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Electricity generation and multi-purpose applications from biogas and biomethane

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ABSTRACT

Biogas produced from biomass is a renewable energy resource with high value potential to support sustainable development. This study presents abridged advances and pathways from biogas and biomethane to electricity with opportunities and challenges in generation, conversion, and storage needed for use in many areas like transportation, power generation and storage, building, and industrial heat production sectors. A high knock resistance, making it suitable for use in thermal systems with high compression rate, characterizes biogas combustion. Various prime movers using biogas as fuel can be used for electricity generation, including direct conversion through fuel cells, which is a significant pathway to sustainable energy storage. Biogas to electricity conversion by a generator set is much more practical today. Turbines, micro turbines, Stirling engines, diesel engines, and petrol engines are only some of the viable possibilities for converting biogas to electricity. Biomethane can be used as a substitute for natural gas in all its applications with little or no modifications to the fuel infrastructure. Finally, this study discusses biogas and biomethane's limits and contribution to the Sustainable Development Goals 2, 6, 7, 8, 9, 11, 13, 14, and 17.

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1. INTRODUCTION

The concerns regarding greenhouse gas emissions and the subsequent increase in global temperatures resulting from using fossil fuels have led to greater acceptance of biogas as an alternative fuel [1], [2]. The overall energy demand, particularly for clean alternatives like renewable sources, is influenced by various factors, including the expansion of economic activities, increased electrification of services and processes, population growth, finite reserves of fossil fuels, concerns about energy supply security associated with fossil fuels, and the necessity to address supply and price volatility. Furthermore, a global commitment is to restrict greenhouse gas emissions and prevent an increase in the Earth's average temperature [3]. The imminent depletion of fossil fuels and concerns about anthropogenic greenhouse gas emissions and global warming have sparked renewed interest in biogas as viable fuel sources. This interest is further fueled by the increasing production of organic waste and growing anxieties about climate change. Biogas is a versatile and flexible energy source, surpassing other renewable sources such as wind and solar in terms of adaptability. In most cases, the lower operating costs and initial relatively high expenses make it a more cost-effective option [4].

As a sustainable energy source, biogas shows significant promise for reducing greenhouse gas emissions. For instance, biogas accounted for 0.29 percent of Switzerland's overall energy consumption in 2014 and contributed over eight percent to the country's total renewable energy generation in the same year, resulting in less toxic gas emissions for the country [5]. Similarly, in 2015, Europe saw its biomethane production from biogas at wastewater treatment plants double compared to regular production levels [6]. As part of the global effort to transition from fossil fuels to renewable and low-carbon energy, biogas serves as an important building block. As a sustainable energy fuel source, biogas is certainly playing a vital role in the shift away from fossil fuels, particularly with its widespread use in biogas-to-power conversion technologies and its tremendous potential for generation from biomass [7]. Rising concerns about fossil fuel depletion, anxieties over energy security, and the urgency to tackle global warming as emphasized in the Paris Agreement have fueled substantial enthusiasm for renewable energy sources. Biogas has garnered significant attention as a renewable energy option due to its cost-effectiveness and renewable characteristics. The conversion of biogas into environmentally friendly transportation fuels and electricity generation is also becoming increasingly popular [8]. A substantial amount of organic waste is produced worldwide, creating the potential to be converted into electrical energy. For example, the United States alone generates around 70 million metric tons of organic waste. A reliable and cost-effective energy supply is crucial for maintaining socioeconomic progress and alleviating poverty [3], [9].

Due to their substantial methane (CH_4) content, biogas resources offer a promising solution to tackle significant energy and environmental challenges. This methane can be utilized as a fuel in various applications such as electricity generation, heating, and transportation. Biogas is created through the anaerobic digestion of organic matter [10], [11]. It serves as an effective waste disposal and sterilization method, contributing to the reduction of greenhouse gas emissions and other forms of environmental contamination. Utilizing waste streams for biogas production effectively minimizes waste disposal through less environmentally beneficial processes such as landfilling and incineration. Anaerobic digestion not only generates fertilizer but also serves as a viable alternative to industrial chemicals and polymers. When agricultural waste is allowed to decay without management, it releases large amounts of extremely potent methane into the environment. CH_4 has a greater greenhouse gas effect compared to carbon dioxide (CO_2), to the point where over a span of 20 years, CH_4 absorbs 86 times more heat than CO_2. Hence, the regulated production of biogas yields useful fuel and mitigates the adverse environmental consequences of unregulated biodegradation [10].

Biogas power generation is relatively novel globally, with the exception of a few countries like Germany in the developed world. However, there is growing interest in applying biogas for electricity generation through various technologies such as gas turbines, internal combustion engines, and fuel cells due to the global commitment to combat climate change and greenhouse gas emissions [4]. Utilizing biogas instead of solid biomass, like firewood, can reduce the amount of wood used. By the year 2040, around 200 million people, largely in Africa and Asia, could have access to clean cooking fuel from biogas. This suggests that biogas could be a key component in achieving the Sustainable Development Goals (SDGs). Biomethane, a more potent fuel source than the initial biogas, is produced during the processing of biogas [12]. This makes biogas a viable choice in the transition to a cleaner, lower-carbon energy and electricity mix.

There are several ways to convert biogas into usable energy and purpose, as in Figure 1. However, investigations into the cost-effectiveness of various power systems have demonstrated that internal combustion engines and the Stirling engine power system are viable options, particularly for localized power generation. Compared to other power generation methods, the cost per kilowatt-hour (kWh) generated by internal combustion engines is lower [11]. Within the range of 3–5 MW, gas turbines are the most efficient option, despite requiring a high overall capital investment for steam turbine and gas turbine power systems [13]. Micro turbines can be connected in series to maximize the number of units, even though the fuel quality standards are not as stringent as those for internal combustion engines.

Multi-purpose energy systems are becoming increasingly common for utilizing inexhaustible fuel sources in various unique applications towards sustainable and cleaner systems. It can be transformed into electrical energy by burning it in engines or turbines, offsetting the intermittency of renewable sources like solar and wind. The thermal storage process involves capturing the heat produced during biogas generation, enhancing the efficiency of multi-energy systems. Biomethane, which can serve as a chemical storage medium, may be introduced into existing natural gas and electric vehicle charging infrastructure, offering an easily accessible and sustainable fuel supply. Therefore, this study highlights the roles of biogas and biomethane in various applications, including electricity generation, storage, and uses in both conventional and non-conventional technologies.

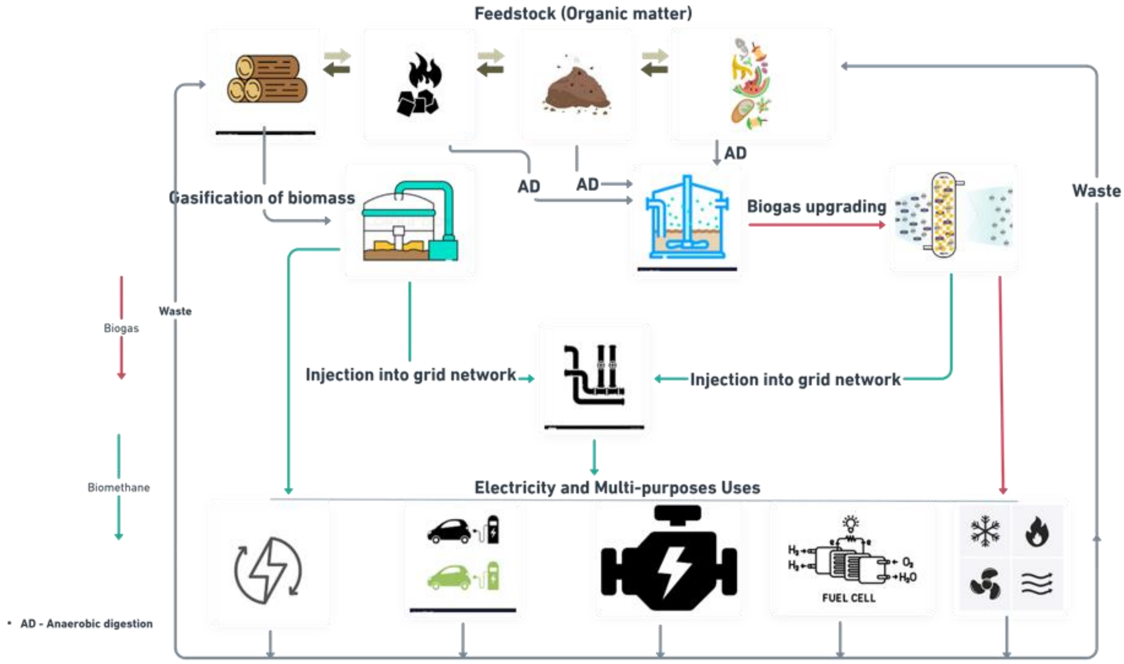

Figure 1. Biogas and biomethane for electricity generation, and conversion for multi-purpose use

2. BIOGAS AND BIOMETHANE IN ELECTRICITY GENERATION

2.1. Overview

Many countries globally have set ambitious emissions targets in line with the Paris Agreement and other regional and national objectives to mitigate climate change and enhance energy supply security. For instance, the European Union directive on renewable energy use established a target of achieving a 50% share of energy by 2040, with biogas identified as a key contributor. Although anaerobic digestion for biogas production is an established technology in Europe and other developed countries, it remains underutilized in many developing nations, which possess significant potential [12].

In 2014, excluding hydropower, Switzerland's biogas production accounted for 8% of all renewable energy generation and 0.29% of the nation's total energy consumption [5]. Using biogas instead of solid biomass for cooking supports forest conservation by reducing the need for materials like firewood. By 2040, biogas is expected to provide clean cooking fuel for 200 million people, mostly in Africa and Asia [12]. Given the significance of biogas, it cannot be achieved without it. Biomethane, a by-product of biogas upgrading, has several applications and is a more efficient fuel source than its raw biogas predecessor [14]. This reinforces biogas's position as a sustainable energy resource essential for achieving the energy transition to a green and low-carbon energy and electricity mix.

Many biomass sources and various waste streams, including different types of organic waste, are available as renewable energy resources and solutions to environmental problems. Therefore, biogas technology is one of the most promising methods for addressing both current energy-related and environmental challenges. Biogas can be produced through the controlled anaerobic breakdown of a variety of biomass sources, such as animal dung, crop waste, and poultry excrement. Raw biogas, resulting from microbial metabolism, can be utilized for various applications, ranging from producing high-value molecules in the energy and industrial processing sectors to providing heat and electricity [11], [15]. The generated raw biogas can be further processed through cleaning and purification to increase methane concentration, allowing it to be injected into natural gas pipelines as a substitute for green fuel. With such great potential for use as a renewable resource, it could help reduce greenhouse gas emissions [16].

Biogas, a mixture of CO_2 and CH_4, serves as a fuel with various thermal and electrical applications. Its chemical profiles vary based on feedstocks and levels of process control. CH_4, in its gaseous form, is highly combustible and can be fatal in enclosed spaces due to the displacement of oxygen (O_2). Its radiative force is twenty times greater than that of CO_2 over 20 years and can remain in the atmosphere for up to fifteen years. The production and management of biogas must be closely monitored and strictly supervised to prevent environmental damage. It can be used as fuel or as an input into chemical, hydrogen (H_2), and synthesis gas production processes. The quality of biogas is significantly affected by trace components, making their removal essential. Biomethane addresses high operational costs and energy consumption associated with biogas upgrading. Table 1 lists the components of biogas, which is a combination of various gases.

The methane content of biogas is the most crucial factor in determining its effectiveness as a heating source. Biogas contains between 55% and 75% CH_4 by volume. This disparity suggests that biogas's lower heating value (LHV) ranges from 16 to 28 MJ/m^3, rather than being a constant amount. The combustion of biogas releases thermal energy that can be used for cooking or other applications, such as internal combustion engines. Biogas's useful qualities as a fuel are significant. In general, biogas engine fuel requires the following.

- CH_4 content needs to be high.
- The mix of water and CO_2 should be as low as possible for high caloric value.
- The Sulphur level should be as low as possible since it promotes corrosion by converting to acids through condensation and combustion.

Table 1. Average composition of biogas [17]

S/N	Symbol	Value (%)
1	CH_4	55 - 75
2	CO_2	30 - 45
3	N_2	0 - 1
4	H_2	0 - 1
5	H_2S	1 - 2
6	Others (O_2, Moisture, CO, and other trace gases)	0.83

While chemical, biological, or physical methods can be employed to decrease the H_2S concentration, condensation in the gas storage or along the gas stream can lower the moisture content. A higher concentration of CH_4 results in biogas with a calorific value that increases from 5,000 to 7,000 kcal/m^3. Approximately 0.77 cubic meters of natural gas, 0.60 kg of kerosene, 0.40 kg of petrol, 3.5 kg of wood, 12 kg of dung briquettes, 4 kilowatt-hours of power, 0.5 kg of carbon, and 0.43 kg of butane make up one cubic meter of biogas [18]. Below, at standard conditions of 273 K and 0.1013 MPa, the characteristics of biogas, which consists of 60% CH_4 and 40% CO_2, are presented in Table 2.

Biogas has an ignition temperature between 650 and 750 ℃, a specific heat capacity of 2.165 J/g·K, and a molar mass of 16.04 g/mol, as shown in Table 2. In terms of thermodynamics, biogas is on par with other alternative fuels. Due to its positive environmental effects, biogas compensates for its slight heat disadvantage compared to fossil fuels. In Table 3, it is evident how biogas compares to other fuels.

Table 2. Thermodynamic properties of biogas [18]

Property	Symbol	Value
Specific heat capacity	C_p	2.165 kJ/kg.K
Molar mass	M	16.04
Gas constant	R	0.518 kJ/kg
Normal density	p	1.2 g/l
Critical density	pc	320 g/l
Relative (to air) density	g_r	0.83
Biogas calorific value	LCV	22.6 Mj/m^3
Critical temperature	T_C	- 2.5 ℃
Critical pressure	p	7.3 – 8.9 MPa
Flammability limit content in air	v	6 -12 %
Ignition temperature	T_I	650 – 750 ℃

Table 3. Fuel equivalents of biogas

Alternative fuel (per kg)	Biogas equivalent (m^3)	Remarks
Firewood	0.25	Advantage in deforestation avoidance
Dried animal dung (cow)	0.1	Higher energy value
Charcoal	0.65	Contributes to forest growth
Kerosene	1.60	Limits dependence on fossils
Natural gas (1 m^3)	0.97	Lower energy content and requires further purification
LPG (1 L)	1.05	Lower energy content
LPG (1 kg)	2.1	Lower energy content

Data on biogas equivalence obtained from Energypedia [19].

From Table 3, it is observed that animal dung has a higher energy value than most substitute fuels, enabling the production of 1 m^3 of purified biogas with an energy value of 6.5 kW. The calorific value of the biogas generally varies between 22.5 and 25 MJ/m^3, or 6.25 and 10 kWh/m^3, assuming CH_4 has a heating value of 35.8 MJ/m^3. The energy content may be enhanced further by upgrading to biomethane [17], [20]. Biogas with 55% CH_4 has an average calorific value of about 21.5 MJ/m^3, compared to pure CH_4, which has a calorific value of about 35. 56 MJ/m^3, which is one of the main reasons for upgrading by removal of CO_2 from raw biogas [17], [21]. Table 4 shows the calorific value of biogas, biomethane and common fossil gases.

From Table 4, it is noted that biogas has the lowest calorific value compared to methane, propane, butane, natural gas and biomethane. Therefore, upgrading to biomethane can improve its calorific value. The electricity potential of biogas depends on the type of prime mover selected and the specific design set up, and hence on the conversion efficiency of the energy conversion system and devices used. Internal combustion engines tend to have higher efficiency and lower implementation costs compared to other prime movers. The choice of the conversion system depends on the quantity of biogas available and the applications [22]. Internal combustion engines have a lower cost per kW compared to micro-turbines and gas turbine systems. Additionally, internal combustion engines are available in many different sizes and designs, making them more flexible for diverse applications [23].

Biogas turbines are generally used for large-scale power generation schemes with a higher biogas generation flow capacity of more than 3 MW, and more typically 5 MW, although this may vary significantly with specific applications. The main advantage of gas turbines as biogas energy conversion systems is that they require lower maintenance. Some of the benefits include low maintenance requirements, facility efficiency, and efficiency that tends to increase with size. As prime movers, micro-turbines can be connected in series to provide greater flexibility in terms of power output and feasible applications. The key advantage of micro-turbines is that they do not require biogas cleaning and treatment due to their good tolerance to H_2S in biogas [23].

Table 4. Calorific value of common gaseous fuels [17]

Fuel (elements)	Calorific value (MJ/m^3)
Biogas	22.5 - 25
Methane	35.56
Propane	92.11
Butane	117.23
Natural gas	31.82
Biomethane	23.02

To estimate the electrical energy available in biogas, the (1) can be used to define the conversion of biogas to useful electricity and (2), the generator power rating [23].

$$E_p(\text{kWh}) = \eta * C_V * M_f * Q * \alpha \quad (1)$$

Where E: Total electricity produced in kWh, Ƞ: Equipment conversion efficiency, Cv: Lower calorific value, M_f: Mass flow rate of biogas fuel (kg/s), Q: Quantity of biogas available per year, A: Conversion factor of MJ heat energy to electricity.

The power rating of the generator is given by (2).

$$P = E * 8760 * CF \quad (2)$$

Where P: Power of the generator (kWh/y), 8760: Total hours available in a year, and CF: The capacity factor of the power plant which is generally assume to be between 80% and 90%.

To establish the economic viability of a biogas power plant, it is necessary to determine the initial investment, total electricity sales revenue, and cost of operation and maintenance of the biogas power plant. Then the net present value (NPV), the levelized cost of energy (LCOE), the internal rate of return (IRR), and payback period (PBP) are important parameters in establishing the economic viability of a power plant. The investment costs depend on the costs generated in building the power plant and include engineering costs, permit costs, construction costs, survey costs, equipment acquisition costs, and commissioning costs.

It is important to establish the investment cost along with the operational and maintenance costs to determine cash flow. These values depend on the conversion technology used to produce electricity and various external factors. Such quantitative reports can be retrieved from studies conducted by international research institutions and other related analyses. The operation and maintenance costs for the operation of a system involve expenses associated with technical personnel, plant supplies, raw materials, and basic services. They are classified into fixed costs and variable costs on an annual basis. The operation and maintenance costs for the power plant can be quantitatively valued using the cost of investment. For a biogas power plant, these costs account for 7.4% of the overall investment [23].

The economic benefits of a power plant depend on electricity sales revenue. It is therefore important to estimate the revenue; hence, the compensation rates obtained from prevailing feed-in rates or tariffs set by the utility company are crucial. The levelized cost of energy provides the minimum cost in USD/kWh per generated unit of energy and is used for comparing different conversion technologies. The LCOE can be computed using (3), while (4) to (6) show the NPV, IRR, LCOE, and PBP, respectively [23], [24].

$$LCOE = \frac{\sum t[Invt + OM] * (1+r)^{-t}}{\sum t * [Elect\ (1+r)^{-t}]} \quad (3)$$

Where, *LCOE* is cost of generation during the plant lifespan (USD/kWh), Invt. is the investment for a year (including interest during construction and all auxiliary elements and electrical infrastructure) [USD/kWh], OM: refers the operation and maintenance cost for a year t [USD/kWh], r is the discounting rate, Elect is electricity produced in the year t (kWh), and t: Refers to the useful lifetime of the power plant operation (year).

The NPV is the total costs, less the present value revenues, and related to a project over the entire useful life by analyzing cash inflows and outflows. The profit is then computed upon measuring the flows and discounting the initial investment, as in (4).

$$NPV = \sum_{n=0}^{N} \frac{F_n}{(1+r)^t} \quad (4)$$

Where F_n is represents the net cash flow rate, r is the effective interest rate, and t is the total number of study years.

The IRR is a measure that represents the highest interest rate that an investor can pay considering minimal risk. It is a useful metric used when loans finance projects, and when a project must be financed, a net profit can be generated. The IRR is related to the NPV because it sets the latter to 0, as in (5).

$$IRR = \sum_{n=0}^{N} \frac{F_n}{(1+IRR)^t} = 0 \quad (5)$$

Where F_n is the net cash flow rate, IRR is the internal rate of return, and n is the total number of years under study. Corresponding to the period in which the project cost is balanced, i.e., PBP, (6) is the simplest calculation approach.

$$PBP(i) = \frac{Invt}{CF} \quad (6)$$

Where, Invt: Refers to cost of investment in the generation (USD) and CF: Refers to is the cash flow achieved by annual revenues from energy saved (USD/year).

To mitigate serious environmental and health risks, biomass waste should be treated in conjunction with improvements in the anaerobic digestion process, utilizing eco-friendly conventional and emerging cleaning and upgrading technologies as discussed in section 2.2. This approach aims to reduce greenhouse gas emissions, minimize the impacts of water pollution, and optimize the use of digestate to enhance agricultural productivity.

Alongside treating biogas waste, various environmental and economic advantages can be derived, such as decreased CH_4 emissions, sustainable waste handling, renewable energy resources, and enhanced soil fertility. It mitigates methane emissions originating from landfills, fosters a circular economy, and supplies clean energy to rural areas. Biogas not only generates employment opportunities but also lowers waste management expenses and improves air quality by capturing potent greenhouse gases. Nevertheless, it is essential to tackle obstacles such as the availability of raw materials, advancements in digester technology, and the long-term viability of feedstock sources. Although there are challenges, biogas holds significant promise for a sustainable future. Sustainability issues in anaerobic digestion concern substrate availability, characteristics, maintenance costs, operation costs, quality of digestate, and the application and cost benefits of biogas [10].

Biogas production and enhancement systems encompass biodigesters, landfill gas recovery systems, and wastewater treatment facilities. Biodigesters are sealed containers or tanks in which organic wastes are mixed with water and decomposed by microorganisms. Landfill gas is generated through the anaerobic decomposition of municipal solid waste, which can be collected via pipes and extraction wells. Wastewater treatment facilities can extract essential nutrients from sewage sludge, which may serve as feedstock in an anaerobic digester.

2.2. Biogas to biomethane production

Biomethane is an upgraded biogas that has drawn attention due to its ease of manufacture from raw biogas, storage, and utilization in various applications, including transportation fuel, power generation, heating and refrigeration fuel, and the simultaneous production of combined heat, power, and cooling systems. Biomethane can also be injected into the gas grids. The energy and exergy efficiencies of biogas are affected by the presence of CO_2 and N_2. It is therefore necessary to limit the concentration of these gases through various biogas-upgrading technologies to increase the lower calorific value of the fuel [25]. The various upgrading technologies include chemical scrubbing, pressure swing adsorption, and membrane separation, which are favored for their high efficiency, low CH_4 loss, and capability to remove H_2S. The distribution of current biogas upgrading technologies around the globe, as highlighted in the IEA bioenergy report [26], is summarized and shown in Figure 2. Figure 2 shows that chemical scrubbing is the most widely used biogas upgrading technology globally, at about 35%, followed by membrane at 21%, water scrubbing at 20%, pressure swing adsorption at about 17%, and organic physical scrubbing at about 5%, while other methods account for about 2%.

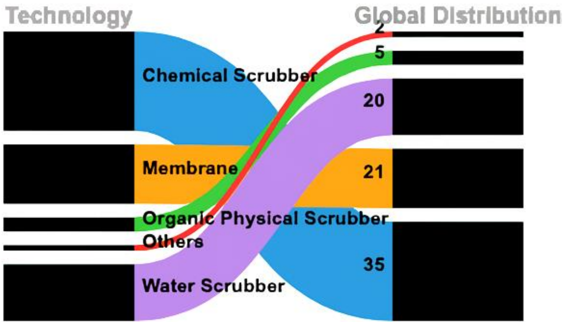

Figure 2. Distribution of current biogas-upgrading methods around the world

3. BIOGAS AND BIOMETHANE IN ELECTRICITY CONVERSION AND STORAGE SUSTAINABILITY

The conversion of the CH_4 to electricity can be estimated using (7).

$$E_p(\text{kWh}) = \frac{[(CH_4)*E_{ff}*LHV_{CH_4}*CF]}{3.6} \tag{7}$$

Where E_{ff} represents electricity generation efficiency, CH_4 produced volume of methane produced, LHV_{CH_4} is the lower calorific CH_4, and CF is the capacity factor, which is the ratio, waste processed to waste that could be processed during the year if the plant works on full capacity.

The most common applications for biogas are direct combustion appliances, such as stoves and lamps that use gas. Although it is not yet widely used, it is rapidly becoming the norm for energy generation in some wealthy nations, like Germany [2]. The technological scale of biogas applications varies depending on the region or level of development and is often influenced by technology adoption, primarily driven by affordability. Additional research based on projections for developing nations revealed that miniature biogas plants could not generate enough electricity from biogas to be economically viable [27]. In contrast, studies that are more recent have focused on the potential of hybrid microgrids incorporating PV, diesel, and biogas for electricity sustainability in rural areas [28], [29]. To promote the implementation of numerous smallholder and medium-scale grid-connected biogas facilities, governments should provide incentives such as attractive feed-in tariffs and other technical and financial support, including technical assistance and training for the life cycle management of biogas-biomethane energy systems.

For biogas, power facilities to be financially sustainable, subsidies, high guaranteed prices, or feed-in tariffs of roughly lesser US dollars per kWh are necessary to ensure affordability. In developed countries like Germany, biogas generation for energy has increased due to guaranteed feed-in prices. Worryingly, most developing world's current biogas power plants rely on funding from overseas donors and financial institutions to promote biogas as renewable energy source in their national energy mixes, primarily for electricity generation, and not necessarily for storage to meet peak demands and other applications.

Biogas and biomethane, which are greener substitutes for conventional fossil fuels, drive sustainable energy conversion and storage. Although petrol was the suitable fuel for the first Otto cycle engines, the debate over biogas for cars has continued since the 1950s. Recent advancements in biogas and biomethane processing have reached a stage where they can serve as viable engine fuels. Beyond transportation, biogas is a significant energy source for various applications, including power generation, motor operation, turbine function, and fuel cell use.

To ensure optimal power production, prime movers must be reliable, affordable, and easy to use. Diesel engines can operate on various fuels, including biogas, biomethane, and combustion gases such as sewage gas, landfill gas, and carbon monoxide. Functioning efficiently in both pure diesel and dual fuel modes, these engines provide energy sustainability and versatility through advanced energy content management. Thus, the conversion and storage options will be discussed subsequently.

3.1. Conversion with fuel cells

It is theoretically possible to convert biogas directly into electricity using a fuel cell, a process that requires very clean biogas and expensive fuel cells, making biomethane more feasible [11]. Since the CH_4 in biogas has four times more H_2 than carbon, it can be utilized in the production of H_2 for use in fuel cells. Biogas-powered fuel cells can generate renewable, low-carbon electricity for the grid [30]. Fuel cells facilitate the direct generation of energy from biogas. A significant disadvantage of biogas fuel cells is the substantial initial cost necessitated by the high purity of the gas they utilize. Conversely, technological advancement has only just begun. Steam reforming of biogas produces "green" H_2, which, when combined with ambient O_2, can be employed to generate thermal energy, steam, and electricity. Cogeneration systems utilizing fuel cells could significantly benefit various establishments, including healthcare facilities, educational institutions, and remote communication centers. Fuel cells use biogas as a fuel for electrochemical reactions that generate direct current electricity. Fuel cells are more environmentally friendly than combustion systems, as they substantially reduce or eradicate emissions. Permanently installed biogas fuel cells, including solid oxide or molten carbonate fuel cells, typically possess high-temperature internal reforming systems. Fuel cells generate H_2 by thermally reacting methane with steam; this H_2 is then subjected to elevated temperatures to facilitate a reaction with oxygen, culminating in the generation of electricity [31].

3.2. Use of a generator and engines for biogas power generation

The most practical way of converting biogas to electricity involves the use of an electric generator set powered by a mechanical prime mover, such as an engine or gas turbine. Biogas has stronger knock resistance than natural gas, allowing for higher compression ratios that boost output and power density when used as a fuel in internal combustion engines [11]. Electricity is produced by the spinning of a generator when biogas is used as a fuel source for combustion engines. Theoretically, biogas might be utilized by a wide range of combustion engines, including gas turbines, diesel engines, Stirling engines, and others [11].

Chemical characteristics of biogas, such as composition and purity, have a substantial impact on an internal combustion engine's performance. Because biomethane and high purity compressed natural gas have comparable chemical compositions, they can both be used as fuel in automobiles [4]. While attributes like fuel flexibility, ease of operation, and maintenance may render alternative options for power generation more beneficial, internal combustion engines offer a lower cost per unit of power generation compared to other heat engines, such as gas turbines [23]. Stirling engines, gasoline engines, and diesel engines can all operate on biogas and biomethane, as discussed below.

3.2.1. Stirling engines

Several years after Rudolf Diesel invented the diesel engine in 1816, Robert Stirling invented the Stirling engine, often known as the hot air engine [32]. This engine can run on a variety of fuels in a closed thermodynamic cycle, giving it a high degree of fuel flexibility. The Stirling engine produces minimal noise and has a relatively clean combustion process. The dynamic behavior of the engine's working mechanism and the performance of the heat exchanger are the main factors limiting the reliability and efficiency of Stirling engines. Stirling engines can be effectively used in micro-combined heat and power systems that utilize solar energy, biogas fuel, or medium-low grade waste thermal energy [33].

A variety of Stirling engines are available on the market. Stirling engines are the best choice for home boilers since they have a thermal power range of 5 kWth to 25 kWth and an electricity capacity ranging from 1 to 9 kWe [32], [34]. The power efficiency of Stirling engines ranges from 13% to 25%, but they can exceed 80% with cogeneration. For instance, in reference [35], a Stirling engine was developed that operated on mid-high temperature waste gases, achieving 26% thermal efficiency but producing only 3.5 kW in output. For Stirling engines to generate power from biogas, the fuel must first be burned off-site, with the resulting heat transmitted to the engine through a heat exchanger. The engine's mechanism operates by the gas expanding due to the transferred heat. Even lower-quality fuel can power the engine; however, the cost, thermal efficiency, and utility of Stirling engines are all lower than those of internal combustion engines, such as diesel and gasoline engines. Utilizing Stirling engines in combined heat and power mode can significantly increase their thermal efficiency, reaching as high as 90%.

3.2.2. Diesel engines

Biogas and biomethane can serve as fuel for diesel engines with specific modifications. Significant changes are necessary for diesel engines to function as biogas engines or in dual-fuel mode with pilot diesel. Diesel may frequently be included in biogas mixtures to enhance the ignition and thermal properties of biogas. Since nearly all diesel engines can theoretically be adapted to operate on either gasoline or diesel fuel [36], it may be feasible to combine diesel with an alternative fuel, often one with a lower calorific value, such as biogas, biomethane, or natural gas, in dual-fuel engines. Diesel fuel, a significant contributor to air pollution, remains widely used in dual-fuel engines. Compared to direct injection engines, pilot injection engines may offer superior performance, efficiency, and return on investment for smaller diesel engines (up to around 200 kW) [37]. Biogas, along with a minimal quantity of ignition gas, can be used to initiate engines, resulting in an approximate 2% increase in ignition oil, a method known as pilot fuel [36]. The principal advantage of dual-fuel engines with biodiesel blend is their potential to function as an economical fuel with high-quality [37].

3.2.3. Petrol engines

Petrol engines can be classified as either spark-ignition engines or Otto cycle engines. They can be modified to run exclusively on biogas instead of diesel. When first starting a biogas engine, it is usual to use a small amount of conventional fuel. Biogas can be utilized in everything from small 0.5-10 kW petrol engines to large power plants. Converting a petrol engine to run on biogas requires several changes since biogas and petrol have distinct fuel characteristics [18]. Among these parts are the exhaust system, engine control unit, fuel storage and distribution, ignition timing, compression ratio, and fuel delivery mechanism. Unlike biogas, which is a gas, gasoline engines use injectors to deliver fuel. It may be necessary to adjust the engine or change the pistons to improve combustion efficiency. The ability to modify some petrol engines with bi-fuel capabilities helps to make the transition more flexible. The technology may require feed-in tariffs and other government interventions to achieve economic success, as improving the grid to accommodate decentralized power generation is essential. Figure 3 illustrates a straightforward biogas-to-electricity conversion system utilizing an engine. From Figure 3, it is noted that biogas to electricity conversion systems require equipment and devices like the biodigester, biogas cleaning and upgrading systems, biogas and biomethane storage, metering systems, the prime movers, generator, and electricity storage devices like batteries.

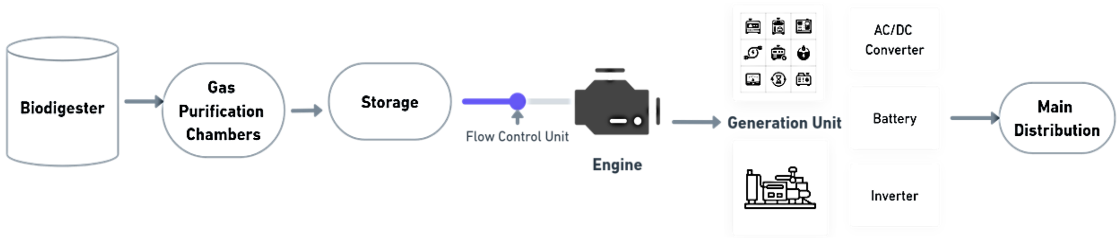

Figure 3. Biogas to electricity conversion using an engine

Several methods for converting biogas into other forms of energy, such as heat or electricity, are listed in Table 5. Some processes that belong to this category include cogeneration, trigeneration, and open conversion. Diesel engines, petrol engines, gas turbines, fuel cells, and Stirling engines represent just a few of the technologies used, with useful output energy products like biomethane and H_2 fuels exemplifying the potential benefits.

Excess biogas electricity can be transferred to the grid using gas turbines and internal combustion engines, doing away with the requirement for imports. Biogas can also be converted to electricity via fuel cells. Biogas-derived hydrogen fuel could find usage in renewable applications. As indicated in Table 5, biogas can be utilized in various sustainable energy transition processes. From Table 5, it is noted that biogas and biomethane to electricity conversion can be done through technologies like cogeneration, regeneration and direct conversion. Prime movers that can be used to produce electricity-using biogas as a fuel include the Stirling engine, diesel engine, gas turbines, gasoline engines, and direct conversion in fuel cells

Table 5. Summary of processes and applications for biogas-to-electricity conversion technologies [11]

Method/Process	Technology	Application	Remarks
Chemical-electrical	Fuel cell	Generation of electricity	Very efficient, reliable, but expensive
Chemical-electrical	H_2	Generation of electricity and processing chemicals. H_2 can be produced by steam reforming, dry reforming, or hydrolysis	Renewable hydrogen process if its biogas or methane is from renewable resources. Hydrogen is difficult to handle and transport.
Chemical	Biomethane nation	Biomethane can be fed to natural gas supply and fuel for vehicles and fuel natural gas power plants	Renewable replacement of fossil natural gas
Thermal-electrical	Diesel engine	Can be used in dual-fuel mode with diesel fuel for ignition. The engine needs modification to run on pure biogas/biomethane	Diesel engines are more efficient than petrol engines and have more fuel flexibility, hence can easily use biofuels.
Thermal-electrical	Gasoline/petrol engine	A petrol or gasoline engine needs little or no modification to run on biogas or biomethane	Less efficient than diesel engines, but are easier to convert to biogas fueled engines.
Thermal-mechanical-electrical	Stirling engine	Stirling engines are also called hot air engines.	Stirling engines have fuel flexibility and can run on a wider range of fuels
Thermal-Mechanical - Electrical	Gas turbine	Can be used as open cycle or combined cycle plants for electricity and heat applications Micro, small, medium, and large-scale turbines can be used based on fuel source and application.	Turbines are versatile and can use raw biogas in an uncleaned form. They are light and simple in construction, easy to operate but need skilled manpower.
Thermal-mechanical-electrical	Cogeneration	Cogeneration is the simultaneous generation and application of both heat and electricity from the same fuel source.	Cogeneration can be applied on various conversion systems to increase overall efficiency. Stirling engines, diesel engines, gas turbines, H_2 and fuel cells can all be operated on cogeneration mode.
Thermal-mechanical-Electrical	Trigeneration	Trigeneration is the simultaneous generation of electricity with both heating and cooling	Trigeneration is the most efficient conversion system but more complex and expensive

4. BIOGAS AND BIOMETHANE IN OTHER APPLICATIONS

Biogas, a combustible gas produced from anaerobic biomass digestion, is a well-established energy resource for thermal applications. While the use of biogas for direct combustion in household stoves and lamps is common, its application for power generation in various prime movers is still relatively new in most countries. Therefore, the subsequent discussion will focus on additional thermal and non-thermal applications of biogas-biomethane.

4.1. Biogas turbine cycles and micro turbines

Biogas turbines are often utilized in larger power plants with electricity output capabilities of 3 MW or more and industrial-scale biogas production. Biogas turbines require relatively low maintenance, and their efficiency increases with the size of the installation. Due to their compact size and ability to connect multiple units in series, micro-turbines provide greater flexibility in power generation. The main advantage of turbines and micro-turbines is their high tolerance for H_2S in biogas, in contrast to diesel and petrol engines [23]. There has been a proliferation of small biogas power plants, each capable of producing 30 to 75 kW of electricity. Despite their low cost and high efficiency, gas turbines are not widely used due to the engineering challenges and material considerations involved in their design, production, operation, and maintenance. The term "micro turbine" refers to gas turbines with outputs ranging from 25-30 kW to 350 kW. A micro turbine operates similarly to a gas turbine. The primary components of micro-turbines and turbines include the combustor, compressor, and turbine. The hot combustion byproducts expand through the turbine, converting thermal energy into mechanical energy. The compressor's induction force pushes air into the micro-turbine, where it is compressed to the required pressure. In more complex cycles, the compressed air is heated by the waste heat from the exhaust gases before being redirected to the compressor. The combustor receives hot, compressed air and burns biogas as an alternative fuel. The combustion of the biogas fuel-air mixture in the combustor generates very high-temperature flue gases. A gas turbine utilizes the expelled gases for expansion fuel.

4.2. Advanced gas turbine cycles

A generator and a compressor for compressing combustion air are both attached to the turbine rotor shaft. By recycling the waste heat present in the gases generated by an open-cycle gas turbine, it is possible to enhance the efficiency of the combustion process. Before the combustion gases and fuel are introduced to the combustor, they can be preheated using this waste heat or preheated simultaneously. The exhaust gases from larger units can power a waste heat recovery boiler that fuels a Rankine cycle steam turbine to produce additional energy. Before compressed air enters the combustor to mix with biogas fuel, it can be warmed up using an air heater (heat exchanger) installed in the gas supply system of a microturbine and turbine.

4.3. Combined heat and power (cogeneration)

As various pathways and technologies for exploiting biogas energy continuously increase, one of the most efficient forms of utilization is combined heat and power generation in gas engines, often installed at the site of biogas production. Cogeneration systems, also known as combined heat and power (CHP) systems, can use biogas as a fuel source to produce both heat and electricity. A bock heat and electricity plant is a type of combined heat and power system that uses a combustion engine to generate both electricity and heat. Both local and regional needs can be met by the power generated. Waste heat from combustion engines can be utilized for various useful purposes, such as district heating and supplying hot water systems. Four-stroke engines, dual engines, micro turbines, and Stirling engines are all examples of generator prime movers that can be utilized in cogeneration mode using biogas as a fuel, with electrical efficiency ranging from around 25% to about 45% [11]. Depending on financial considerations, a CHP unit can be located near a biogas source, or the fuel itself can be piped or transported to the CHP plant or a nearby district heating unit. In addition to contributing to the grid electricity transition for sustainable development, the use of heat from biogas as opposed to fossil fuel sources is particularly essential because of the added economic and environmental benefits, as gas engines typically range in size from 60 kWe to over 2 MWe for standalone use [11], [38].

4.4. Use of biogas in trigeneration

Trigeneration has attracted attention as worries about the future price of fossil fuels and the release of pollutants fueling climate change have grown. Essentially, an improved version of cogeneration, a "trigeneration" system combines heating, cooling, and power generation [39]. While using biogas as a heating source reduces greenhouse gas emissions and the effects of global warming, the primary advantages of cogeneration systems are savings on fuel and expenditures for power generation. Trigeneration enables the same energy source to produce three distinct beneficial types of energy: electricity, heat, and cold. Typically, a trigeneration system consists of four components: a heat recovery system, a steam generator, a compression mechanical heat pump, and an absorption heat pump [40]. In this setup, a mechanical compression heat pump receives low-temperature heat from an absorption chiller, which extracts cold water from the heat recovery plant and warms it to the needed temperature. Instead of burning fossil fuels, biogas is used as a renewable heating source.

Trigeneration is a system for large facilities like hotels, schools, and hospitals that produces heat, cold air, and electricity. Absorption refrigerators are often used to generate cold heat for cooling needs. Often employed with water as a refrigerant-absorbent in systems operating at 75 °C to 90 °C, lithium bromide helps generate cold water for air conditioners in the 12 °C to 7 °C range [41], [42]. Though its inefficient operation limits its cooling power per unit of volume and weight (0.3-0.5), adsorption cooling produces cold through latent heat.

4.5. Biogas to hydrogen

Fuel cell systems that use biogas to generate electricity are still in their early stages of research, but they hold great promise for the future. H_2 fuel cells are high-tech machines that can produce power. The fact that fuel cells do not release any toxic waste makes them an attractive option for power generation. The use of fuel cell technology to generate emission-free electricity from H_2-rich natural gas is highly promising [43]. Replacing coal and oil in power generation and industrial thermal applications will help reduce the emission of harmful pollutants, as natural gas is a cleaner fuel. Additionally, substituting coal with natural gas from existing natural-gas-fired power plants for combined-cycle natural-gas plants with increased utilization is expected to displace a reasonable percentage of the CO_2 emissions attributed to coal-fired electricity generation in the coming years. Simultaneously, using biomethane in natural gas could yield net negative greenhouse gas emissions. Sustainability in the use of biogas can be enhanced by utilizing it for H_2 production combined with CO_2 capture and storage [44]. H_2 can be produced by electrolysis, steam CH_4 reforming, or autothermal reforming for syngas production. Using biogas digestate as fertilizer supports long-term viability. Even if carbon capture and storage are not incorporated into the process, biowaste-based H_2 could still result in lifecycle greenhouse gas emissions reductions.

4.6. Biogas and biomethane in transportation

Approximately 14% of all greenhouse gas emissions worldwide are commonly attributed to the transportation industry. Since diesel is so common in the transportation industry, switching to low-carbon and renewable energy sources is crucial. Liquefied biogas is a fuel that some locomotives and power plants can use. These are only two of the numerous potential uses of this adaptable substance, which can also be burned as a fuel or as a raw material for the manufacture of other fuels. All of these have in common that they were produced using fossil fuels. Biogas, or compressed and liquefied methane, is the only fuel that can be produced directly from biological matter. A fuel cell car that produces almost no pollution can run on biogas. In a few countries, enhanced biogas or biomethane is already used as a transportation fuel. Studies comparing the usage of fossil fuels and other transportation fuels and biogas have demonstrated that the latter has a significantly lower environmental impact [45], [46]. Bio-CNG, or compressed biomethane, is an alternative to traditional fossil fuels like CNG due to its similar features in terms of fuel economy and emissions. Water, N_2, O_2, H_2S, NH_3, and CO_2 must be removed from biogas before it can be used to make Bio-CNG. The end product is a gas with a pressure range of 20–25 MPa, a composition of more than 97% CH4, and 2% O2. Conventional natural gas takes up over 1% of the area at room temperature and pressure compared to bio-CNG [47]; hence, liquefied biogas can be utilized as a transportation fuel. A pressure range of 0.5 to 15 MPa is required for the transformation. Biochemical and biological processes transform clean biogas, largely composed of CH_4 and CO_2, into methanol, diesel, LPG, and gasoline. It was initially noted in 1923 that CH_4 can be partially oxidized to form methanol. Besides CNG and LPG, syngas can also be produced by reforming clean biogas. The Fischer-Tropsch method, which also incorporates partial oxidation, can produce chemical fuels, such as methanol, petrol, diesel, and jet fuel.

5. OTHER BENEFITS AND LIMITATIONS

Biogas can significantly contribute to a wide variety of Sustainable Development Goals (SDGs) and to achieving sustainable energy futures, as outlined in Table 6. The benefits are highlighted based on the number of SDG targets and indicators, as well as the applications of biogas production and technologies. Biomethane, a byproduct of upgrading biogas, presents several challenges, including high energy and operational costs. The potential contribution of biogas to a more sustainable energy system is greatly influenced by its source and conversion method.

Table 6. The contribution of biogas to the SDG and sustainable energy futures

SDG No	Description of SDG	Biogas contribution to enhancing sustainable multi-energy futures
2	SDG 2: Zero hunger	The digestate, a byproduct of biogas production, acts as a nutrient-rich fertilizer, improving soil quality and boosting agricultural productivity.
6	SDG 6: Clean water and sanitation	Biogas digesters may be used to efficiently tackle wastewater treatment, resulting in a decrease in pollution and improving the accessibility of clean water.
7	SDG 7: ensuring access to clean and affordable energy	Biogas provides a sustainable and eco-friendly alternative to fossil fuels, thereby reducing greenhouse gas emissions and promoting the use of renewable energy sources, therefore contributing to the goal of clean energy.
8	SDG 8: Decent work and economic growth	The biogas industry plays a role in fulfilling SDG 8, which emphasizes the need of creating decent work and promoting economic growth. This is achieved via the creation of job opportunities in the manufacture, installation, operation, and maintenance of biogas plants. The introduction of biogas digesters in impoverished countries has the potential to alleviate poverty by creating income via energy production and waste disposal, therefore empowering local communities.
9	SDG 9: Industry, innovation, and infrastructure	Improved low carbon and eco-friendly infrastructure such as electric charging from bio-resources can be achieved.
11	SDG 11: Sustainable cities and communities	The utilization of abundance local bioresources for electricity generation, transport, heating, and cooling needs.
13	SDG 13: Climate action	Biogas helps combat climate change by responsible capturing of CH4 for value-added use from waste, thereby diminishing a potent greenhouse gas.
14	SDG 14: Life below water	Biogas helps to save forests and mitigate water pollution by decreasing the need on conventional biomass for cooking.
17	SDG 17: Revitalize the global partnership for sustainable development	The use of biogas alongside other energy resources for multi-energy generation towards sustainable electricity generation.

The main limitations of biogas engines include the slow ignition process, severe backburning, and the high temperature of the flue gas. The presence of CO_2 reduces the combustion rate from 37.3 cm/s with CH_4 to just 23 cm/s. Consequently, post-combustion burning continues in the stack, degrading combustion quality [25]; hence, continuous studies, improvement, and upgrades are needed in this regard to accelerate the engine combustion rate, given the varying quantities of greenhouse gas generation owing to the technology used, engine conversion needs, and biogas source. Notwithstanding the greenhouse gas generation, the production of digestate during anaerobic digestion acts as a valuable biofertilizer. Thus, biogas generation increases the value of biowaste, still promoting a clean and healthy environment. Greenhouse gas emissions (mostly CO_2, CH_4, and N_2O) still occur even with contemporary biogas production techniques, and these emissions might vary based on the biogas source or the technology employed to generate the gas. Although CH_4 is considered safe, handling it carries a risk of asphyxiation. Since CH_4 is an extremely potent greenhouse gas, it is imperative to find ways to prevent emissions into the atmosphere, such as by absorbing it or allowing it to break down. As a fuel substitute that can be converted into chemicals, hydrogen, and other products, all of which have the added advantage of lessening environmental damage, biogas has tremendous value addition potential.

The provision of clean energy from biogas is linked to reducing greenhouse gas emissions, which helps mitigate global warming, as stated in SDG 13. Waste treatment, emission reduction, energy generation, and environmental preservation are activities included in the biogas circular economy [48], [49], a resource management strategy designed to restore and replenish products and materials, thereby enhancing their value throughout every phase of use through responsible management practices of life cycle greenhouse gas emissions in biogas production [50].

Biogas remains a sustainable energy option, offering increasing access to electricity, as outlined in SDG 7, which is crucial for promoting economic growth and enhancing quality of life, thereby relating to SDG 8. Additionally, it contributes to reducing hunger under SDG 2 by providing healthy food resources and clean water through treated bio-based fertilizer, a more environmentally friendly means of agriculture, essential for safeguarding water resources from toxic chemicals, necessary to achieve SDG 6. Industries depend on energy to operate equipment and conduct various activities, while households utilize electricity for tasks such as lighting, cooling, air conditioning, refrigeration, and charging phone batteries. Furthermore, electricity powers communication systems and supports cooking, which may use forest resources managed by decreasing reliance on conventional biomass. This approach not only helps achieve SDG 14 but also promotes a sustainable environment, as articulated in SDG 11, promoting partnerships as with SDG 17, aimed at achieving further innovations and clean technological biogas infrastructure, SDG 9.

Therefore, there is a demand for environmentally friendly and renewable energy sources, with biogas regarded as one of the leading options. Utilizing biogas for electricity generation offers the significant advantage of decentralizing the production process for many applications. This has a substantial impact on rural economies by creating job opportunities, providing financial support for rural businesses and individuals, maintaining a stable electrical infrastructure, and enhancing energy security in power production and distribution.

6. CONCLUSION

There are several uses for biogas, a renewable energy resource that produces minimal pollution and can be used to generate both thermal energy and electrical power. Produced from biodegradable waste, it can be transformed into biomethane, a substitute for fossil fuel. A wide range of technologies can harness biogas, including micro gas turbines, diesel engines, gasoline engines, Stirling engines, fuel cells, biofuel production, and hydrogen generation, among others. One of its main advantages is distributed power generation, and it can also be used for home heating and lighting. Various methods exist to convert biogas into usable energy, including internal combustion engines, gas turbines, micro gas turbines, on-site turbines, boilers, steam generation, tri-generation, combined heat and power, and steam. Vehicles, refrigerators, and cooling plants can all benefit from biogas. There are several practical applications for this feedstock, including the manufacture of fuel cells, methanol, and hydrogen. Particularly for towns undergoing a sustainable energy transition and those located in rural areas, there are substantial socioeconomic benefits to producing biogas. Profitable exploitation and high biomethane production costs, inconsistent output quality, contaminants, and a lack of technical advancements are some of the obstacles.

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C : **C**onceptualization
M : **M**ethodology
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Va : **Va**lidation
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R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

No conflicts of interest exist among the authors.

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The research has provided all data and information used and did not use any undeclared data and information.

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