling and sublimation elements are used for the duration of the cryogenic upgrading approach. Figure 6 shows the cryogenic separation method for biogas purification. In this instance, the sublimation point of CO_2 is -78.48ºC and the boiling point of CH_4 is -161°C (Mata-Alvarez *et al.*, 2000). Raw biogas is compressed by the use of intercooling facilities over some ranges. In order to save you from freezing at a few degrees within the cooling system, the fuel is likewise dried. Heat exchangers are used in some unspecified time in the future to further cool the gasoline to about -55°C. Approximately 97% of the CH_4 is inside the gas section following the ones cooling and strain modifications (which have been made proper right down to -110°C) (Mata-Alvarez *et al.*, 2000). Prior to being launched from the plant, the upgraded biomethane needs to be heated. H_2S ought to be supplied to the plant one after the alternative, and that is essential.

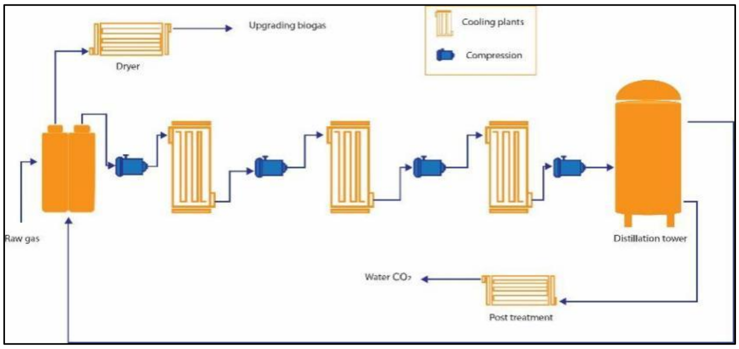

Figure 6: Cryogenic separation for biogas purification

During the cryogenic separation, water is usually separated. This, in turn, affects the solubility of the water within the gas and thus the efficiency of energy produced or used in the process. In other words, there are mainly three approaches to moisture removal. For instance, it may be used as an absorptive, adsorptive, and/or cooling medium. Also, a few contaminants are removable with water, for instance, debris and siloxanes, due to the fact that they are soluble in water. To offset H_2S, there is utilisation of activated carbon as the means of absorption in the course of applying this method, ions in the form of ferrous chloride ($FeCl_2$), ferric chloride ($FeCl_3$) or ferrous sulphate ($FeSO_4$) are transported to the digester (Karthikeyan and Visvanathan, 2013). After the reaction described below, insoluble ferrous sulphide (FeS) is then formed within the digester, which can be taken away with the digestate. Air or O_2 is dosed into the biogas system (digester) within the organic technique. After that, it reacts with H_2S to form sulphur (S) in its maximum fundamental form. This method, known as organic cardio oxidation, is pushed by using a specific class of microorganisms referred to as Thiobacillus, which is commonly present inside the digester. Membranes or low-temperature PSA are used to get rid of oxygen and air. Here is some degree of air and oxygen elimination in the course of marvellous upgrading and sulphur-removing strategies. These biogas components nonetheless, are usually hard to eliminate and needs to be covered from gaining access to the manufacturing biogas system within the course of the digesting degrees as an alternative to being handed and disposed activated carbon and certain biogas upgrading strategies, like adsorption and absorption strategies with water putting off NH_3 without a separate cleaning step, may be used on a small scale siloxanes are removed by way of absorption using silica gel, activated carbon, strong acids, or strong bases, in addition to through cryogenic processing (as an adsorption technique) (Abbassi-Guendouz *et al.*, 2012). Drying the generated fuel and allowing it to pass through filters or cyclones removes extra impurities that might be available as particles. Adsorption with activated carbon is the principle used to take away halogenated hydrocarbons (Table 7).

Table 7: Effectiveness of cryogenic separation

Component	Raw biogas composition	Cryogenic upgrading process impact	Upgraded biogas (Methane) composition
Methane (CH_4)	55–60%	Remains in the gas phase after cooling, separated effectively	97%
Carbon dioxide (CO_2)	35–40%	Sublimates at -78.48°C and is removed as a solid	<2% (removed)
Nitrogen (N_2)	2–3%	Remains mostly unaffected, low permeability during cooling	<1% (kept low)
Oxygen (O_2)	2–3%	Remains mostly unaffected, with low permeability during cooling	<1% (kept low)
Hydrogen sulfide (H_2S)	Trace (ppm level)	Removed prior to cooling in the desulfurization step	<1 ppm (removed)
Ammonia (NH_3)	Trace (ppm level)	Removed prior to cooling in the desulfurization step	<1 ppm (removed)
Water (H_2O)	Trace (ppm level)	Removed during the drying phase before cooling	Trace (minimal presence after separation)

Source: Selection of appropriate biogas upgrading technology

Raw biogas contains 55–60% CH_4, which survives the cryogenic upgrade process as a gas phase for an effective separation, leading to 97% pure CH_4. Under sublimation conditions at -78.48°C, CO_2 solidifies and leaves behind reduced levels of less than 2% impurity. The low permeability of N_2 and O_2 enables them to remain at trace amounts below 1% content, while the upgraded biogas forms (Liu *et al.*, 2019). H_2S, together with NH_3, initially found in trace concentrations in raw biogas, receives pre-treatment desulfurization preceding cooling to achieve their complete elimination from the upgraded biogas. H_2O water is eliminated during drying before the biogas undergoes cryogenic processing, which results in tiny water residuals in the final upgraded biogas product.

Purification standards for applications of biogas

The presence of impurities both diminishes energy content and harms equipment while creating potential safety hazards unless these impurities are properly cleared from gases. The purification approach, which carries CO_2 removal alongside H_2S scrubbing and moisture control, and siloxane filtration, operates to produce a finished product that fulfils strict benchmarks for top performance. The required degree of biogas purification depends on the targeted application; thus, processes need adaptation by end-user specifications (Zhou *et al.*, 2020). Different biogas applications demand specific purification standards that must be fulfilled to guarantee both efficiency and safety within sustainable biogas utilisation.

Static direct combustion system

On the digester site, biogas may be utilised in direct combustion systems (boilers, generators, or gsasoline cells) to supply steam, dry warmth, warmth water, and absorb heat. This includes the gasoline that is, without delay, used to generate power in hydrogen gas cells and static gas generators. The power used to run the biogas plant's pumps and mixers can also be used to power the owner's manufacturing unit or other commercial enterprise, power the farm, or export the electricity to the nearby power grid and sell it to an electricity delivery company. Utilising biogas in stationary internal combustion engines to supply cogeneration of strength and shaft horsepower is one choice for biogas conversion. Future capability is an awful lot higher due to the fact that one cow's waste products can supply sufficient power to run a well-known light bulb for a complete day (Niesner *et al.*, 2013).

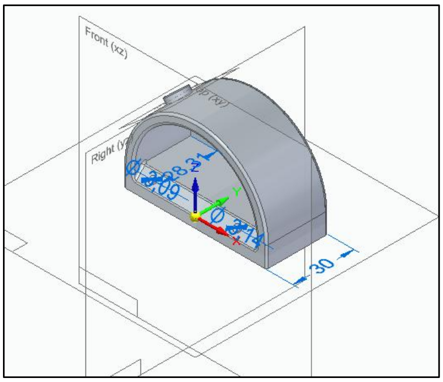

Figure 7: Biogas-fired furnace

Figure 7 illustrates a biogas-fired furnace used in power generation facilities. Biogas processing within power generation facilities removes H_2S alongside siloxanes and moisture to clean the raw material before its use in internal combustion engines and cogeneration systems. The levels of H_2S require reduction below 50 ppm, while siloxanes need to stay under 1 mg/m³ to stop engine deposits. The number of water molecules in biogas needs to be controlled for condensation prevention through maintaining this gas below 0°C dew point. Fuel cell operation requires biogas with a CH_4 content exceeding 95% to prevent catalyst damage, and strict limits exist for CO_2, N_2 and O_2 content (Xu *et al.*, 2018). Industrial boiler systems using biogas demand low levels of H_2S and siloxanes below 10 ppm while requiring drying operations to stop system corrosion.

Mobile direct combustion systems

There are various techniques involved in the use of biogas for transportation, such as production, purification, compression or liquefaction, and automobile utilisation. Moisture, CO_2 and H_2S are a number of contaminants found in raw biogas that need to be removed. Eliminate sulphur dioxide (SO_2) to stop corrosion. Take out CO_2 to raise awareness of CH_4. Eliminate water vapour to forestall corrosion and ice formation. Biogas needs to be compressed or liquefied after it's been purified to be used as fuel. To obtain compressed biogas, which is in fact the same as compressed natural gas, the pressure of biogas must be raised to excessive levels (200–250 bar) (Petersson and Wellinger, 2009). To produce liquefied biogas, which is similar to liquefied natural gas, cool the biogas to incredibly low temperatures (-162°C). Automobiles can be modified to run on biogas: to have the present petrol or diesel vehicle run on biogas, fit conversion kits. Design automobiles that would specifically be made to use compressed biogas or liquefied biogas. This involves establishing the complexes that would be utilised in the dispensing of the refuelling and distribution services that place depots with the capacity to provide liquefied biogas or compressed biogas for automobiles (Poggi-Varaldo *et al.*, 1997).

Less than 1.5 g/m³ water content and less than 2–3% CO_2 remain in the purified biogas before it satisfies the conditions for transportation and energy-based applications. Engine and pipeline protection starts with moisture elimination which brings the content to less than 1.5 g/m³ to avoid corrosion and stop ice formation. The CO_2 removal process increases CH_4 concentration to levels below 2–3% which raises the energy value of biogas. Engine components require protection through the reduction of corrosive H_2S to 50 ppm with activated carbon filtration, followed by SO_2 reduction to 10 ppm or lower levels (Nasir *et al.*, 2012).

Producing biomethane from biogas

One good use of biogas is to enrich it and turn it into biomethane or renewable matural gas after the following: water and CO_2 have been separated, and all H_2S and other impurities have been removed. Thus, CH_4 is the only compound of conventional natural gas; biomethane can be used wherever conventional natural gas is used, and conventional natural gas has a vast demand. The biogas producer can provide a higher value fuel by upgrading the crude biogas to biomethane that is purified to natural gas pipeline quality. The market is large but in order to have a more accurate picture it is reasonable to introduce more factors. The fact that the producer cannot flood the local market means that there is a natural constraint on supply and this sustains consistent dynamics of demand. As such, the producer is assured of stable and sustained returns in the long term because of this market structure.After the above-mentioned purification processes, the biogas is nearly pure CH_4; normally, >95% CH_4 (Hejnfelt and Angelidaki, 2009). To be stored or injected into the natural gas grid, biomethane should be compressed to the required level of pressure. Biogas can be used to power engine vehicles, to produce electricity, or as a source of heat energy by incorporating the biogas into the natural gas network. In CHP facilities, biomethane can be used directly as fuel for the production of heat and power for distribution. It can also be used as a renewable source of energy as a liquid fuel for automobiles known as liquefied natural gas or compressed natural gas when cooled to a liquid state. Estimation of prospective revenues that are likely to be gained on sales of each biomethane and biofertiliser by-products of upgraded biogas in both the local and the regional markets, economic assessment of the viability of biogas upgrading process in terms of capital and operational costs.

Biogas as a raw material for other chemicals

High-value chemical production from biogas components, including CH_4 and CO_2, requires strict biogas purification for successful conversion to hydrogen , methanol, ammonia, synthetic natural gas and acetic acid. The diverse selection of downstream applications needs precise gas quality specifications because hydrogen production through steam CH_4 reforming requires biogas with reduced sulfur content to protect catalyst effectiveness. Methanol and ammonia synthesis requires high CH_4 purity while eliminating CO_2 and H_2S contamination to achieve both efficient processes and prolonged equipment serviceability. The successful deployment of conversion technologies requires satisfying defined purification requirements, which emphasise the necessity of end-use specific biogas upgrading systems design (Al-Wahaibi *et al.*, 2020).

Methane to hydrogen (steam methane reforming)

Biogas contains CH_4, which may be reformed to create hydrogen (H_2), and is a critical feedstock for lots of industrial processes(Sun *et al.*, 2015).

$$CH_4 + H_2O \Rightarrow CO + 3\,H_2$$

$$CO + H_2O \Rightarrow CO_2 + H_2$$

Methane to methanol (direct methanol synthesis or indirect *via* syngas)

Methanol (CH_3OH), which is derived from CH_4, can be utilised as gasoline, antifreeze, a solvent, and a feedstock for the synthesis of other compounds (Sun *et al*., 2015).

Direct reaction, $CH_4 + O_2 \Rightarrow CH_3OH$

Indirect *via* syngas, $CH_4 + H_2O \Rightarrow CO + 3\,H_2$

$CO + 2\,H_2 \Rightarrow CH_3OH$

Methane to ammonia (Haber Bosch process)

CH_4 can be utilised to create H_2, which, whilst combined with atmospheric N_2, can create Ammonia (NH_3). One crucial component in fertilisers is ammonia (Rasi *et al*., 2011).

$N_2 + 3H_2 \Rightarrow 2\,NH_3$

Methane to synthetic natural gas (methanation of syngas)

Synthetic natural fuel, which may replace natural fuel in quite a few applications, may be created from CH_4 (Sun *et al*., 2015).

$CO + 3H_2 \Rightarrow CH_4 + H_2O$

Carbon dioxide to chemicals

Through various chemical tactics, the CO_2 in biogas may be utilised to create compounds like urea, methanol, and carbonates (Rasi *et al*., 2011).

$CO_2 + 2\,NH_3 \Rightarrow NH_2CONH_2 + H_2O$

Methane to acetic acid (oxidation)

Acetic acid (CH_3COOH), which is extensively used in the manufacture of plastics, vinegar, and different chemicals, can be produced by using oxidising CH_4 (Rasi *et al*., 2011).

$CH_4 + O_2 \Rightarrow CH_3COOH + H_2O$

Intergrated heat and power production from biogas (CHP)

Biogas is burned in gas engines, which have hot sections inside and cooling jackets of water on the outside. That hot water can be used to heat factories, stores, and homes, for example, in areas such as making tea. Washing can be done by using a gas engine cooling jacket, hot water, and additional aspects in production processes can also be done using hot water. Thus, the main features of a typical CHP plant are the generator, heat recovery equipment, and a biogas engine or turbine. Combined heat and power systems of whose efficiency levels range from 80–90%, are more efficient than individual production of heat and electricity. Electricity generated by CHP units is more efficient than that produced by engines because they convert biogas to capture the energy that would normally be lost as heat. Reduces the emission of greenhouse gases relative to fossil fuels and enhances the disposal of waste. Ideally recommended for district heating systems, landfill sites, and wastewater treatment plants. Sewage and other bio-waste can be handled by the farms using CHP systems, which helps in the generation of power for the operations of the farms. Some form of cleanup is required to remove tough impurities such as siloxanes and H_2S that are damaging to CHP's equipment. However, one of the demarks of CHP systems is often the preliminary costs, which although are generally offset over the mid-long term in terms of savings and matrices of incentives (Rasi *et al.*, 2011).

Complete pre-use purification of biogas is essential to guarantee extended lifespans and durability of CHP systems. The removal of key impurities such as H_2S and siloxanes remains crucial because these substances can degrade engine parts while depositing hard material that affects combustion. Engine efficiency depends heavily on this purification step, which simultaneously decreases emissions and engine maintenance expenses. The combination of clean biogas prolongs equipment survival, together with adherence to environmental requirements, which results in improved energy production stability (Papacz, 2011). The initial expensive investment required for CHP systems yields multiple advantages when coupled with biogas purification, which results in reduced emissions and efficient waste processing and brings extended energy savings.

Table 8 demonstrates complete information regarding biogas purification processes across applications, together with their post-purification gas composition standards. Significant purification steps with CO_2 removal, followed by H_2S removal and moisture extraction and potential siloxane removal are necessary for high-quality biomethane and grid injection applications, which require methane concentrations above 95% with CO_2 content not exceeding 2% (Poggi-Varaldo *et al.*, 1997). Vehicle fuel produced from compressed biogas must reach CH_4 levels higher than 97% while maintaining CO_2 and H_2S contents at similar restrictions and requiring strict controls on water and NH_3 levels. The power generation sector and industries employ a CH_4 concentration range of 50% to 55% while requiring CO_2 removal with moderate tolerance for H_2S (Priadi *et al.*, 2014). There must be special moisture and NH_3 removal systems in applications, to reach preset limits, which define the gas as fit to undergo combustion and industrial treatment. Table 8 further illustrates the various level of purification necessitated by certain applications of biogas based on operational safety, cost effectiveness and performance requirement.

Table 8: Biogas purification standards for various end use applications

Biogas application	Purification process	Purification standard (Threshold)	Required gas composition after purification
Biomethane (upgraded biogas)	CO_2 removal, H_2S removal, moisture removal, Siloxane removal	CO_2: <2%	Methane (CH_4): >95%, CO_2: <2%, H_2S: <5 ppm
		H_2S: <5 ppm	Water: <50 ppm, Ammonia (NH_3): <10 ppm
Grid injection	CO_2 removal, H_2S removal, moisture removal, odour removal, Ammonia removal	CO_2: <1–2%, H_2S: <5 ppm	Methane (CH_4): >95%, CO_2: <2%, H2S: <5 ppm
		Water: <50 ppm, NH_3: <10 ppm	Nitrogen (N_2): <1%
Vehicle fuel (Compressed biogas)	CO_2 removal, H_2S removal, moisture removal, Siloxane removal	CO_2: <2%, H_2S: <5 ppm	Methane (CH_4): >97%, CO_2: <2%, H_2S: <5 ppm
		Water: <50 ppm, NH_3: <10 ppm	Water: <50 ppm
Power generation (Combined heat and power)	CO_2 removal, H_2S removal, moisture removal, Ammonia removal	CO_2: <5%, H_2S: <100 ppm	Methane (CH_4): >50%, CO2: <5%, H_2S: <100 ppm
		Water: <50 ppm, NH_3: <50 ppm	
Boilers/Heating systems	CO_2 removal, H_2S removal, moisture removal, particle removal	CO_2: <5%, H2S: <50 ppm	Methane (CH_4): >55%, CO_2: <5%, H_2S: <50 ppm
		Water: <50 ppm, Ammonia (NH_3): <10 ppm	
Industrial use (Drying, Steam)	CO_2 removal, H_2S removal, moisture removal, Siloxane removal, Ammonia removal	CO_2: <5%, H_2S: <50 ppm Water: <50 ppm, Ammonia (NH_3): <10 ppm	Methane (CH_4): >55%, CO_2: <5%, H_2S: <50 ppm

Source : Biogas Upgrading to Vehicle Fuel Standards and Grid Injection

Technological evaluation

Biogas upgrading is a major technology in generation of highly-pure biomethane that could be injected into the natural gas infrastructure, and/or utilized into vehicles. The various levels of the upgrade technologies such as PSA, Water scrubbing, Membrane separation, and upgrading by cryogenics vary on their efficiency rate, cost of operation, complexity and their suitability in application. The assessment identifies the extent to which each technology meets its efficiency in the recovery of CH_4, ease of operations, its environmental and economic impacts.

The PSA technology attacks biogas of CO_2, H_2S, NH_3, and H_2O by separation using activated carbon, zeolites, and carbon molecular sieve adsorbents at high pressure between 4- 7 bar.The adsorption process rejects contaminants by passing through unobstructed CH_4 molecules. The PSA technology reaches CH_4 purity levels of more than 96% while recovering 85–90% of CH_4 from the feed gas (Riadi *et al.*, 2020). The PSA technology functions with moderate efficiency levels and demonstrates medium-level capital expenses while operating costs and needs periodic adsorbent replacements. Carrying out pre-treatment procedures to remove H2S and moisture comes along with a complicated procedure due to its large desorption requirements. There is some CH_4 slip during the desorption stage, but emissions into the environment are assuredly not at the excessive level. This is rather beneficial to medium plants (PSA process), as there is less energy consumed in the process of operation compared to cryogenic separation.

High-pressure systems (4–8 bar) enable water scrubbers to eliminate H_2S, NH_3, and CO_2 because of their different solubility properties in water. Raw biogas is fed at the bottom of an absorption column in order to enable water, which is the counterflow, to absorb the unwanted gases as CH_4 remains at the gas phase. CH_4 greater than 95 percent is obtained in water scrubbers with over 96 percent materials being recovered. The start-up is high or of medium level which is countered by the fact that there are low operating costs since the water used is recycled. This solution has a simple approach to it as it requires periodic water maintenance as well as constant circulation. The process requires a moderate environmental impact because wastewater treatment operations must be performed. The scrubbing method suits operations of medium to large scale, which require a steady water supply.

Polymeric membranes function as selective barriers for membrane separation to extract CH_4 from CO_2 and different traces. The main separation mechanism derives from pressure differences between the feed and permeate sides of the system. The separation method produces CH_4 that approaches 97% purity by exceeding a 97% recovery rate (Chua *et al.*, 2013). Although membrane installation requires a major upfront financial investment, the system delivers low operating expenses because the maintenance needs are minimal. The system offers a basic design with interchangeable units and unlimited expandability that makes it appropriate for numerous biogas projects.

Membrane separation uses stimuli that minimise environmental harm because the method eliminates chemical substances and generates little manufacturing waste. The membrane separation method proves effective in reducing CO_2 concentration from raw biogas due to its capacity to handle small to medium-sized installations with concentrated CO_2.

Cryogenic upgrading utilises temperature control at -110°C to divide CH_4 from CO_2 and other gases through the distinctive boiling points of biogas elements. The CO_2 extraction as a solid thus generates high-purity CH_4 through this method. Using this method, operators can generate virtually pure CH_4 with a recovery rate above 95% that reaches 97% purity. High operational expenses and capital costs accompany this upgrading method because of its energy-consuming cooling requirements. Sophisticated technical requirements lead the process to need sequential compression followed by cooling operations. The high-power requirements of this method do not impact its minimal CH_4 leakage, while the extracted CO_2 becomes available for industrial purposes. The cryogenic method works best in large facilities producing maximum CH_4 output while also enabling CO_2 commercial utilisation (Scholwin *et al.*, 2018).

Upgrading technology implementation includes various benefit-cost relationships among different solutions. PSA and membrane separation operate effectively on small to medium-scale operations by combining reasonable efficiency and affordability. Water scrubbing delivers good results for medium to large-scale operations, although it requires a large water supply as part of the process. The highest level of CH_4 emerges from cryogenic upgrading. However, the process works best for large-scale industrial settings because it needs large amounts of power. Multiple factors determine the technological selection, including CH_4 extraction needs together with operational expenses, as well as environmental restrictions and business expansion potential. Membrane separation provides flexible and low-maintenance operation, but PSA remains competitive because of its durable nature. Prospective facilities should consider water scrubbing technology when sufficient water is available, while facilities needing high-purity CH_4 along with CO_2 valorisation should use cryogenic upgrading (Ryckebosch *et al.*, 2011). Research and development of hybrid upgrading systems combining membrane separation with PSA or water scrubbing operations will yield improved efficiency and sustainability results.

The results of CH_4 purity tests and recovery measurement illustrate how well different techniques produce premium biomethane products (Table 9). The directory of techniques includes PSA and membrane separation, where PSA delivers high-purity CH_4 yet varies in cost relative to membrane separation, which requires initial capital investments yet produces cleaner systems. Water scrubbing represents an affordable choice that yields good recovery results, yet requires water handling to maintain operations. Large-scale implementations benefit from cryogenic upgrading processes thanks to their minimal CH_4 waste, together with supreme gas purity, although they require large capital investments coupled with substantial energy costs. Table 9 demonstrates that gas quality, along with operational scale, environmental responsibility and economic feasibility, must be balanced when selecting a technology.

Economical evaluation

PSA systems need moderate financial commitments because activated carbon, zeolites and carbon molecular sieves serve as the main expense for adsorbents. The costs for PSA initial setup lie below those of cryogenic separation, while being more expensive than water scrubbing. Operating expenses fall in the medium category because it includes regular replacement of adsorbents, plus the power needed to maintain these pressure ranges between 4-7 bar. When operating with PSA plants, achieve CH_4 purity exceeding 96% at 85–90% recovery rates, which makes the process economically suitable for plants ranging from small to medium-scale size (Sakar *et al.*, 2009). Minor revenue losses occur through CH_4 slip that happens during desorption. The technology maintains average affordability because the replacement of adsorbents occurs periodically.
The expenses related to water scrubbing operations start at medium levels before reaching high figures based on the installation scope. The primary expense component consists of the absorption column together with its water recycling equipment. The substantial initial expenses for setup will yield low operating costs because of water recirculation that reduces overall consumption. However, continuous water supply and wastewater treatment increase maintenance costs. The procedure successfully recovers 96% of CH_4 while attaining yields higher than 95% to deliver efficient results (Mohan and Jagadeesan, 2022).

Medium-sized and large operations are suitable for this procedure since they require enough available water resources. The economic disadvantage of this method consists of wastewater treatment expenses that will increase operational costs in areas facing water scarcity.

The initial expense of polymeric membranes for membrane separation keeps the process cost high; however, this technology can expand in phased stages to support diverse plant capacities. The system operates with low expenses due to its basic, easy maintenance capabilities and the absence of quick-wearing moving components or chemical processing requirements. Pressurised membrane separation methods need less energy than cryogenic methods to operate, hence the energy expenses stay affordable. Gravitational flight technology demonstrates high efficiency because it recovers 97% of CH_4 at a near-perfect purity level of 97%. This technology remains economically attractive due to its ability to scale up operations as well as its simple maintenance requirements and decentralised biogas project capabilities. The replacement of the number of membranes required periodically increases the overall expenses of the system.

Table 9: Comparison of biogas upgrading Technologies: Technical, economical and environmental

Technology	Methane purity (%)	Methane recovery (%)	Operating pressure (bar)	Capital cost	Operating cost	Environmental impact	Suitable scale
Pressure swing adsorption (PSA)	96+	85–90	04	Medium	Medium (adsorbent replacement required)	Moderate (methane slip occurs)	Small to medium
Water scrubbing	95+	96+	04	Medium to high	Low (water recycling reduces costs)	Moderate (requires wastewater treatment)	Medium to large
Membrane separation	97	97+	Variable	High (initial)	Low (minimal maintenance)	Low (no chemicals, minimal waste)	Small to medium
Cryogenic upgrading	97+	95+	High (cooling required)	Very high	High (energy-intensive cooling)	Low (minimal CH_4 leakage, CO_2 valorization possible)	Large

Source: Trace compounds affecting biogas energy utilization

Precise temperature control at -110°C requires specialised cooling equipment along with substantial energy requirements that cause cryogenic separation to become the most expensive method. The main elements that comprise costs are multi-stage compressors, refrigeration units, and insulated storage facilities. The high operational expenses of cryogenic upgrading result in CH_4 with greater than 97% purity while enabling CO_2 commercial usage that might reduce the overall costs (Petersson and Wellinger, 2009). The implementation of this technique makes the most sense at large facilities because the costs can be spread across bulk operations. The operational expenses rise due to increased energy consumption, but the profit gained from high-purity CH_4 and CO_2 valorisation enhances total financial returns in industrial operations.

Table 10: Comparison of biogas upgrading technologies: Capital, operating, revenue characteristics

Technology	**Capital cost**	**Operating cost**	**Maintenance cost**	**Energy consumption**	**Revenue potential**	**Suitable scale**
PSA	Medium	Medium	Medium	Moderate	Medium	Small to medium
Water scrubbing	Medium to high	Low	Medium	Moderate	Medium	Medium to large
Membrane separation	High	Low	Low	Low	High	Small to medium
Cryogenic upgrading	Very high	High	High	Very high	Very high (CO_2 valorisation)	Large

Source: Biogas upgrading technologies; developments and innovations

PSA provides a cost-effective solution using moderate amounts of energy, which works best for small to medium-scale installations (Table 10). Water scrubbing needs an expensive setup at startup, but operates at low expenses suitable for medium to large-scale ventures (Angelidaki and Ellegaard, 2003). Membrane Separation provides suitable technology for small to medium-sized projects that generate high revenues because it requires high capital investments, yet operates efficiently with minimal operating expenditures. The high capital expenses, operational needs and energy requirements of cryogenic upgrading make it the costliest yet this system creates valuable CO_2 products that maximise revenue potential, thus becoming the optimal choice for big installations. The technology choice between PSA and membrane separation aligns with operations of medium and small size, yet water scrubbing and cryogenic upgrading serve larger projects which demand more capital expenditures.

CONCLUSION

Technology efficiency collides with economic viability and environmental sustainability in the biogas upgrading sector through features that surpass basic process selection considerations. Our critical evaluation shows that today's discussions about biogas upgrading technologies do not effectively consider the dynamic relationship between thermodynamic barriers and lifecycle pollution, together with the market influence that determines actual implementation results. The negative relationship between methane recovery efficiency and energy usage presents an essential thermodynamic limitation which exists beyond technological boundaries. The energy-intensive cryogenic separation method demonstrates clear inverse correlations between CH_4 purity achievements and overall energy consumption. The natural trade-off demands a complete change in evaluation standards from individual technology evaluations to system-wide assessments, which combine exergy assessments alongside process integration principles. Metabolic or exergy analysis frameworks allow us to understand processes across different operational scales and development applications.

The present-day economic analysis of biogas upgrading systems fails to account properly for external costs and gives priority to short-term capital investment values. Our assessment shows that proper CH_4 leakage accounting using its 28–36 times stronger global warming effect transforms the sustainability assessment of water scrubbing technology due to elevated emission rates. Carbon pricing mechanisms integrated appropriately into economic models should trigger a critical review of CO_2 valorisation technologies, especially cryogenic methods. Hybrid separation systems represent a fundamental conceptual development beyond incremental advancements, whereas they question standard definitions among specific upgrading methods. Hybrid separation systems take advantage of different technology mechanisms to produce more effective results than singular-process systems. Research needs to develop theoretical models which describe the combined operational benefits of various hybrid separator setups while finding optimal process parameters for different feedstock combinations.Biogas upgrading technology will likely progress in alignment with neighbouring fields through technological development. Novel advancements in materials science, which focus on creating improved PSA adsorbents and next-generation membranes with superior CH_4/CO_2 selectivity combined with enhanced permeability-selectivity characteristics, hold the potential to transform the efficiency limits of these technologies definitively. New process intensification methods should minimise the energy requirements of cryogenic separation by implementing advanced heat integration techniques with work recovery systems. We recognise a significant research gap which lacks integrated analysis between upgrading technologies and wider energy system dynamics. The need to balance the grid presented by other renewable energy sources that supply intermittent energy makes the establishment of biogas upgrading installations promising in terms of delivering the gridbalancing service as well as enjoying the aspect of flexible operation, which was not discussed much in previous literature. These facilities can increase or decrease the process of the gas upgrading according to the real-time availability of electricity and prices and hence make the process more cost effective and help stabilize the grid, which helps to improve the economic viability of these facilities by integrating energy storage, or demand-side management strategies. Furthermore, biogas upgrading can be synchronized with times when there are lowered demands of electricity or renewable energy becoming more than enough to meet the demands, thus, limiting operational costs of the energy system. A transition to Hydrogen Economies could establish power-to-gas systems through biological or catalytic methanation of captured CO_2 to generate novel value opportunities for upgrading facilities.

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