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Review Article

Biogas Production and Applications in the Sustainable Energy Transition

Moses Jeremiah Barasa Kabeyi and Oludolapo Akanni Olanrewaju

Industrial Engineering Department, Durban University of Technology, Durban, South Africa

Correspondence should be addressed to Moses Jeremiah Barasa Kabeyi; moseskabeyi@yahoo.com

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Biogas is competitive, viable, and generally a sustainable energy resource due to abundant supply of cheap feedstocks and availability of a wide range of biogas applications in heating, power generation, fuel, and raw materials for further processing and production of sustainable chemicals including hydrogen, and carbon dioxide and biofuels. The capacity of biogas based power has been growing rapidly for the past decade with global biogas based electricity generation capacity increasing from 65 GW in 2010 to 120 GW in 2019 representing a 90% growth. This study presents the pathways for use of biogas in the energy transition by application in power generation and production of fuels. Diesel engines, petrol or gasoline engines, turbines, microturbines, and Stirling engines offer feasible options for biogas to electricity production as prme movers. Biogas fuel can be used in both spark ignition (petrol) and compression ignition engines (diesel) with varying degrees of modifications on conventional internal combustion engines. In internal combustion engines, the dual-fuel mode can be used with little or no modification compared to full engine conversion to gas engines which may require major modifications. Biogas can also be used in fuel cells for direct conversion to electricity and raw material for hydrogen and transport fuel production which is a significant pathway to sustainable energy development. Enriched biogas or biomethane can be containerized or injected to gas supply mains for use as renewable natural gas. Biogas can be used directly for cooking and lighting as well as for power generation and for production of Fischer-Tropsch (FT) fuels. Upgraded biogas/biomethane which can also be used to process methanol fuel. Compressed biogas (CBG) and liquid biogas (LBG) can be reversibly made from biomethane for various direct and indirect applications as fuels for transport and power generation. Biogas can be used in processes like combined heat and power generation from biogas (CHP), trigeneration, and compression to Bio-CNG and bio-LPG for cleaned biogas/biomethane. Fuels are manufactured from biogas by cleaning, and purification before reforming to syngas, and partial oxidation to produce methanol which can be used to make gasoline. Syngas is used in production of alcohols, jet fuels, diesel, and gasoline through the Fischer-Tropsch process.

1. Introduction

Energy is a fundamental requirement for man's comfort and basic needs of everyday life. A vast majority of countries especially developing countries have energy crises with over reliance on fossil fuels [1, 2]. The national energy drivers of all countries globally are energy security, environmental protection, and economic growth. It is predicted that fossil fuel sources like coal, gas, and oil are headed for depletion within the next 10 decades, hence the need for alternative sources of energy [3]. Additionally, international treaties like Agenda 21 and Kyoto Protocol advocate for a transition to renewable and low carbon sources of energy due to high greenhouse gas emissions associated with fossil fuels and the related climate change caused [4, 5]. Biogas has proved to have significant potential as a renewable energy source for industrial as well as domestic applications and an efficient solution to the global energy crisis [6, 7]. The increasing use of fossil fuels and environmental concerns over greenhouse gas emissions and climate change has generated interest in biogas as an alternative renewable energy resource [8]. Increasing environmental and policy concerns and measures have generated increasing interest in the use of biomass resources as renewable feedstock for electricity generation, fuel production, chemical processing, and hydrogen production [9]. This has been further compounded by depletion of fossil reserves, growing organic waste production, and global warming threats have combined to increase interest in anaerobic digestion and biogas fuel resources [10]. The main application for biogas is electricity generation, thermal applications like cooking, heating, and lighting, and production of biofuels. Over 7000 MW of electric power is generated from biogas annually [11].

Agriculture is the main economic activity for over two-thirds of the world population besides supplying food to the entire mankind [12]. Additionally, smallholder agriculture and associated sectors constitute the main economic activities for many developing countries, accounting for about 82% of the world's population directly or indirectly [12]. Access to modern energy services is a challenge for most developing countries, for example, in India alone, about 836 million people had no access to modern energy in 2012 [13]. Development and adoption of technologies that conserve resources and income in agriculture are the most valuable tools and strategies for sustainability in food and energy production [12]. Coal, oil, and gas which are fossil fuels contribute about 60% to global electricity, although renewable sources increased their share from 26% to 28% in the first quarter of the year 2020, with variable renewables growing from 8% to 9% over the same period [14]. The average annual growth of renewable energy contribution to global electricity production has been growing at 2% compared to the average growth in electricity demand of 1.8% beginning the year 1990. Of this growth in renewable source generation, biogas is registered the third-fastest annual growth in global capacity at 11.5% behind solar PV with 36.5% followed by wind at 23.0%. As an indicator of the important role of biomass in global electricity generation, biofuels have grown at an average annual rate of 9.7% since 1990 [15]. This shows the important role that biogas can play in the energy transition and hence the need to promote its production and consumption.

Biogas, biomass, and biofuel are all renewable energy sources existing in different phases of the transformation. Biogas can be made from different biomass like poultry droppings, agricultural crop wastes, and cattle manure by controlled anaerobic degradation. Produced biogas can be processed further and concentrated to produce biomethane which can be injected into natural gas pipelines [16]. Biogas which is a byproduct of microbial metabolism can be used in its raw form for heat and power generation or can be upgraded to biomethane and for production of value-added chemicals for energy and industrial process application [8]. The use of biogas can reduce greenhouse gas emissions as it has huge potential for use as a renewable resource [17–19]. As an example, 0.29% of total energy consumption in Switzerland for the year 2014 was in the form of biogas and it accounted for close to 8% of the total renewable energy production without accounting for hydropower [20]. Biogas can be used to reduce dependence on solid biomass like firewood as cooking fuel. Biogas has the potential to provide clean cooking fuel for about 200 million people by the year 2040, particularly in Africa and Asia. This implies that biogas has a significant role in the realization of the social development goals (SDGs). With upgrade, biogas produces biomethane as a superior fuel to unprocessed biogas [21]. This positions biogas as a reliable energy resource in the energy transition to green and low carbon energy and electricity mix [18, 19, 22, 23].

Biogas is produced by anaerobic digestion (AD) process whose benefits include production of a renewable energy resource while the process can lead to treatment of feedstock during the treatment and also produce digestate which is a useful organic fertilizer that can substitute chemical fertilizers in sustainable agriculture [18, 24]. Biogas has a significant role to play in the global energy transition because of the need to transform the global electricity systems from fossil fuel-based generation to low carbon and renewable energy-based power generation. With huge biomass to biogas conversion potential and many feasible biogas to electricity conversion technologies, biogas will play an extremely important role in the energy transition as a renewable energy fuel resource and feedstock for industrial production of chemical fuels and renewable products [25–29]. Microbially controlled generation of biogas is a significant part of the global carbon cycle where we have a natural anaerobic biodegradation estimated to generate 590–800 million tons of methane into the global atmosphere [30].

Biomass with significant energy potential is produced in increasing quantities by the society globally [22, 26, 31]. Various organic feedstocks can be used to produce biogas through anaerobic digestion which can be processed through enrichment to produce natural gas like biomethane. Biomass waste conversion to biogas provides a sustainable pathway for a more circular economy with benefits like reduced carbon emissions, better and useful organic waste management, and greater resource use efficiency [26, 32]. There are various options for conversion of biogas to electricity, but economic studies favor internal combustion engines and Stirling engines as the most economical, especially in small-scale power production. Internal combustion engines generate low cost of power per kWh, are available in various sizes, and are more efficient and flexible while operation and maintenance are easier. Gas turbines are preferred for slightly bigger sizes of 3 to 5 MW and more. Microturbines can be connected in series, and hence, as many units as possible can be connected while the fuel quality requirements are not quite as stringent as internal combustion engines [33, 34]. Higher total capital investment costs face both the steam turbine and the gas turbine power systems for biogas to electricity conversion [35–39].

Biogas and biomethane which is enriched biogas also provide a way to integrate rural communities and industries into the transformation of the energy sector through grid-connected electricity generation and avoided load on the grid by own electricity and heat generation [21]. Biogas is methane that is a renewable energy resource produced by anaerobic digestion of organic matter under controlled conditions [40, 41]. Biomass substrate is used for biogas production as long as it contains cellulose, hemicellulose, proteins, fats, and carbohydrates that are indigestible [42]. Biogas has multiple applications in heat and electricity production as well as a raw material for production of several biofuels and can also be used for production of biomethane, carbon dioxide, and hydrogen [43]. The energy content of biogas is a function of methane composition which is influenced by the process and the substrate type used in its production. Biogas may also contain constituents like sulfur which make it undesirable as a fuel for internal combustion engines and many other industrial chemical and thermal applications. The calorific value of biogas varies with composition and is mainly determined by the proportion of methane. The heating value generally varies from 21 to 23.5 MJ/m^3 which implies that 1 m^3 of biogas is equivalent to 0.5-0.6 liters of diesel fuel or about 6 kWh of electricity [44]. The biogas yield of a biodigester is a function of the type of feedstock used, digester design, fermentation temperature, and retention or residence time applied. Maize silage generally yields about 8 times more biogas per ton of feedstock compared with the yield from cow dung of similar quantity. Generally, 2 livestock units or about 2 cows or 12 rearing pigs plus 1 ha of maize and grass can yield a constant output of about 2 kWe or 48 kWh. In studies by ESMAP in South East Asia, about 14 kg of fresh cattle dung corresponding to about one cow per day plus 0.06 liters of diesel fuel can generate 1 kWh of electricity [43]. Therefore, farmers who intend to establish biogas units should plan the mix of their livestock and crops in a way that can also maximize biogas production.

Humanity initially relied almost entirely on biomass for its energy needs before the 1800s [45]. The industrial revolution led to a transition to a fossil fuel-dominated energy mix led by coal and later petroleum products like diesel and natural gas. The early 1970s to late 1980s witnessed a high increase in oil price which necessitated the search and development of renewable, sustainable, and environmentally friendly sources with biogas being among the top sources of alternative energy [46–48]. According to [49], there is a need to conserve the environment and dispose of wastes in an eco-friendly manner to prevent environmental degradation and greenhouse gas emissions. Biogas can be produced by rural communities who are the majority in many developing countries living as peasant farmers. As an example, about 70% of the population lives in rural areas in India [13], but the huge energy potential of biogas is currently underutilized globally. In many developing countries, most of the population lives in rural areas as smallholder farmers who can adopt biogas technology for most of their energy needs [50, 51].

Biogas has proved to be a futuristic renewable energy with huge current and future potential. Despite the prospect of biogas to play a leading role in attaining sustainable development goals and the sustainable global energy transition owing to limited contribution to greenhouse emissions, widespread availability, and access to raw materials, it has limited to the global energy and electricity mix, hence the need to change the situation [2, 4, 52, 53]. The overall objective of this research is to identify technologies and potential of using biogas in sustainable global transition and realization of the sustainable development goals. The study seeks to establish the potential of biogas in grid electricity generation and other energy applications to reduce emissions and effectively define a roadmap for biogas to electricity conversion in the energy transition. This will contribute towards the mitigation of the twin threat of increasing greenhouse gas emissions and climate change in line with emissions and climate targets set by the Paris agreement. Options, strategies, and feasible technologies of biogas to electricity generation at the farm- and industrial-scale level are reviewed and evaluated. The potential, requirements, and challenges of biogas production are presented while the various technology options in biogas to heat and electricity are presented [31, 47, 48, 51, 54].

1.1. Problem Statement. The growing world population especially in developing countries has led to an increase in food and energy demand which leads to pressure on production and consumption of energy which is currently associated with greenhouse gas emissions and climate change [12]. Whereas biogas possesses huge potential to supply rural as well as urban populations with clean energy, there has been a growing concern over many nonfunctional and disused biogas plants raising the question of sustainability of biogas technology for reliable production, supply, and use of biogas fuel. As an example, 65 out of 75 combined biogas and biomass gasification projects for the Village Energy Security Program (VESP) in India were commissioned, yet just about 42% were operational by the end of the project against the expectation of policymakers whose objective was to meet total energy requirements of rural communities [13, 55]. The USA has got just over 2200 operating biogas systems while the current potential is well over 13,500 [41]. There is a growing need to provide a reliable, efficient, affordable, and adequate energy source with the least carbon footprint [50]. New York City alone spends about US$ 400 million to transport about 14 million tons of waste for incineration, yet this can be converted to useful energy and revenue [41]. Using biogas technology, crop and animal waste can be best utilized to generate renewable energy used in electricity production and heating purposes, and the end product is effectively utilized as fertilizer in the rural farms and households and reduces handling and disposal costs [49]. Biogas energy can be used to improve the standard of living and socioeconomic status of rural households globally.

Many smallholder farmers in developing countries burn biomass as a means of disposal; yet, it has the potential as a source of valuable fertilizers which can substitute expensive chemical fertilizers. For poor smallholder farmers, biogas technology can be used to produce organic fertilizer to supplement expensive chemical fertilizers [56]. In the design aspect of the study, it is necessary to define the different parameters needed to ensure biogas systems can continuously meet their total energy needs through biogas [50, 57]. Although biogas is mainly used in direct heat application, diversified applications in electricity generation and fertilizer production will help maximize the benefits from the investment in a biodigester with multiple benefits of agriculture, electricity supply for electrical needs of farms and households alongside traditional biogas heating applications.

In electricity generation, it is necessary to identify the most effective and cost-effective biogas to electricity conversion technology from various options which include fuel cells, internal combustion engines, microturbines, and the Stirling engine among others. Important is to sustainably generate electricity because of overwhelming evidence of poor performance of farm-level biogas systems and eventual collapse. Optimum design and selection of appropriate electricity generation infrastructure is the solution for sustainable electricity generation from farm-level biogas systems [23, 58].

Allowing agricultural wastes to decompose naturally leads to the release of significant quantities of methane to the atmosphere as a serious greenhouse gas. In 2015, livestock manure alone contributed about 10% of all the methane emissions in the United States of America, yet just 3% of all the livestock waste is recycled through anaerobic digestion [41]. The main challenge to the use of biogas is unsteady production and quality variations which can lead to interference in generation or biogas applications, hence lower reliability [59]. This study investigates the role of biogas in sustainable grid electricity transition as a renewable energy resource. Optimal and sustainable production of biogas is investigated and proposition on sustainable biogas to grid electricity production as well as production of biofuels like biohydrogen, methanol, and syngas [48, 60, 61].

1.2. Rationale of the Study. The growing concerns over the depletion of fossil fuels, energy security considerations, and concern over global warming as spelt in the Paris agreement have generated significant interest in renewable energy sources like biogas. Biogas has significant potential as a low-cost energy carrier [34, 62–64]. There are huge quantities of organic waste generated in all countries, for example, the US alone generates over 70 million tons of organic waste which can be converted to energy [65]. A sustainable and affordable electricity supply is critical for poverty alleviation and sustained socioeconomic development [13]. Biogas use is positive to the environment as it helps in fossil fuel substitution, and its production prevents uncontrolled production and emission of methane to the atmosphere. The use of waste streams in biogas production reduces waste disposal costs and control of pathogens by sterilization [66]. Anaerobic digestion (AD) has proved to be an efficient alternative technology combining biofuel production with sustainable waste management, and various technologies do exist to enhance biogas production and utility [7, 34]. Biogas, produced from either biological or thermochemical processes, has significant potential for use in the generation of heat, electricity, and various transport and process fuels and chemicals. However, the market remains dynamic and the technology complex with several feasible technologies is still at nascent stages of development [67]. Biogas has positioned itself strategically in the sustainable energy transition because of the global pressure to reduce greenhouse gas emissions, high cost of waste disposal, development of new technologies in electricity generation like hydrogen and fuel cells, and wide availability and access to biodegradable biomass from farms and waste collection centers [68–70]. The challenges of heat and electricity generation, the desire for sustainability, the high cost of power generation, and related environmental challenges have created interest in alternative sources of energy and technology globally [71]. Traditional energy sources face different challenges that affect the economic growth and their adaptation [72]. A majority of the population in many developing countries live in rural settlements and engage in agriculture which generate biomass that can be used for biogas production and organic fertilizers [49]. With the right infrastructure, farmers can meet their own biogas energy needs and sell excess electricity or biogas as well as organic fertilizers leading to sustainable agriculture and energy. They also have energy needs which are often met by various forms of energy like diesel and kerosene, conventional dry cells, and rechargeable batteries which are costly to sustain their smallholder and often subsistence farming. They need fertilizers, yet the conventional chemical fertilizers are expensive and have several negative effects to the land, and therefore, the long-term productivity of land is hampered [50]. Therefore, generating their own power at the farm level will solve many energy supply challenges they face and in the process can even sell excess electricity to the grid earning themselves additional revenue while playing a role in the energy transition [52].

If organic wastes are not properly managed, they can cause serious environmental and health risks [41]. Biodigestion of organic wastes leads to reduction in greenhouse gas emissions as well as the danger of polluting waterways. The digestate can be used in soil amendment [41, 73]. Mixing of different substrates in the digester also known as codigestion increases biogas yield. The economics of biogas production and consumption is not only about profits and income generation, but an issue of project sustainability which is influenced by the substrate availability, access and characteristics, cost of operation and maintenance, digestate production and application, and the cost benefits involved in biogas application or usage which should be diversified for sustainability [74]. Biogas technology has developed over the years from small individual units to large-scale industrial plants using sophisticated technology. This technological development has however concentrated on the production side at the expense of the utility side. There is a need to transform biogas to a high-value thermodynamic state to enable it to perform mechanical work for several useful applications like the use as a fuel in heat engines [75]. This study identifies and suggests methods to add value to biogas on the demand side while paying attention to the production or supply side of biogas.

Left alone, agricultural wastes decompose uncontrollably and emit huge quantities of methane to the atmosphere [76]. This leads to a serious greenhouse gas effect since methane is more potent than CO_2 to the extent that in 20 years period, methane would absorb 86 times more heat than CO_2. Therefore, sustainable biogas production from agricultural wastes will prevent this negative environmental impact while, at the same time, displace the use of fossils in many households [41, 77].

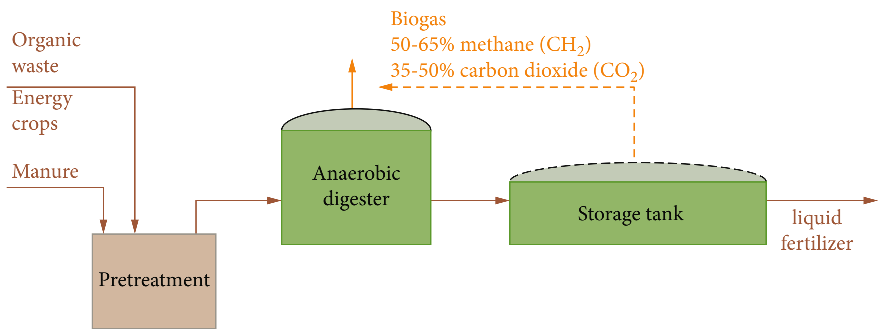

Figure 1: Biogas and fertilizer production.

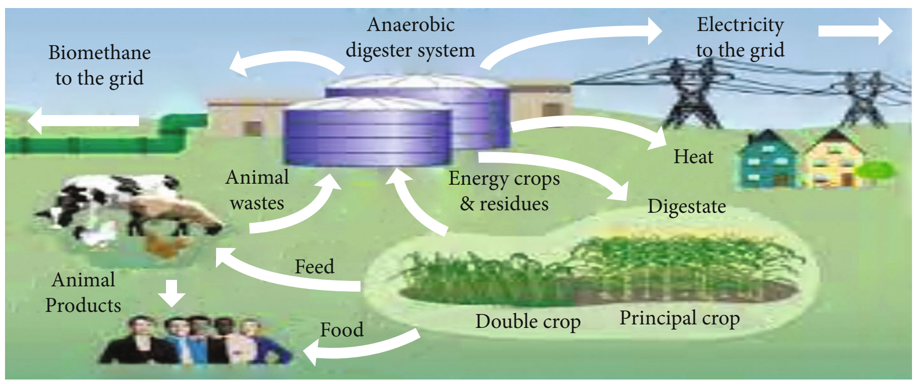

Figure 2: Diversified biogas production with fertilizer, lighting, and electricity applications.

Biogas production from various biomass will make farmers and other institutions handling biomass active participants in the global sustainable energy transition [78]. Therefore, biogas provides a business opportunity to farmers and biomass waste handlers. The use of locally available materials will enhance the local industry like the use of homemade bricks which are common and cheap to use [50, 79]. Other business outcomes will be realized through large-scale manufacture and service of plants and appliances to sustain a growing biogas industry. With increased application for biogas plants, biogas-run generators, gas nozzles and taps, gas pipings, and other small appliances will need to be available in the market to satisfy the demand. With these needs, manufacturing companies will produce different appliances for distribution to biogas producers. Plastic tank-making companies can also take the initiative of designing a biogas plastic tank that is easy to fit and run at a lower cost than the conventional biogas plant that needs a longer construction time [78]. Since the biogas tank is commonly buried in the ground, a plastic tank would also be viable with the appropriate standard for manufacturing these tanks being developed for overall use and application. Figure 1 demonstrates the value chain arising from the development of farm-scale biogas electricity producing plants.

Figure 1 shows a simple arrangement where smallholder producers can generate biogas and fertilizer through anaerobic digestion. Although the setup is simple and cheap, it may be less sustainable due to limited applications and interconnection with agricultural activities which supply the feedstock. The solution to sustainability at the household level is to diversify biogas applications and sources of feedstock for the biodigester [18, 19, 22, 80]. A diversified and more sustainable biogas system is demonstrated in Figure 2.

Figure 2 demonstrates a more diversified biogas system connecting upstream and downstream activities. This makes biogas systems more diversified and more sustainable as all activities at home are directly or indirectly connected to the biogas systems which effectively enhances system sustainability [28, 34, 53, 63]. Figure 2 shows the main requirements for a farm-level biogas system being the source of biomass substrate which is farm animal waste, plant waste, gas storage, lighting and electricity generation system, and fertilizer supply stem all connected to the biogas plant.

The advances in electricity technology, power electronics, communication, and information technology have led to the development of the smart grid and the decentralization of electricity generation. This has effectively converted electricity consumers, both large and small scale to prosumers. Prosumers are customers who are both producers and consumers of electricity [34, 80]. Figure 3 demonstrates a grid electricity-connected biogas production and electricity generation system made possible by the advances in decentralized generation and smart grid technology.

From Figure 3, it is observed that the basic requirements and infrastructure of a biogas system with electricity export capability are the biogas digester with gas purification system, gas storage/reservoir, and gas flow rate controller, the engine with generator, battery for electricity storage, inverter, and the main distribution board [81]. Therefore,

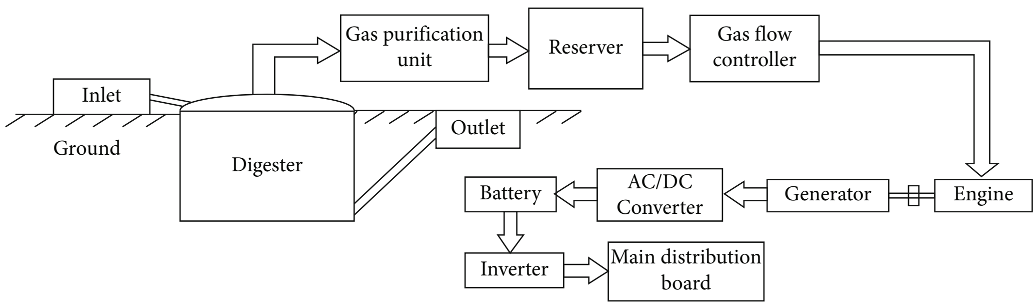

Figure 3: Block diagram of a typical grid-connected biogas electricity system.

with the decentralization of electricity generation and advances in microgrids and smart grid technologies, biogas will play a critical role in the sustainable electricity transformation and transition.

1.3. Methodology. This research involved a review of published peer-reviewed papers and official reports on sources of biogas, its production processes, and applications. The literature used was published between 1932 and 2022 to give a clear view of the past and status of biogas technology and applications. The sustainability dimensions of biogas energy were covered including social, institutional, technical, economic, and environmental at local and international levels. A review of policies and regulations on national and international levels is presented. Based on literature and the requirements of sustainable energy transformation, the role of biogas is clearly defined now and in the future. Biogas feedstocks, feed preparation, conditions for optimal production, and composition of both biogas and biomethane are presented. Additionally, biogas upgrading technologies are also presented including quality and process sustainability. Finally, current and future applications of biogas are also presented as a sustainable energy option in the energy transition.

2. Biogas Production

At the end of 2019, the global amount of biogas plant capacity was about 19.5 GW with growth in capacity being fueled by among others, high fossil fuel prices, cheap and easy access to biomass feedstock, and concerns over emissions and global warming. The most common feedstock used to produce biogas are wastes, like domestic wastes, i.e., food, vegetables, fruits, and animal wastes like dung, poultry dropping, or public moist wastes from food cafes and restaurants, markets, and biological waste from industries having high moisture content and high degradability. Biogas production by anaerobic digestion enhances the country's energy basket status and significantly contributes to natural resource conservation and environmental protection [17, 18, 22, 34, 53, 63, 82].

Biogas is produced by the anaerobic action of a class of bacteria under suitable conditions. Gas is an environmentally friendly energy resource with a calorific value between 21 and 24 MJ/m^3 [30]. Natural anaerobic biodegrading of organic matter releases 590–800 million tons of methane into the atmosphere due to uncontrolled natural biodegradation. Biogas recovery systems apply controlled conditions in the biodegradation of biomass for the production of biogas for energy application [30]. Biogas generally contains 50–70% methane and 30–50% carbon dioxide, based on the type of substrate used and process control and management. Other constituents are hydrogen sulfide and nitrogen, among others. With larger plants, biogas can be supplied into gas networks upon enrichment. Anaerobic digesters are generally designed to operate in the mesophilic (20–40°C) or thermophilic (above 40°C) temperature zones [19, 30].

Anaerobic digestion of wastes for sanitation and use of biogas as an energy carrier has existed for long worldwide. Digested wastes from biogas plants are also used widely as a valuable fertilizer in farming. In Germany, the share of biogas in electricity generation was about 4.5% in 2013 because of favorable pricing of electricity generated from renewable sources which saw biogas plants increase from about 140 in 1992 to about 7,720 by the end of 2013. As a midterm strategy, biogas has a potential to fill up the residual load from electricity generation based on wind and photovoltaic [24].

Biogas generally contains 30–70% methane and 30–50% CO_2, which depends on the substrate fed to the digester. Other constituents of biogas are small volumes of hydrogen. The typical heating value of 21–24 MJ/m^3 or 6 kWh/m^3 is suitable for cooking, heating, lighting, or electricity production while a large plant with biomethanation can supply enrichedbiogas into gas supply networks or mains [30, 83, 84]. Biogas production technologies used to recover biogas from biomass harness anaerobic degradation pathways by the action of a suite of bacteria which exist in form of at least three bacterial communities needed by the biochemical chain that finally produce methane alongside other gases [19, 30].

2.1. Historical and Theoretical Background. The idea of rotting matter that generates flammable gas was identified and well understood since the era by the ancient Persian. Today, the world has also gone ahead to work on the idea with the first sewage plant that utilizes the biogas technology being built in 1859 in Bombay and, later, the UK using the idea in 1895 for use in the production of biogas for lighting street lamps [49]. There is anecdotal evidence showing that biogas was used for heating bath water in Assyria during the l0th century BC and in Persia during the 16th century.

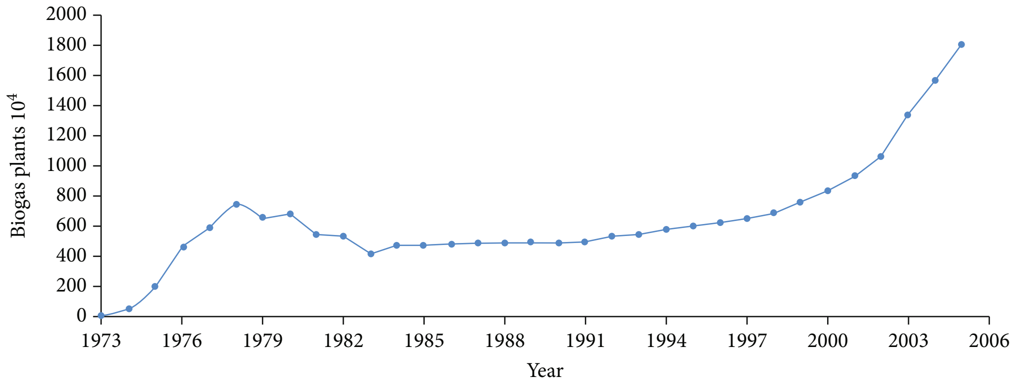

Figure 4: Number of biogas plants between 1973 and 2006.

It is Jan Baptista Van Helmont who first established in the 17th century that flammable gases evolved from decaying organic matter. Work by Count Alessandro Volta showed in 1776 that there was a direct correlation between the quantity of organic matter and the quantity of the flammable gas generated. Sir Humphry Davy confirmed in 1808 that methane existed in the gases produced during the anaerobic digestion of cattle manure.

A well-documented effort to use anaerobic digestion dates from the mid-nineteenth century, with digesters being constructed in New Zealand and India, and a sewage sludge digester is constructed at Exeter, UK, to supply power for street lamps in the 1890s. Guorui Luo is credited for the commercial development of biogas in Guangdong Province, China [30]. It is in 1921 that he developed an 8 m^3 biogas tank that used household waste as feedstock and later founded a company to promote biogas technology [85].

In India, the first biogas plant was built at a leper colony in Bombay, India, in 1859. In 1895, biogas from a sewage treatment facility was used to fuel street lamps in Exeter. Research by Buswell and others in the 1930s identified anaerobic bacteria in the anaerobic digestion and the conditions that promote the production of biogas. About 6 million family-sized, low-technology biodigesters are used for biogas production, but the size and sophistication are increasing particularly in India. In 1999, India had over three million family-sized biogas plants, and more were built when at the end of 2007, the Indian government decided to subsidize the construction of biodigesters. As a result, therewere close to 4 million family-sized biogas digesters with state subsidies ranging from 30% to 100% in the 1980s–1990s[30, 85]. This demonstrates the importance of state subsidies in the promotion of investment in biogas technology.

In Europe, anaerobic digestion is widely used in organic waste treatment. Environmental regulations have also helped to promote anaerobic digestion as a means of waste treatment and disposal while the energy transition to low carbon energy and grid is a further incentive to the development of biogas as a fuel [86]. A key policy tool widely applied to promote biogas technology and deployment is the “green pricing,” which allows manufacturers of biogas-generated electricity to sell at a premium. As a further incentive, the sale of cogenerated hot water to specially-built district heating systems is growing as a source of revenue for investors [86].

The first digester to use municipal solid waste (MSW) feedstock was developed and operated in the US between 1939 and 1974. Today, municipal solid wastes (MSW) are increasingly used for biogas production and different types of systems have been developed to supplement other solid waste disposal methods like landfilling and incineration [22, 86]. Anaerobic digestion and composting are the only biological pathways for recycling nutrients, and organic matter from the organic portion of municipal solid waste with composting is an energy-consuming process requiring about 50-75 kWh of electricity for each ton of municipal solid waste. On the other hand, anaerobic digestion is a net energy-generating process capable of producing 75-150 kWh of electricity per ton of MSW [18, 86]. In 1920, biogas from a sewage treatment plant was used to supply biogas to the gas supply system in Germany, while the first large agricultural biogas plant began operations in Germany in the year 1950. Biogas technology spreads faster in the 1970s because of high oil prices which motivated research into alternative energy sources. It is in the 1970s and first quarter of the 1980s that many Asian, Latin American, and African countries experienced the fastest growth in biogas use. In China alone, the Chinese facilitated the installation of over 7 million biodigesters, especially in rural areas over the same period [85].

It is from the 2nd half of the 1980s that biogas technology was applied in industrial and urban waste treatment and energy conservation systems. However, development in rural areas declined with only 4.7 million household biogas being reported in China, by the end of 1988 [85]; in 2007, 26.5 million biogas digesters were in operation by household with common sizes ranging from 6 to 10 m^3. Figure 4 shows the development of biogas digesters between 1973 and 2007.

Figure 4 shows that the number of biogas plants rose steadily between 1973 and 1978 mainly due to the energy crisis which led to high fuel prices and increased search for alternative sources of energy but started to decline until the early 1980s when the number started to rise again due to increased demand and state subsidies that encouraged the use of biogas for heat and electricity production [30, 85].

2.2. Global Status of Biogas as a Source of Energy. The advantages of biogas have been reported since the 19^{th} century, but its interest has increased currently mainly because of the depletion of natural gas reserves and growing concern over the greenhouse gas emissions. The use of high-value fertilizer began in the 20^{th} century [55]. In Europe, biogas technology is widely used with biogas production growing from about 7,934 TOE (9.298×10^9 L) in 2009 to 14,120 TOE (1.6548×10^{10} L) in the year 2016 [7]. Biogas electricity generation is a feasible pathway in the transition to a low carbon grid power. The technologies available are generally easy to adopt and roll out at both domestic and industrial scales. Biodegradable biomass resources are widely available as an alternative source of energy in the form of animal waste, human waste, industrial and municipal waste, and agricultural farm waste [78, 87].

Biogas production is done under controlled conditions in biodigesters which are classified into two main designs, namely, the fixed dome design and the floating dome design. There are however new designs under development to improve on the existing designs due to the increasing need to develop more economical, sustainable, and practical biogas designs [78]. Biogas production and use globally is yet to realize its full potential due to lack of urgency in the implementation of biogas technologies, availability of cheaper fossil fuel sources, high costs of biogas production, and low conversion efficiencies [88].

2.3. Global Development of Biogas Energy Resources. In 2011, biogas accounted for 27% of the global biofuel market and about 0.25% of the global energy market [42, 78]. Biogas production and use can improve people's income and hence the living standards of rural communities, especially by the sale of power to the grid and higher agricultural products from the use of organic manure. Biogas can be used for lighting, cooking, heating, and powering diesel engines which in turn run machinery at home and even at schools [78]. Today, biogas can be converted to biomethane which can be used as fuel for vehicles, substitute for natural gas in industrial, commercial, and domestic uses, or fed into natural gas grids to replace natural gas. Carbon dioxide can be extracted from biogas and used as feedstock for greenhouses and also as a raw material for chemical fuel production [88]. In the year 2005, there were about 16 million small household biogas digesters in the world, with China and India having most of them. In 1996, an equivalent of 16 million tons of firewood was replaced by biogas in India while in China, about seven million biogas digesters met 4% of the then country's energy demand [78, 82]. Biogas use efficiency can be significantly increased through cogeneration in which both electric power and heat are produced simultaneously. Excess electricity can be sold to the grid and thus help stabilize the grid and mitigate against global warming by substituting generation from fossil fuels [52, 89].

A notable application of biogas in Africa has been evident in Rwanda where different projects have stood out to show the potential of biogas energy. The Kigali Institute of Science Technology and Management (KIST) in Rwanda was able to build a $150\,m^3$ fixed-dome biogas digester [52, 72]. The digester is built in Cyangugu prison, and human waste from prisoners is used to generate biogas. The prison contains more than 6000 inmates, and the biogas produced provides for over 50% of all the cooking energy needs for the prison facility [72]. KIST was also able to solve the hygiene and sewerage problem in Lycee de Kigali School through the construction of a $25\,m^3$ fixed-dome digester that was connected to 6 biolatrines. The gas produced from the digester was used in cooking for more than 400 students and operates all the Bunsen burners within the school laboratories. This has been a common trend in Rwanda as the government has also used biogas technology in another prison; Nsinda prison was able to cut firewood costs by 85% of the average cost of 1 billion Rwandan Francs on firewood. The biogas system was able to power 12 biogas ovens and all from human excreta [57, 72]. This demonstrates the potential of biogas in solving energy and hygiene problems in crowded facilities. Europe has also been at the forefront of using biogas technology primarily out of municipal waste. More than 70 anaerobic digesters have been installed and are operational in Europe and are responsible for converting more than 14% of all municipal solid waste to biogas [72, 87].

2.4. Challenges of Biogas Development. The statistical evaluation shows that many biogas digesters operate below design capacity, while others remain dormant soon after construction [72]. This is because of poor or lack of technical management skills, and economic and sociocultural factors. In 2002, during the World Summit on Sustainable Development, it was noted that renewable energy will play an important role in poverty alleviation for many countries [90]. In Kenya, the National Domestic Biogas Program was initiated in 2003 and tasked to facilitate the energy provision for lighting and cooking through biogas plants. The program aimed to construct 8,000 biogas digesters before the year 2013, which also would contribute to meeting the Millennium Development Goals [36, 57]. Through biogas plants, Kenya aimed at providing a solution over the use and availability of energy, while improving the standard of living through poverty reduction [50, 91]. The main problem affecting biogas technology penetration is the high maintenance cost for digesters. Other challenges are lack of technical know-how and complex nature of some biogas digester designs [83]. Challenges facing the biogas technology adoption have been identified as follows:

(i) Poor maintenance and management

To archive optimal production from any biogas system, there requires a certain management level for the digester and the zero-grazing units for livestock. However, there are many different zero-grazing management requirements that compete with the digester's management, and in most cases, farmers direct most of their efforts to the farms as opposed to the digester. This results in low biogas production; hence, the farmer may never realize the value of biogas investments.

(ii) Lack or low technological awareness

Most biogas users are not aware of the working principle of the biogas technology. This lack of knowledge makes it difficult to operate, maintain, and even service the biogas digesters. This also results in below optimal production as the biogas requirements are not met in full for optimal production.

(iii) High installation cost

High volumes of biogas technology installation cannot be undertaken due to lack of capacity in terms of technicians and artisans. There is also a lack of specific biogas installation materials and adjustments need to be made from what is available in the market.

(iv) System failure

Many biogas digesters fail while the remaining digesters operate way below optimal capacity. This has created a bad image and name for biogas technology as it is seen not to be sustainable.

(v) Lack or poor postinstallation support

Lack of capacity in terms of technicians and artisans with proper biogas technology has resulted in limited postinstallation support. In situations where a "12-month guarantee period" is given after installation, support tends to seize immediately after the period. The farmers or operators also have little knowledge on maintaining the systems due to poor technological know-how.

(vi) Standards

Biogas technology operates freely without any laid-out standards to regulate it. This makes it hard to ensure quality control measures are undertaken.

(vii) Limited awareness and capacity building

There are very few institutions that promote biogas technology in many countries, and hence, it is not a popular energy source [83, 92, 93].

2.5. Biogas Production Process. Biogas is generated from different organic matter through anaerobic digestion. Anaerobic digestion is the culmination of different chemical and biological processes that organic matter goes through for biogas production and also waste management [87]. The process of biogas production constitutes a systematic breakdown of large organic polymers by the anaerobic action of different microorganisms into smaller molecules [87, 90]. Anaerobic digestion for the production of biogas from biomass is a chemical process that involves hydrolysis, acidogenesis, acetogenesis, and methanogenesis [42, 87].

Biogas is produced by the microbial action in the digester soon after biomass is prepared and fed into a reactor by a gradual fermentation process. Therefore, the process is a result of microbes feeding on the organic matter in form of proteins, carbohydrates, and lipids/fats, whose digestion leads to production of gases mainly in form of methane and carbon dioxide. The stages in biogas production can be classified as pretreatment, hydrolysis, hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The process of biogas production starts with feedstock processing or pretreatment before feeding the digester for actual digestion process through anaerobic degradation. Feedstock pretreatment is a necessary procedure to minimize failures and improve the generation and quality of digestate among other benefits [18, 19, 28, 94].

2.5.1. Pretreatment Stage. Pretreatment enhances the substrate degradation and hence the process efficiency. Pretreatment methods can be classified into chemical, mechanical, thermal, and enzymatic processes, all meant to speed up decomposition but do not necessarily lead to higher biogas production [7]. The pretreatment process generally starts with feedstock cleaning by washing, feedstock maceration, screening, and pressing depending on the type and status of the feedstock. Impurities like plastic materials are removed, while magnetic traps can be used to remove magnetic impurities, to prevent erosion and damage of moving parts. The pretreatment stage also involves the removal of nonmetallic impurities like glass, eggshells, ceramics, bones, and sand which may not be digested as they form solid deposits at the bottom of the digester leading to loss of digestion space [18, 19, 88].

Lignocellulose digestion needs the use of enzymes for hydrolyzation. The complex structure of lignocellulosic waste creates an economic and technical limitation for biogas production. Lignocellulose contains cellulose, hemicellulose, and lignin which strengthen linkages between molecules, leading to the formation of a compact and strong structure. Biogas generation efficiency of lignocellulose relies on pretreatment performance. Generally, pretreatment fastens reaction and increases the biogas yield and generates a wide range of new substrates for use [3, 7].

Advances in pretreatment enhance biogas yields from lignocellulosic feedstocks and lead to lower atmospheric methane emissions, which positively impact the environment. The role of pretreatment is to overcome the structural barriers of lignocellulose and its polymers, namely, cellulose and hemicellulose through microbial breakdown leading to enhanced biomass digestion and higher biogas production. Studies show that autoclaving and microwaving lead to hydrolysis of part of nonbiodegradable constituents in municipal waste. The overall effect of biomass pretreatment is to make the substrate easily accessible through partial or complete degradation of the feedstock to form fermentable sugars and reduce lignin resistance and reduce crystalline structure of cellulose [3, 7].

From Table 1, it is noted that various pretreatment techniques with varying degrees of effectiveness and cost implications can be used. Pretreatment improves the process performance and biogas yield but can introduce challenges like increased energy input, can increase operation and maintenance costs, and can also introduce inhibiting compounds to the process.

Table 1: Pretreatment methods and applications [7].

	Technology	Advantages	Disadvantages
1	Feedstock milling	(i) Does not produce any process inhibitors (ii) Increased methane (5%–25%)	(i) High energy requirements (ii) High maintenance cost
2	Feedstock extrusion	(i) Extrusion increases the surface area to volume ratio	(i) Leads to increased energy consumption (ii) Increases equipment maintenance cost
3	Steam pretreatment/ steam explosion	(i) Increased cellulose fiber reactivity (ii) Can make use of process energy/biogas	(i) Risk of producing inhibitors (e.g., furfural and HMF) (ii) Reduces digestible biomass due to lignin condensation (iii) More process energy input and reduced net energy output (iv) Precipitation phenomena
4	Hot water treatment	(i) Solubilized hemicellulose and lignin products are present in lower concentrations (ii) Reduced risk of producing inhibitors like furfural and HMF (iii) Increased enzyme accessibility	(i) High heat demand and hence energy consumption (ii) Not effective at all temperature ranges
5	Microwave	(i) Leads to more biogas production by 4%–7%	(i) Increased process energy input (ii) Increases labor and maintenance cost
6	Diluted or strong acid pretreatment	(i) Used to solubilize hemicellulose component (ii) Methanogens can adapt to inhibiting compounds	(i) Acids are expensive (ii) Can form inhibiting compounds (iii) Causes corrosion problems
7	Alkaline pretreatment	(i) Used to solubilize hemicellulose and some lignin (ii) Increased methane production	(i) Can produce inhibitors (ii) Can cause high alkali concentration in the reactor

2.5.2. Anaerobic Digestion Process

(i) Hydrolysis

Hydrolysis is a chemical process that involves the breakdown of water to form OH-anions and H+ cations. Hydrolysis takes place in the existence of an acidic catalyst to break down large biomass polymers in the substrate [40]. Biomass has large organic polymers in the form of proteins, carbohydrates, and fats, which are broken down into simple sugars, fatty acids, and amino acids which are smaller molecules [40, 87, 90]. During hydrolysis, fermenting bacteria (FB) like bactericides, Clostridia, and bifidobacterial breakdown biopolymers, i.e., carbohydrates, proteins, and lipids into sugar, fatty acids, and amino acids which are soluble [95]. The main products of hydrolysis are acetate and hydrogen which are used in later stages of anaerobic digestions by the action of methanogens. Most hydrolysis products are still large molecules that need further breaking down to create methane through the acidogenesis process [1, 50].

(ii) Acidogenesis

This process involves the creation of mainly organic acids, alcohols, hydrogen gas, and hydrogen sulfide by the anaerobic action of acidogens [40, 95]. Hydrolysis products are broken down by acidogenic microorganisms, in an acidic environment created by the action of the fermentative bacteria to generate ammonia, carbon dioxide, hydrogen sulfide, carbonic acid, and fatty acids with shorter volatility, alcohol, and other trace products based on the substrate composition and products of hydrolysis [95]. The products of acidogenesis are still large and therefore are not ideal for methane production. They are therefore subjected to the acetogenesis process [83].

(iii) Acetogenesis

Acetogenesis creates acetate, which is from acetic acid [74]. The products of acidogenesis are anaerobically digested during acidogenesis to produce acetic acid, hydrogen, and carbon dioxide. The digestion by acetogens is done to a point where methanogens can act on products of acetogenesis as well as some products from other processes to generate methane [83].

(iv) Methanogenesis

In methanogenesis, which is the last stage, methane and carbon dioxide are produced because of the action of acetoclastic methanogens (AM) and carbon dioxide (CO_2) reducing methanogens (CM), respectively. The methanogenesis is finished strictly by anaerobic bacteria known as methanogens like Methanosarcina barkeri, Methanosaeta concilii bacteria, and Methanococcus mazei as the final anaerobic digestion which generates methane by methanogens from the final products of acetogenesis as well as other intermediate products from acidogenesis and hydrolysis processes [40, 79, 95]. The use of carbon dioxide and acetic acid from the first three steps in creating methane in methanogenesis are as follows:

$$\begin{aligned} CO_2 + 4\,H_2 &\longrightarrow CH_4 + 2H_2O \\ CH_3COOH &\longrightarrow CH_4 + CO_2 \end{aligned} \tag{1}$$

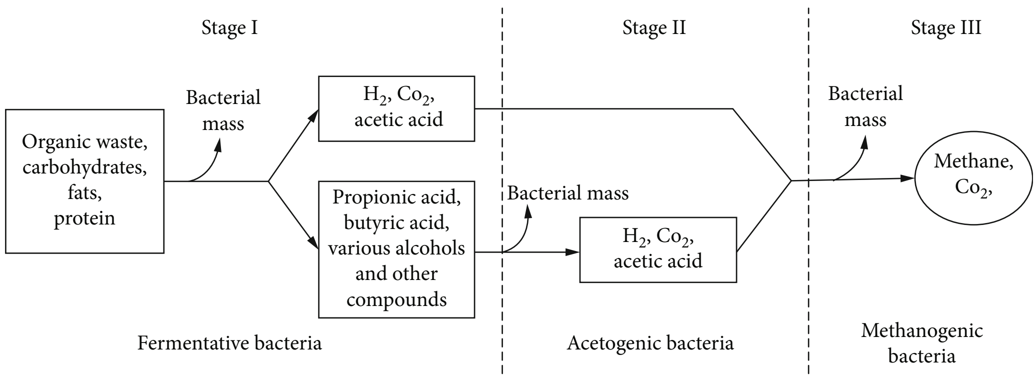

Figure 5: Summary of the biogas formation process [56].

The main methane creation mechanism in this stage is the path involving acetic acid even though carbon dioxide (CO_2) could be converted into water and methane. Hence, through the acetic acid path, CO_2 and methane are created as the main products of anaerobic digestion [83]. Therefore, methanogenesis metabolizes gas mixtures (H_2 and CO_2) into biogas with CH_4 (60–70%) and CO_2 (30–40%) in composition [12]. Figure 5 shows the three stages in biogas production and related activities and bacteria.

Figure 5 summarizes the process into three stages with hydrolysis and acidogenesis combined.

From Figure 5, it is noted that biogas production is divided into three main stages, i.e., stage I which involves the action of fermentative bacteria, stage II which involves the action of acetogenic bacteria, and stage III which involves action by methanogenic bacteria. Proper management of the three stages ensures optimum production of biogas.

2.5.3. Factors Influencing Digester's Efficiency and Performance

(i) Temperature

The application of heat to reactions normally accelerates the process within acceptable limits. This applies to biogas production processes too. The microorganisms in anaerobic digestion are thermophiles which undergo thermophilic and mesophilic digestion. The thermophiles operate efficiently at a temperature range of 45-80°C while mesophilic bacteria work well at a temperature range of 25-40°C [83].

(ii) Digester instrumentation

It is important to constantly measure the production level and parameters in any anaerobic digester to identify biomass quantity, any abnormalities, and the well-being of microorganisms for efficient and optimum process control and hence output [79]. The gasses emitted should indicate how much biomass is not yet broken down and the time to be used. This help in identifying when new biomass should be added and the effectiveness of the digester. In a system where biomass is added continuously, measuring the gas produced helps in ensuring that the microorganisms are at their peak digestive capability [83]. Measuring the gas also indicates any abnormalities in the digester like changes in pH and temperature that will affect the gas production.

(iii) pH

The acid-forming bacteria work best at a PH of about 5 while the methane-forming bacteria flourish at a pH above 6.2 [40]. Generally, the biomethane process bacterial population flourishes over a pH range of 6.5 to 8.0 with an optimum range of 6.8 to 7.2 [96]. Therefore, any deviation from this range makes the digester acidic or basic and hence inhibits methane production. The health of the microorganism is quite crucial in the creation of methane, and hence, a good environment is required for them to live and prosper. Without the microorganism, the digester will not be able to produce the required gas. Hence, this should be measured at all times [74, 97].

(iv) Carbon/nitrogen ratio (C/N ratio)

This is the ratio of total carbon and nitrogen in the substrate. A ratio from 20 to 30 is recommended for anaerobic digestion while a very high ratio of C/N enhances the growth of methanogen population which results in little or no action on the leftover carbon in the substrate leading to low methane production. A too low C/N ratio leads to high ammonia which then becomes toxic for methanogenic bacteria and thus low methane production [74].

(v) Toxicants

Toxicants include antibiotics and other residues which inhibit methanogenesis, hence reducing methane production and instead increasing the concentration of volatile acids. A high nitrogen-to-carbon ratio is more likely to lead to toxic conditions for the bacteria and so should be avoided [40].

(vi) Loading time

The loading rate is the amount of volatile solids fed to the digester per day per unit volume of the digester [40]. High loading rates are desirable for higher methane production.

(vii) Redox conditions

Table 2: Four leading crop residues to GHG emissions in CO_2 gigagram equivalent.

	Crop	Percentage contribution
1	Maize	45
2	Rice	26
3	Wheat	25
4	Sugarcane wastes	4

In the biodigester, the methanogenic bacteria require redox conditions in the range of -300 and -330 mV for optimal performance [98].

2.6. Process Energy Requirements. The biogas production process requires energy input in the form of heat to maintain the temperature within range and regular stirring of the substrate manually by an electric motor-driven stirrer [74]. The heat energy required is given by the formulae.

$$Q_T = M \times C \times (T_2 - T_1), \quad (2)$$

where Q_T is the total heat needed to heat the slurry in Kilojoule (kJ), M is the mass of the slurry in kg, C is the specific heat capacity of slurry and is expressed in kJ/kg°C, T_2 is the desired digester slurry temperature in °C, T_1 is the temperature of the digester charge/slurry in °C, M is the digester size (V) in $m^3 \times$ density of slurry (ρ) kg/m^3, density of slurry (ρ) = (density of water + substrate density dung)/2, and specific heat of slurry = (specific heat of water (4.2 kJ/kg°C) + specific heat of the substrate, e.g., cow dung (2.8 kJ/kg°C)/2 = 3.5 kg/kg°C.

The heat energy required can be obtained by recovery and recycling of waste heat in the digester effluent. This can result in a 2–3°C temperature rise of the slurry at the inlet. This can lead to energy saving of about 50% total heat requirement in thermophilic digesters [31, 99]. For large and medium digesters, external heating is more suitable. It is less efficient than internal heating requiring almost two times the rate of internal heating. Typical values are 850–1000 W/m^2 K^{-1} for external heating and 300–400 W/m^2 K^{-1} for internal heating [99].

Biogas production involves control of technical and economic parameters like microorganism species, feedstock pretreatment and biogas purification processes, substrate composition, substrate properties, and optimal reactor conditions. Cost-effective production of biogas is dependent on optimization of the combination of these parameters. There is a need for further research to improve biogas production and biogas use by use of engineering and biology/biotechnology and technological innovations [7, 100].

3. Biogas Feedstocks

Biogas can be produced from both animal wastes and crop residues. To use biomass in biogas production, the feedstock can be liquid as concentrated or diluted or as solid or slurry form. Common feedstocks include animal manure, agricultural by-products like straw, household biowaste, industrial and commercial waste like waste from markets and restaurants, wastes from bioethanol and biodiesel production, and sewage sludge from wastewater treatment plants, energy like maize, silage, grass, sorghum, cereals, and sugar beet. Although wood is biomass, the high lignin content makes it unsuitable for anaerobic digestion and hence biogas production [101].

A wide range of biomass waste can be used as substrates in the production of biogas. Lignocellulosic waste can be obtained from agricultural waste, municipal waste, and other activities. Typical waste for use as feedstock includes animal manure and slurry, sewage sludge, municipal solid waste, and food waste [7]. Biomass feedstock is made of fats, proteins, carbohydrates, cellulose, and hemicellulose which are necessary ingredients for biogas generation. Cosubstrates were added to modify the organic content for a higher biogas yield. Common cosubstrates are organic wastes from industries, food waste, and municipal biowaste. Although carbohydrates and proteins show faster conversion rates than fats, fats have a significantly higher biogas yield [7]. Therefore, biogas potential and yield vary with feedstock and cosubstrates used and process conditions applied in the production.

3.1. Crop Residues for Biogas. Crop residues are byproducts of crop husbandry that can be put to various uses and applications. These residues can be burnt, composited, biodigested, or processed to useful products like animal feeds among others. Crop residues are huge with India alone producing about 500 Mt (million tons) per year of crop residues [12]. The United States of America generates close to 70 million tons of organic waste annually. These wastes include agricultural crop and livestock waste inedible food and wastewater [41].

On-site burning of crop residues results in CH_4 and N_2O generation which can further be oxidized as well as several greenhouse gas emissions. Among crop residues, the leading contributors to greenhouse gases (in CO_2 equivalent–gigagram) are maize followed by rice, wheat, and sugarcane wastes. Finding alternative uses for these wastes can help mitigate the greenhouse gases and value addition to products like fertilizer [12].

From Table 2, it is noted that the burning of maize residues is the large source of carbon dioxide emissions from combustion of crop residues as a means of waste disposal.

Cellulosic waste like bagasse, energy crops, agricultural residues, and sewage possesses a huge potential for biofuel production. Lignocellulose has three main organic components, namely, cellulose, hemicellulose, and lignin [7]. Cellulose is the main structural component responsible for the mechanical strength of plant cell walls. The hemicellulose macromolecules are made of repeating polymers of pentoses and hexoses. On the other hand, lignin has 3 aromatic alcohols (coniferyl alcohol, sinapyl alcohol, and p-coumaryl alcohol) produced by a biosynthetic process. Lignocellulose composition varies highly based on sources and season. Cellulose is a linearly linked polymer with several β-1,4-glycosidic bonds. The structure is a mix of crystalline structure and amorphous arrangement [7].

Table 3: Gas yield and methane content for different biomass [43].

Substrate	Gas yield (L/kg Vs*)	Methane content (%)
Pig manure	340-550	65-70
Cow manure	90-310	65
Poultry droppings	310-620	60
Wheat straw	200-300	50-60
Rye straw	200-300	59
Barley straw	250-300	59
Oats straw	290-310	59
Corn straw	380-460	59
Flax	360	59
Hemp	360	59
Grass	280-550	70
Elephant grass	430-560	60
Sunflower leaves	300	59
Agricultural waste	310-430	60-70
Fallen leaves	210-290	58
Algae	420-500	63

Crystalline cellulose can be changed to cellulose with a nonorganized structure by heating to a temperature and pressure of 320°C and 25 MPa, respectively. Cellulose constitutes the most abundant organic compound globally and is over 25% of the mass of plants. The hemicellulose component of biomass is a complex and changeable structure made of different polymers like pentoses, e.g., xylose, arabinose, hexoses like mannose, glucose, and galactose, and sugar/uronic acids, e.g., glucuronic, galacturonic, and methylgalacturonic acid. Xylan is the most dominant compound in the hemicellulose arrangement accounting for about 90%, but its actual composition varies with the feedstock type or origin. Hemicellulose needs a wide variety of enzymes to be fully hydrolyzed into free monomers [7]. Hemicellulose has shorter lateral chains, has lower molecular weight compared to cellulose, and consists of many sugars in polymers that are easy to hydrolyze. Hemicellulose increases the compactness of the entire cellulose-hemicellulose-lignin network by forming a linkage between lignin and cellulose molecules. The solubility of hemicellulose compounds depends on the temperature of the environment, i.e., whether it is acidic, neutral, or alkaline but ranges between 150 and 180°C [7, 102–104]

Lignin is a heteropolymer that occurs naturally in the cell wall and consists of three phenylpropane-based units, namely, p-coumaryl alcohol, coniferyl alcohol, and sinapyl alcohol that are held together by linkages. Lignin structure resists microbial attack and oxidative stress. Lignin is also difficult to dissolve in water leading to low degradability for biogas production. Lignin and hemicellulose dissolve in water at a temperature of about 180°C in a neutral environment. Lignin solubility in acidic, neutral, or alkaline environments is a function of the phenylpropane-based unit in its structure. Lignin makes up about 30%–60% of wood, but agricultural residues and grasses have about 5%–30% of lignin. The crops are mainly composed of hemicellulose [104]. The characteristics of lignin like its composition and structure positively affect the hydrolysis process leading to increased biogas generation. However, higher lignin content in feedstock lowers degradation efficiency [7, 104].

3.2. Animal Wastes for Biogas

(1) Dung

If the daily amount of available dung (fresh weight) is known, gas production per day in warm tropical countries will approximately correspond to the following values:

(i) 1 kg cattle dung 40-liter biogas

(ii) 1 kg buffalo dung 30-liter biogas

(iii) 1 kg pig dung 60-liter biogas

(iv) 1 kg chicken droppings 70-liter biogas

(2) Biogas potential of farm animals and humans

Different farm animal dung yields differing quantity biogas which can be estimated based on the live weight of the animals. The daily gas production can be estimated as follows:

(i) Cattle, buffalo, and chicken: 1.5 liters of biogas per day per 1 kg live weight

(ii) Pigs and humans: 30-liter biogas per day per 1 kg weight [43]

Some additional facts are as follows:

(i) Each kilogram of biodegradable material yields 0.4 m^3 (400 liters) of gas

(ii) Gas lights consume around 0.1 m^3(100 liters) of gas in one hour [56]

Table 3 shows gas yields and methane contents for various substrates at the end of a 10-20 day retention time at a process temperature of roughly 30°C [43, 56].

From Table 3, it is demonstrated that the various biodegradable biomass from different plant material has different biogas potential both in terms of quantity and quality. Biogas with the highest methane content from Table 3 comes from algae, cow manure, pig manure, agricultural solid wastes, and grass, among others. In terms of quantity of biogas produced, the highest yield can be gotten from algae, sugar beet, elephant grass, sewage sludge, clover, elephant grass, and corn straw giving the highest yield of biogas. The lowest biogas yield is gotten from rice seed straw, sugarcane bagasse, rice seed coat, and reed [23, 82, 94, 105, 106]. Therefore, optimum biogas production calls for careful selection of biomass feedstock and hence what crops to grow or what mix of crops and livestock to have on his farm for maximum biogas production [79].

3.3. Estimation of Biogas Potential. According to [79, 107], biogas can be converted into heat whose value can be estimated by the following equation:

$$E_{pi} = E_m^{cd} \times \eta_i, \quad (3)$$

where E_{pi} is the production of the energy (heat only, electricity only, or heat and electricity in cogeneration) (GWh/year), η_i is the efficiency of energy conversion process, and $E_{pi} = E_m^{cd} \times \eta_i$ is the possible production of total biogas energy

The calculation of total biogas energy potential from livestock manure is based on the following equation:

$$E_{\mathrm{m}} = \sum (N_{\mathrm{i.n}} \times M_{\mathrm{i.n}} \times \mathrm{ODM}_{\mathrm{i.n}} \times \mathrm{CH}_{4\mathrm{i.n}}) \times \mathrm{NCV} \times 365 \times 10^{-6}, \quad (4)$$

where E_{m} is the expected production from livestock manure available in the region (GWh/year), $N_{\mathrm{i.n}}$ is the animal of the same category (cattle, pigs, poultry, etc.) in the region (number of animals, $M_{\mathrm{i.n}}$ is the manure outcome of each category of animals (kg of manure/animal/day), $\mathrm{ODM}_{\mathrm{i.n}}$ is the organic dry matter content in the manure for each category of animals (%), $\mathrm{CH}_{4\mathrm{i.n}}$ is the methane outcome (Nm^3 CH_4/kg organic dry weight of the animal manure), and NCV is the net calorific value (kWh/Nm^3).

3.4. Electricity Potential of Biomass. Table 4 shows the biogas and electricity potential of different biomass waste. The conversion is based on 35% electrical efficiency of combined heat power, heating value of 21 MJ m^{-3}, 55% methane content, and 3.6 MJ·(kW h)$^{-1}$ [7]. From Table 4, it is noted that fat gives the highest biogas yield and has the largest biogas and electricity potential followed by maize silage, chicken droppings, and disinfected food waste, respectively.

Table 4: Comparison of biogas yield and electricity produced from different potential substrates [7, 100].

	Type	Biogas yield per ton of fresh matter (m^3)	Electricity produced per ton of fresh matter (kW h)
1	Cattle dung	55–68	122.5
2	Chicken litter/dung	126	257.3
3	Fat	826–1200	1687.4
4	Food waste (disinfected)	110	224.6
5	Fruit wastes	74	151.6
6	Horse manure	56	114.3
7	Maize silage	200/220	409.6
8	Municipal solid waste	101.5	207.2
9	Pig slurry	11–25	23.5
10	Sewage sludge	47	96.0

3.5. Biogas Production and Fertilizer Application. The composition of the feedstock as well as process control influences the quality and composition of the products of anaerobic digestion in terms of biogas yield, biogas quality, state of digestate, and stability of biogas plants and operations [108]. The sludge from anaerobic digestion can be used as an organic fertilizer [30]. The use of biodigester slurry is good for soil fertility and productivity improvement leading to a 10-20% increase in crop yield. For farms without irrigation, application of 5 tons of the digestate is recommended per hectare, while for farms under irrigation, about 10 tons per hectare is recommended [109]. Upon extraction of biogas and other waste material of anaerobic digestion, the resulting sludge can be used as a fertilizer, supporting general soil quality, increasing crop yield, and hence contributing to sustainable agriculture and development [56].

The composition of the biodigester substrate and digestate varies in composition and nutrient content based on the process effectiveness and feedstock composition. The substrate or digestate can be spray applied to the farm or can be used as bedding material for the livestock with little processing [41]. The direct application of digester slurry is 25% more effective as a fertilizer compared to adding manure to the farm directly. This implies that direct application of digestate increases farm productivity. Since biogas slurry is better decomposed, the nutrients needed by plants can be attained with ease as compared to direct manure application [18, 19, 56].

In addition to the high nutritive value, biodigester slurry does not have negative environmental effects like the chemical fertilizers do. The digestate can be applied to the farm directly by using it as a foliar fertilizer by mixing it with water and then applying it to appropriate leaves. The slurry may be collected from the digester through a ditch which is fed as the biogas plant is recharged with fresh feedstock and the pressure of building gas. For proper functioning, the biodigester operator should empty the ditch from time to time to avoid overflow as well as back pressure which ensures efficient and proper system operation [110].

Digestate byproduct is composed of water and undigested organic and inorganic materials from the feedstock and cosubstrates fed to the digester. It is necessary to ensure proper treatment and management of digestate as part of biogas production control and management. Digestate may be discharged to a storage tank or a lagoon, and land applied on crops in agricultural farms. The biogas plant effluent would contain significant coarse fiber if feedstock and cosubstrates are not screened before digestion and will also lead to a slow rate of biodigestion and lower gas yields. The isolated solids from screening process may be used as bedding material or soil amendment. Upon removal of fiber, the main digestion product is a liquid organic substance known as filtrate. The filtrate from manure contains nitrogen, phosphorus, and potassium in percentages ranging from 3% to 4.5% on dry matter basis. This filtrate can be spread directly onto farmland to provide nutrients [18, 19].

The filtrate can be further processed into a liquid material called concentrate and a solid product called filter cake. This is critical when wastes from offsite sources are being incorporated into the digester influent. These wastes may contain significant concentrations of the primary plant nutrients nitrogen, phosphorus, and potassium. Thus, the impact on the ultimate disposal site's comprehensive nutrient management plan must be considered. Nutrient recovery technologies help manage the amount of nutrients in the digestate [111].

Table 5: Average composition of biogas [16, 33, 40, 56, 114].

	Element	Composition (%)
1	Methane	30-80%
2	Carbon dioxide	20-45%
3	Nitrogen	1-10%
4	Ammonia	0-0.05%
5	Moisture	2-8%
6	Hydrogen	0-3%
7	Hydrogen sulfide	0.1-0.5%
8	Oxygen	0.1-3%
9	Ammonia	0-0.5%
10	R_2SiO	0-0.5 mg/m^3
11	C_xH_y	0-1%

Therefore, biogas production can be a cost-effective option to the expensive chemical fertilizers and is part and parcel of sustainable development through improvement in agricultural production and yields and savings to farmers besides supplying them with renewable and sustainable energy resources. The digestate or filtrate can also be sold for extra revenue to farmers [18, 19, 63, 105].

4. Composition and Energy Potential of Biogas

Biogas is a mixture of gases with methane and carbon dioxide being the main constituents. Others are carbon monoxide, hydrogen sulfide, hydrogen gas, moisture, and siloxanes. The combustible constituents are carbon monoxide, hydrogen, and methane which produce heat for various thermal and electricity applications [67]. The exact composition of biogas varies from feedstock to feedstock and the quality of the process control applied. However, biogas mainly consists of methane (CH_4) and carbon dioxide (CO_2) [33]. Pure methane is an odorless gas made up of one atom of carbon and 4 atoms of hydrogen. Methane is lighter than air and is highly flammable. It can form explosive mixtures with air at concentrations of 5 to 15%. Although methane is not toxic, it can cause death due to asphyxiation through oxygen displacement in confined environments. Methane is a powerful greenhouse gas having the ability to remain in the atmosphere for up to 15 years and is close to 20 times more potent in trapping heat in the atmosphere than carbon dioxide for a timescale of 20 years [111, 112]. This shows that uncontrolled biogas production and handling is very dangerous to the environment and effort should be made to have controlled biodegradation of organic wastes for production of biogas energy resources.

Biogas can be used as a fuel or as a raw material for production of chemicals, hydrogen, and/or synthesis gas, etc. Other than methane and carbon dioxide as the main constituents of biogas, common contaminants present as trace elements include ammonia (NH_3), moisture, hydrogen sulfide (H_2S), nitrogen (N_2), methyl siloxanes, oxygen, halogenated volatile organic compounds (VOCs), hydrocarbons, and carbon monoxide (CO). Some of the trace elements significantly affect biogas as fuel and must be removed for quality purposes. They include hydrogen sulfide and carbon dioxide. As a fuel, biogas in form of biomethane, biogas upgrading has high operating costs and energy consumption which needs to be addressed [113].

Biogas is a mixture of several gases mainly 50-80% methane, 20-45% carbon dioxide, 2-8% water vapor, effluent, and trace gases consisting mainly of O_2, N_2, NH_3, H_2, and H_2S [40, 43]. Table 5 shows the average composition of biogas.

From Table 5, it is noted that methane and carbon dioxide is the main constituent of biogas, and its composition generally varies from 30 to 80% based on the quality of the feedstock and process control.

The main determinant of the heating value of biogas is the composition of methane in biogas. The composition of methane in biogas varies from 45% to 75% by volume [115]. This variation implies that the lower heating value (LHV) of biogas is not constant but varies between 16 MJ/m^3 and 28 MJ/m^3. Biogas can be used directly to produce electricity and or can be combusted to release heat energy for cooking to perform some work as in internal combustion engines. The following are general requirements of biogas engine fuel:

(i) Should have high methane content

(ii) Water and CO_2 composition should be as low as possible for high caloric value

(iii) The sulfur content should be as low since it is converted to acids by condensation and combustion and causes corrosion

The moisture content can be reduced by condensation in the gas storage or along the gas path while hydrogen sulfide (H_2S) content can be reduced by chemical, biological, or physical techniques [29, 43]. The calorific value of biogas is 5000 to 7000 kcal/m^3 and is a function of methane concentration. Generally, one cubic meter of biogas is the equivalent of 0.7 m^3 of natural gas, 0.7 kg of fuel oil, 0.6 kg of kerosene, 0.4 kg of petrol, 3.5 kg of wood, 12 kg of manure briquettes, 4 kWh of electrical energy, 0.5 kg of carbon, and 0.43 kg of butane [116, 117].

At 0.1013 MPa and 273 K, biogas has the following properties for 60% methane and 40% carbon dioxide composition summarized in Table 6.

From Table 6, it is noted that biogas has a molar mass of 16.04 and specific heat capacity of 2.165 kJ/kgK and ignition temperature of 650 to 750°C.

Biogas has got thermodynamic properties comparable with other known fuels. Although biogas has slightly inferior thermal properties compared to fossil fuels, it is an attractive fuel because of its environmental benefits [60, 118, 119]. In Table 7, the biogas equivalent to different fuels is provided.

From Table 7, it is noted that biogas has less energy content than fossil fuels, it has more energy value than manure briquettes, and its use can substitute fossil fuels and limit forest destruction for fuel.

4.1. Fuel Quality Management. Various methods can be used to improve biogas fuel quality for use in power generation.

Table 6: Biogas properties [43, 75, 116].

	Property	Symbol	Value
1	Specific heat capacity	Cp	2.165 kJ/kgK
2	Molar mass	M	16.04
3	Gas constant	R	0.518 kJ/kg
4	Normal density	g	1.2 g/L
5	Critical density	g_c	320 g/L
6	Relative (to air) density	g_r	0.83
7	calorific value of biogas	LCV	22.6 MJ/m^3
8	Critical temperature	T	-2.5°C
9	Critical pressure	p	7.3-8.9 MPa
10	Flammability limit content in air	v	6-12%
11	Ignition temperature	T	650-750°C

Biogas production can be optimized by ensuring a steady fermentation process through a continuous supply of feedstock of correct quality and digestion under optimum conditions of C/N ratio, PH, dilution, and digester temperature. Hydrogen sulfide (H_2S) can be oxidized by injection of a small amount of oxygen or air into the storage fermenter headspace for oxidation of H_2S by microorganisms and hence the elimination of a considerable part of the sulfur from the gaseous phase. This method is the cheapest and most common desulfurizing method used to eliminate as much as 95% of the sulfur from biogas [7].

The second method used is external chemical treatment, which is a filtration process that can be done using iron hydroxide and activated carbon. The use of iron hydroxide is a reversible process in which filter regeneration can be done by oxygen addition. Alternatively, adsorption materials like iron-rich soils and waste material from steel or aluminum production can be used. The governing equation is given by $Fe(OH)_2 + H_2S - >FeS + 2\,H_2O$. Activated carbon use carbon filters as standard components, which are provided for the system [19, 43].

4.2. Biomethane. Biogas is composed of some undesirable contaminants mainly in form of CO_2 and H_2S from the production stream which can be removed by biogas upgrading [120]. All regions of the world have significant potential to produce biogas and/or biomethane, and the potential is set to grow as available sustainable feedstocks are projected to grow by about 40% over the period to 2040 [3, 21]. Biomethane is often referred to as "renewable natural gas" and is taken as a renewable source of methane. Biomethane can be made by upgrading biogas through the removal of carbon dioxide, and other constituents of biogas can also be made by gasification of solid biomass then followed by methanation to increase methane composition to greater than 90% [21, 106]. Biomethane can be used as a substitute for natural gas and can also be used as transportation fuel leading to emission reduction of 60-80% depending on the type of feedstock used in biogas production. Higher emission reduction potential is realized when waste and residues are used for biogas production [4, 121].

4.2.1. Upgrading Biogas. This process accounts for about 90% of total biomethane produced globally. Upgrading processes apply process techniques to remove the biogas impurities, mainly carbon dioxide. The most common processes are water scrubbing and membrane separation which combined account for about 60% of global biomethane production [115, 122]. Biogas upgrading provides an alternative avenue for CO_2 sequestration by increasing biogas utility for use in commercial conversion technologies [123]. Conventional upgrading processes are cumbersome and energy-intensive upgrading technologies [124]. These technologies can be substituted with photosynthetic microalgae which use the carbon dioxide in biogas to produce value-added products resulting in the upgrading of biogas to attain the energy-rich biomethane quality [120].

4.2.2. Thermal Gasification of Solid Biomass Followed by Methanation. In this process, high temperatures between 700 and 800°C are used to break down solid biomass at high pressure in an oxygen-deficient environment. This process converts biomass into a mixture of gases, consisting of CO_2, H_2, and CH_4 often collectively called syngas [94, 125]. Syngas is cleaned to remove corrosive and acidic constituents. Then, by use of catalysts, methanation is done by reaction between H_2 and CO or CO_2 to produce methane. Any remaining CO_2 or water is removed at the end of this process. Biomethane gas has a lower calorific value (LCV) of about 36 MJ/m^3. This gas is fully compatible for use in natural gas vehicles [21]. Figure 6 shows the various biogas/biomethane to heat and power pathways.

From Figure 6, it is noted that gases are produced through thermal gasification process but must be further treated to form biomethane.

Biomethane is a gas produced by any process that improves the quality of biogas through reduction of CO_2 H_2S, H_2O, and other contaminant gases [18, 19, 127]. The refined biogas has a high methane content of at least 90%, but normally 96% to 99% and low share of impurities [101]. Biomethane is chemically the same as methane and is derived from the method of production rather than the gas content [42]. Biomethane plants are generally found in areas close to agricultural farms or food processing plants. Biomethane installation may also be associated with downstream applications like gas storage and transportation, home heating, and cooking connections, industrial use, and distribution through small-scale local natural gas pipeline grids. Therefore, biomethane is a gas that results from any process that improves the quality of biogas by reducing the levels of carbon dioxide, hydrogen sulfide, moisture, and other contaminant gases. Chemically, biomethane is the same as methane, and its name refers to the method of production rather than the content [42, 92].

Biomethane has properties that are equivalent to methane or natural gas, so it can be used directly as a fuel for vehicles. Can be injected in the natural gas grid mains and can also be used in power plants for power generation. Upgrading biogas to biomethane consumes about 20% of the biogas energy using existing conversion technologies mainly in compression. As a clean fuel, biomethane can mitigate

Table 7: Energy equivalents of biogas [43, 75, 116].

	Alternative fuel	Biogas equivalent	Remarks
1	1 kg of firewood	0.29 m^3	Biogas can be used to avoid deforestation
2	1 kg of dried cow dung	0.1 m^3	Biogas has more energy value than dry cow dung
3	1 kg charcoal	0.5 m^3 biogas	Biogas use limits forest destruction
4	1 liter of kerosene	2.0 m^3	Biogas can limit fossil fuel dependence and use
7	1 m^3 of natural gas	1.43 m^3 of biogas	Has lower energy content, may need purification
8	1 kg of petrol	2.5 m^3 of biogas	Has less energy content than petrol
9	1 kWh of electricity	0.25 m^3 of biogas	Biogas can substitute grid electricity use
10	1 kg of fuel oil	1.42 m^3 of biogas	Has lower energy content than fuel oil
11	1 kg of carbon	2.33 m^3 of biogas	Carbon has higher energy value than biogas
12	1 kg of manure briquette	0.083 m^3 of biogas	Biogas has more energy value

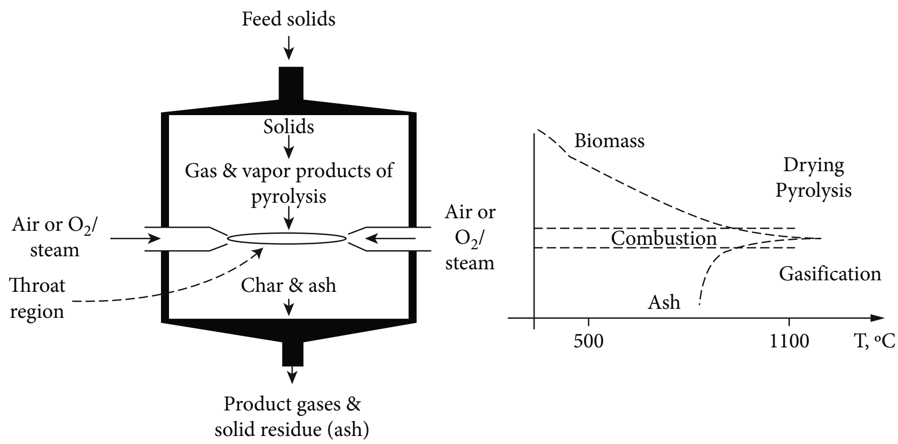

Figure 6: Thermal gasification of biomass [21, 126].

environmental pollution as a substitute to natural gas [92]. The well-to-wheel greenhouse emissions from biomethane and other fossil fuels is shown in Table 8.

From Table 8, it can be deduced that biomethane has the least environmental impact when used as a fuel substitute for fossil fuels, namely, petrol, diesel, and natural gas. From Table 9, it is noted that there are four established methods for biomethane production which are membrane separation (MS), water scrubbing (WS), chemical absorption with amine (CA), and pressure swing adsorption (PSA) technology. The table does not, however, include biological methods, namely, biological separation via hydrogenotrophic methanogenesis consisting of hydrogenotrophic-methanogens to convert carbon dioxide and hydrogen to methane which have limited application.

4.2.3. Production and Properties of Biomethane. Refined natural gas (RNG) or biomethane is biogas that has been processed further to remove carbon dioxide (CO_2), moisture (H_2O), and other trace gases to give it the quality and properties of natural gas. This gas can be used directly as a fuel, liquefied, or fed to the natural gas pipelines for consumption. About 26% of the US electricity is derived from natural gas while 40% of all-natural gas consumed is used in power generation. The potential of biogas is significant and can replace up to 10% of the US natural gas [41]. As evidence of the growing popularity of biomethane, the number of upgrading plants in Europe increased from 187 in 2011 to 435 in 2015 [41, 92].

Biomethane has superior properties like methane, and so it can be used as vehicle fuel directly or be injected into the natural gas grid. Alternatively, biomethane can be or be used in combined heat and power. However, the challenge with

Table 8: Well-to-wheel (WTW) GHG emissions in gCO_2eq/km [92].

	Fuel type	WTW emissions gCO_2eq/km	Remarks
1	Petrol	164	Has high environmental impact
2	Diesel	156	Cleaner than petrol
3	CNC	124	Cleaner than petrol and diesel
4	Bio-CNG (20%)	100	Less impact than natural gas
5	Bio-CNG (100%)	5	Least impact

Table 9: Summary of the various methods used in biomethane production.

	Methods	Process description and performance
1	Membrane separation (MS)	Membrane separation uses membranes in form of hollow fiber bundles made of polymeric materials like polysulfone, polydimethylsiloxane, and polyimide or incorporated in a stainless-steel tube. The materials used are permeable to carbon dioxide (CO_2), moisture (H_2O), and ammonia (NH_3) but are less permeable to oxygen (O_2) and hydrogen sulfide (H_2S) but less permeable to methane (CH_4)and nitrogen (N_2). A flow called "permeate" mainly composed of CO_2, H_2O, NH_3, and other residues penetrates the micropore, but CH_4-rich gas (called "retentate") passes through the membranes without removal. A set of multiple modules are used to provide sufficient surface area [131].
2	Water scrubbing (WS)	Water scrubbing is based on different solubility of carbon dioxide in water with respect to that of methane. Based on Henry's law, carbon dioxide has got 26 times higher solubility than methane in water at 25°C. Raw biogas is first passed through a scrubber to remove hydrogen sulfide, utilizing the same type and amount of desulfurization solvent utilized for the membrane unit. The desulfurized biogas is compressed to 4–6.5 bar and passed through a washing column from the bottom, where it meets water injected from the top leading to absorption of carbon dioxide by water as methane from the top of the washing column. The methane is dried before refining by means of an activated carbon filter which removes traces of VOCs. The water living in the scrubber is rich in CO_2 and has 5–6% methane content in the compressed biogas. The water with methane and CO_2 is taken to a flash column where the pressure drops to 2–4 bar to facilitate methane separation. Upon methane separation, the water is taken to a stripping column for removal of CO_2, before it can be reused. Water scrubbing technology has CO_2 removal efficiency greater than 98% with methane slip from 1 to 2%.
3	Chemical absorption (CA) with amine solvent	This is a variant the scrubber techniques, since it uses organic amines as solvent, such as monoethanolamine (MEA), diethanolamine (DEA), methyldiethanolamine (MDEA), and diglycolamine (DGA). Its operating principle is like water scrubbing using amine. Using amine which is more selective in absorbing CO_2 with respect to water, hence more CO_2 per unit volume is removed, hence requiring smaller upgrading units in size [131]. However, the process requires some amount of thermal energy for amine regeneration inside the stripper, and amine solvent make-up to avoid loss of process efficiency [131]. In this process, raw biogas is desulfurized and fed to the absorber where it meets the amine solvent (MEA), which absorbs CO_2 from biogas in an exothermic reaction that increases the temperature of the amine solvent. Biomethane then exits from the top of the and supplied to the refining phase followed by final compression. The "rich" amine solvent now has CO_2 contents heated in a heat exchanger, using heat from the "lean" amine solvent living in the stripping column, and is directed to the absorber before being fed to the stripper. The gas is heated in the re-boiler before before the stripping reaction. After the makeup phase, CO_2-free amine solvent is sent to the heat exchanger. Traces of steam and amine solvent are removed from the off-gas and recirculated to the stripping column with the remaining portion which is mainly CO_2 being released to the atmosphere. The CA technology allows the highest methane recovery because of its low methane slip of (up to 0.04%[131].
4	Pressure swing adsorption (PSA) technology	This method makes use of the ability of a porous adsorbent medium to adsorb molecules out of a gas mixture and release them based on pressure applied released by applying different values of pressure. The technique takes advantage molecular dimensional differences of CO_2 (0.34 nm) and CH_4 (0.38 nm). An adsorbent material having cavities of 0.37 nm retains CO_2 in the pores and allows CH_4 to flow. The most used adsorbent materials are zeolites and activated carbons as they are more efficient. The process starts with a pretreatment phase using activated carbon for removal of H_2S and drying to remove water, before compressing about 4 bar and fed to PSA unit which has four columns in series (Skarstrom cycle), packed with zeolites as adsorbent material. Compressed biogas is fed in a column where CO_2 is adsorbed by the adsorbent material with methane passing through. In the second column, pressure drop enables CO_2 desorption; in the third phase, the column is cleaned from residual CO_2 injecting a part of biomethane, and in the fourth phase, the gas is repressurized. The residual VOCs are removed in another activated carbon filter followed by compression of biomethane to about 24 bars. The zeolite must be replaced after some time. The pressure swing adsorption technology has the lowest efficiency with methane slip varying from 1.8% to 2%.

From Table 9, it is noted that there are four established methods for biomethane production which are membrane separation (MS), water scrubbing (WS), chemical adsorption with amine (CA), and pressure swing adsorption (PSA) technology.

biomethanation is that current technologies can consume up to 20% of biogas energy for upgrading and compression. Biogas and biomethane can help in the management of environmental pollution by providing as an alternative to the consumption of natural gas. Commercialization of small-scale plants for biogas enrichment is feasible but may often require state subsidies and incentives for strategic reasons [92]. Carbon dioxide is removed from biogas by means of pressure swing adsorption (PSA) process, chemical (amine) scrubbing, or a spray tower or membrane separation. Moisture can be removed by refrigerated drying and media adsorption processes. Hydrogen sulfide is removed by media adsorption chemical scrubbing and biological scrubbing while siloxane is removed by media adsorption and pressure swing adsorption [111]. The cost of a biogas system is a function of the type of feedstock processed and the size of the plant size, but the investment in biomethanation is a function of the refining technology adopted and the capacity of the processing facility [92].

4.2.4. Application of Biomethane. Biomethane has superior properties compared to biogas and is an attractive substitute to natural gas. It has both industrial and domestic applications like use as cooking gas; cogeneration can be packed in containers/cylinders as compressed biomethane and can be injected to natural gas mains for distribution [18, 19]. The main challenge is the cost of processing which is a function of technology used. Bio-CNG is a methane-rich compressed fuel in form of biomethane [3, 105]. Bio-CNG is made from pure biogas with more than 97% methane composition pressurized to 20–25 MPa. Compressed Bio-CNG is similar in properties to regular CNG in terms of its fuel properties, economy, engine performance, and emissions. Like regular CNG, Bio-CNG has high octane number and yields high thermal efficiency. It can therefore substitute the regular compressed natural gas in gas pipelines and other applications including fuel for natural gas powerplants [3, 95].

4.2.5. Energy Production Potential of Biogas Fuel. Feedstock needed for biogas production is widely available in huge quantities in many rural-based households and institutions. Therefore, biogas energy resources are a guarantee of energy security as the resources are locally available [128]. Therefore, with the decentralized generation, many small- and medium-size biogas units can be developed to sustainably supply electricity to the grid besides other energy applications like eating, cooking, cooling, and refrigeration. As demonstrated by Germany, it is possible for farmers and institutional investors to provide a significant contribution to national electricity grids besides meeting their own electricity demand. Since the average calorific value of biogas of 21-23.5 MJ/m^3, 1 m^3 of biogas is equivalent to 0.5-0.6 liters of diesel fuel or 6 kWh of electric energy. However, the low average conversion efficiency of many small biogases to electricity systems gives an average of 1.7 kWh/m^3. For more efficient larger biogas conversion systems, the average electricity potential is 10-100 kW/m^3 [7, 43]. A biogas-fueled generator can be used to generate enough electricity to meet local demand and excess for sale to the public, or local electricity grids will be required to generate electricity and cater for the day-to-day electricity requirement by the household [79, 128].

4.2.6. Challenges of Biomethane. The existence of contaminants in biogas is a challenge smooth integration of biomethane to the natural gas infrastructure causing some resistance to the injection of biomethane into pipelines [129]. Besides methane (CH_4) raw biogas contains carbon dioxide (CO_2), oxygen (O_2), nitrogen (N_2), water vapor (H_2O), and corrosive elements like hydrogen sulfide (H_2S), mercaptan sulfur, and sulfur (S) and siloxanes which generate concerns for natural gas suppliers. Siloxanes can be converted into silicon dioxide (SiO_2), when combusted and can damage engines, turbines, and fuel cells [18, 66, 129, 130].

Biogas may also contain pathogens, bacteria, and substances that can harm people and the environment [3, 66]. Another limitation of biomethane injection to natural gas systems is that the production of biogas can significantly fluctuate due to changes in environmental and digestion parameters like feedstock quality, humidity, temperature, and seasonal variations, and this can cause supply challenges to small gas distribution systems thus limiting economic viability of the gas supply systems [66, 128].

4.2.7. Upgrading Methods. Various techniques are available in the market for upgrading biogas to biomethane. They include membrane separation, chemical absorption, water scrubbing, and pressure swing adsorption which are well-developed techniques. Methods still under development include organic physical scrubbing, cryogenic separation technologies, hot potassium carbonate, and biological method [131].

The total life cycle costs are negative varying from −203 €/FU to −210 €/FU for PSA and MS, respectively. This shows that biomethane revenues and diesel-avoided costs are greater than direct and indirect costs. Therefore, the biogas-to-biomethane upgrading stage gives life cycle saving of greater than 1764 k€/y, and the difference between the analyzed techniques can reach 60 k€/y. The contributions of the investment costs vary from 11 €/FU to 16 €/FU for PSA and WS, and maintenance costs vary from 26 €/FU to 33 €/FU for WS and PSA, respectively. Comparison of the conversion technical lower has a difference of less than 4% and hence is not significant [131]. The pressure swing adsorption has the worst performance due to activated carbon and zeolite consumption [3, 131].

Studies have shown that all the major biomethane production methods are fully sustainable with membrane separation technique yielding the best performances but not so much different from other techniques of biomethane production from biogas [131].

5. Biogas to Electricity Conversion Technology

Biogas is mainly used in direct combustion applications in cooking stoves and gas lamps. Its use in electricity production is not quite common although it is slowly becoming standard practice in a number of developed countries like Germany [43]. A study modeled on a 50 kW biogas powerplant plant by German GTZ experts in Kenya for medium and large plants (>50 kW) showed that the average payback period based on price electricity tariff price of 0.15 US$/kWh is about 6 years under very favorable conditions, and about 9 years for unfavorable conditions. Further studies based on scenarios for other developing countries in Africa showed that biogas grid-connected electricity generation is not economically viable for small biogas plants [43, 110] [43, 77]. Therefore, for many smallholders and medium-scale grid-connected biogas plants, governments should provide incentives in form of attractive feed-in tariffs and other technical and financial incentives including technical support [26, 32].

Therefore, based on available studies, biogas power plants are not commercially viable without subsidies or guaranteed high prices or fed in tariffs of about 0.20 US$/kWh for the generated electricity from biogas power plants that is sold to the grid. It is only through guaranteed feed-in tariffs that biogas power generation has developed in Germany and other industrialized countries. Of concern is that almost all known biogas power plants in developing countries rely on financial support from international donors and financial which is evidence of doubtful economic and financial feasibility [43].

The first engines were gas-fired Otto cycle engines. Biogas has been an issue or subject as a fuel for vehicles since the 1950s. Today, the use of processed biogas or biomethane as a fuel for engines is a significant development [75]. Electricity generation from biogas is feasible using engines and turbines as well as conversion to energy careers like fuel cells [43, 75]. Prime movers for power generation should be easy to operate and have high reliability and low cost per unit output and low investment cost [73, 132].

Diesel engines can run on gas in various forms such as natural gas, biomethane, gas from dumpsites, gas from dumpsites, gas from sewage, biogas of various quality, carbon monoxide, and various other types of combustible gases [75]. Diesel engines would perform efficiently whether using pure diesel or when running in dual fuel mode as long as the calorific value of fuel is controlled [75, 133].

Electricity from whichever source should be reliable, affordable, and produced in an environmentally benign manner [43, 52, 73, 134]. To realize this, the following guiding principles should be followed:

(i) Excess electricity should be stored or sold to the grid

(ii) Excess biogas should be stored or used in the generation of exportable power

(iii) In case of grid connection, buy from the grid during off-grid and sell during peak power demand

(iv) Have more than one generation units sized to meet various loads, e.g., for your own variable load and exportable load to avoid over- and undersizing which affects the efficiency and performance of the engines

(v) Avoid designs that use fossil fuel, i.e., diesel and petrol unless it is not technically feasible to reduce on the cost of generation [75].

5.1. Conversion with Fuel Cells

5.1.1. Fuel Cell Concepts. Fuel cells convert chemical energy in fuel efficiently to electricity without combustion, with low emissions compared to conventional equipment/techniques. It is therefore a fuel cell defined as an electrical chemical device that directly converts chemical energy to electricity. The three main parts of a fuel cell assemble are the anode, cathode, and electrolyte. A catalyst oxidizes fuel with ions traveling via the electrolyte. At the cathode, ions are reunited with the electrons. It is the electrons produced at the cathode that generate electrons which make the electrical circuit [135]. Fuel cell development partially focuses on the optimization of the catalytic layer of the catalytic electrodes and involves reducing metal without appreciable loss of the fuel cell performance [136]. For fuel cells, power supply is uninterrupted during fuel supply and the oxidant, unlike a battery which relies on stored energy and is affected by the amount of reagent available. The theoretical thermodynamic efficiency of fuel cells is about 90% while in thermal engines, the efficiency is about 40% for optimum conditions. However, practical fuel cell efficiency is usually less than 60% [136].

5.1.2. Types of Fuel Cells

(i) PEM fuel cell (PEMFC)

The proton exchange membrane fuel cells are equipped with a polymer electrolyte and have an efficiency range of 40-50%. They operate at a temperature of about 80°C and therefore can be referred to as low-temperature cells. Because they are ideal for use in homes and vehicles, the fuel for proton exchange fuel cells needs to be purified while the catalyst used is normally platinum, which increases the cost.

(ii) Molten oxide fuel cell (MOFC)

The electrolyte in these fuel cells uses salt components same as sodium or magnesium, and carbonates. Their efficiency varies between 60 and 80% and has a working temperature of about 600-700°C. So far, molten oxide fuel cells with a capacity of up to 2 (MW) have been developed. The main challenge is that the increase in temperature is limited as it leads to carbon monoxide (CO) poisoning which halts its operations.

(iii) Solid oxide fuel cell (SOFC)

The solid oxide fuel cells use a ceramic compound of metal like calcium or oxides as the cell electrolyte. They operate with efficiency of about 60 percent, and operating temperatures of 1000°C [3]. Fuel cells are the cleanest energy conversion systems but are limited by high investment costs compared to other energy conversion systems like gas turbines and internal combustion engines. They also operate at high operating temperatures which further limits their applications, especially in automotive and domestic applications except for the proton exchange membrane fuel cells. The fuel cells also have high conversion efficiencies compared to conventional thermal conversion systems making them more competitive and attractive for long-term investments. The fuel cells have a wide range of applications and markets, with main limitations being size or weight and temperature for domestic and automotive use [136].

5.1.3. Internal Reforming of Biogas in Fuel Cells. The technology to convert hydrogen to electrical energy is developed and close to commercialization, but parallel attempts for the direct use of biogas in fuel cells by internal reforming are also promising. This is feasible in high-temperature fuel cells like solid oxide fuel cell (SOFC) and molten oxide fuel cell (MOFC) because they have a higher capacity to thermally integrate internal reforming and higher tolerance against contaminants while maintaining electrical efficiency close to 50% which is attractive [136]. The main limitation of the internal reforming process for biogas is the generation of carbon monoxide (CO) poison which poisons the fuel cell for concentrations of 50 ppm and higher. Other challenges of biogas reforming are the variability of biogas quality and the poisoning of fuel cell catalysts by carbon deposition (coke) by CO disproportionation as well as the presence of sulfur traces [136]. Coke formation inhibits catalyst activity and blocks the pores leading to structural destruction destroying their structure. This carbon deposition can be reduced by the addition of promoters like Sn, Li, Ru, Mo, Ca, Mg Sr, Ru, Ce, Rh, Pt, and Pd at the anode [3, 136]. Sulfur causes a substantial decrease in the process of conversion to hydrogen because of strong sulfur chemisorption on the surface and within particles of the electrodic catalyst; hence, the removal of sulfur is important. Poisoning is partially reversible but it limits conversion due to a slow desorption process [136]. Additionally, temperature gradients from endothermic reforming reactions cause destruction of the electrolyte an effect that can be reduced by addition of air to the biogas which prevents coke formation and also removes the high-temperature gradient due to exothermic reactions of methane [18, 19, 22, 64, 136].

Fuel cells using biogas offer a pathway to renewable and low carbon grid electricity generation [137]. Biogas can directly be converted into electricity using fuel cells. The main challenge with biogas fuel cells is that they need a very clean gas and the system is quite expensive and is currently still research and development stage [43]. Through steam reforming of biogas, "green" hydrogen can be produced which is hydrogen with oxygen from air to produce electricity water vapor and heat. Fuel cells have wide application in cogeneration systems for use in hospitals, learning institutions, and remote telecommunication stations as a reliable source of energy. Other applications are transport as emergency electricity supply systems [10].

In fuel cell generation, biogas is used to produce direct current electricity through electrochemical process. Fuel cells using biogas are cleaner than combustion as it produces less or no emissions at all [137]. Typical stationary biogas fuel cells are the high-temperature internal reforming systems like solid oxide fuel cells and molten carbonate fuel cells [138]. High internal temperatures in the fuel cells reforms methane with steam to produce hydrogen which is used to generate electricity by reacting with oxygen. The state of California alone in the USA has more than 400 stationary fuel cells of which more than 11 are biogas fuel all producing about 180 MWe [139]. In a typical biogas fuel cell, synthesized biogas with about 65%methane + 35%carbon dioxide is reformed over a rhodium catalyst supported on a porous alumina-foam support. Reforming methods used include steam reforming and catalytic partial oxidation which use oxygen in air or pure oxygen for oxidation [140].

5.1.4. Generation Efficiency of Biogas Fuel Cell. The efficiency of converting biogas into electricity by means of internal-reforming biogas fuel cells is between 42 and 54% based on the higher calorific value and surrounding air temperature of 60°F [139].

5.1.5. Emissions Associated with a Biogas Fuel Cell. Biogas fuel cells generate extremely low atmospheric emissions with the only notable emissions being a result of oxidation or combustion of anode off-gas consisting of free hydrogen that has not reacted with oxygen (O_2), carbon monoxide (CO), and volatile organic compounds. The anode gas is usually processed by means of surface or catalytic burners which oxidize components, and in the process, little low nitrogen oxide emissions are emitted [138].

The emission factor for biogas fuel cell emissions is 0.09 kg CH_4/MWh while the for carbon dioxide produced, the average GHG emission factor is 658.3 kg CO_2/MWh, and while for N_2O (nitrous oxide), the emission factor is 0.001 kg N_20/MWh [138]. Based on these emission factors, the global warming potential over 100 years' time scale (GWP100) of the greenhouse gases, i.e., the output-based greenhouse gas emissions in terms of CO_2 of methane for biogas fuel cells about 0.3 kg CO_2eq/MWh. The biogenic GHG of carbon dioxide is about 658.3 kg CO_2eq/MWh [138]. For nitrous oxide, the greenhouse gas emissions are about 0.26 kg CO_2eq/MWh [139]

5.1.6. Cost of Fuel Cells. The installation costs for biogas fuel cells range from over $8,000/kW for a fuel cell with a 250-300 kW capacity to about $3,800/kW for a 6,140 kW fuel cell. This cost includes the cost of gas cleaning equipment, engineering, permits, and other direct costs [139]. The estimated levelized cost of biogas fuel cell energy is $0.164 per kWh for a 200 kW fuel cell to $0.079 per kWh for a 6,000 kW fuel cell.

High installation costs require state-backed incentives to encourage the development of fuel cells. With 30% of the project or $3,500/kW incentives, a payback period of less than five years can be realized. Through trigeneration of electricity, heat, and hydrogen from fuel cells, a feasible route to solving the hydrogen infrastructure problem facing fuel cell vehicle deployment can be achieved [137].

The most practical system of biogas to electricity conversion is the use of an electric generator set driven by a mechanical prime mover like an engine or gas turbine. Biogas is superior to natural gas as a fuel because its combustion is characterized by a high knock resistance and hence can accommodate higher compression ratios leading to more output and higher power density when used in internal combustion engines [43]. In some applications, biogas is used as fuel for combustion engines, which convert it to mechanical energy that rotates a generator to produce electricity. Theoretically, biogas can be used in all types of combustion engines, engines like gas turbines, diesel engines, and Stirling engines, and others [43, 46, 56].

5.2. Engines for Biogas Power Generation. Biogas to electricity is a feasible process with different engines being optional prime movers for the electric generator. Both diesel and gasoline (Otto cycle) engines can be used as biogas-fueled prime movers for electricity generation. Dual-fuel engine options with fuels like diesel and petrol are common in variable substitution rations. The efficiency of electricity generation is a function of the prime mover and fuel combustion characteristics. Internal combustion engines have a lower cost per unit of power generation compared to other viable options like gas turbines and microturbines, and although factors can make alternative options favorable too in power generation like fuel flexibility and ease of operation and maintenance [33].

5.2.1. Stirling Engines. The Stirling engine also known as the hot air engine was invented in 1816 by Robert Stirling several years after the invention of the diesel engine by Rudolf Diesel [141]. The engine has got high fuel flexibility and can be powered by multiple fuels in a closed thermodynamic cycle. The Stirling engine generates low noise levels and facilitates clean combustion [93, 141, 142]. The main limitations associated with the use of Stirling engines are the dynamic behavior of the engine working mechanism and the heat exchanger performance which reduce the reliability and efficiency of the engine [49, 141]. The Stirling engines can efficiently be used in microcombined heat and power systems powered by solar energy, biogas fuel, or medium–low-grade waste thermal energy [49, 141, 143].

The market has a wide range of Stirling engines with electricity capacities of 1 to 9 kWe with thermal power dispersion of 5 kWth to 25 kWth, which is ideal for household boilers [98, 114]. Stirling engines have electric efficiencies of 13% to 25% which can be increased through cogeneration to 80% and higher. As an example, reference [144] developed a Stirling engine driven by mid-high temperature waste gases and obtained and generated 3.5 kWe against a theoretical of 3.9 kWe at thermal efficiency of 26% [40, 98].

To use biogas to produce electricity with Stirling engines, biogas is externally combusted, and heat generated is transferred to the Stirling engine via a heat exchanger. The heat transferred to the engine heats the gas in the engine and expands to move the engine mechanism. The engine can use fuel of lower quality. However, Stirling engines are relatively expensive, have lower thermal efficiency, and have limited applications compared to internal combustion engines like diesel and petrol engines [43].

Using Stirling engines in combined heat and power mode can significantly increase the thermal efficiency of the engine to as high as 90% [93].

5.2.2. Diesel Engines. Diesel engines also called compression ignition engines or self-igniting engines can be modified to run on biogas or biomethane as a fuel. Different modifications are needed for diesel engines to be dedicated biogas engines or for them to run on dual-fuel mode with a pilot oil, i.e., diesel at appropriate substitution rates [75]. Diesel is mainly used to facilitate the ignition of biogas and to improve the heating value of the mixture. In theory, almost all diesel engines can be converted into dual-fuel engines. Dual-fuel engines run on both diesel and biogas or biomethane or natural gas or another fuel usually with a lower calorific value [61, 118]. Dual-fuel engines however still consume a considerable amount of polluting diesel fuel. Studies show that for diesel engines of engine sizes up to about 200 kW, the pilot injection engines appear to have superior performance with slightly higher efficiency of 3-4% higher and at lower investment costs [43].

Germany alone has over 4,000 biogas plants with internal combustion engine prime movers in operation. This however was achieved over lengthy and determined investment and policy measures aimed at making the technology feasible, reliable, and acceptable as it is today. Compared to other prime movers like microturbines and Stirling engines, internal combustion engines have more stringent fuel quality requirements [61, 145]. Biogas constituent elements like hydrogen sulfide can corrode the engine and so quality should be controlled for use in internal combustion engines. The engine components used with biogas fuel should also be robust. However, all engines designed for use in cars, trucks, and ships can run on biogas, making biogas to electricity conversion with engines technically feasible [43].

Converting a diesel engine to biogas engines involves several changes like the removal of the injector pump and injection nozzles and reduction of the compression ratio to about 12 or less which helps prevent preignition by increasing the size or volume of the combustion chamber. This can be affected by means of exchanging the piston(s) for one that affects a lower compression ratio, machining off material from the piston, machining off material from the combustion chamber in the cylinder head, or exchanging the standard cylinder head for a special low compression head.

Other changes in converting a diesel engine to pure gas engine include the following:

(i) Mounting of an ignition system with a distributor (cum angular gear), ignition coil, and spark plugs. The ignition system chosen is a function of the number of cylinders for the engine. A single-cylinder engine may require a transistor type system, and often, a magnet is installed on the flywheel. For multicylinder engines, an ignition distributor has to be installed. The distributors for Otto cycle engines are usually centrifugal advancing with respect to the engine speed

(ii) Installation of electric supply (alternator). The introduced ignition system requires a source of electricity in form of an alternator and batteries as well as a regulator which can be obtained from a vehicle-type engine. Some diesel engines already have alternators and batteries for the stator

(iii) Provision of a mixing device for the supply of an air/fuel mixture with constant air/fuel ratio as a venturi mixer, simple mixing tank, or pneumatic control valve [75]. Engine control in form of power and speed is achieved by variation of the supply of the air/fuel mixture to the engine

This implies that changing a diesel engine to a biogas engine involves extra investment and requires highly qualified expertise and tooling in form of workshop and equipment. This makes them more expensive.

Diesel engines can be converted to biogas engines in dual-fuel mode or gas alone mode with spark ignition. For part load operation and control, the fuel gas supply can be controlled by means of a gas valve. Biogas engines can maintain their normal performance characteristics with the substitution of diesel between 0 and 80%. Dual-fuel mode operation requires diesel for ignition purposes [75].

5.2.3. Petrol Engine Conversion. The petrol engines are also called spark ignition engines or Otto cycle engines. They can operate on biogas alone with minor adjustments unlike the diesel engines [75]. For petrol or gasoline engines to run on biogas, some amount of petrol or gasoline is often used as a pilot fuel in the engine starting [70, 146]. Gasoline engines can use biogas for a very small of capacity 0.5-10 kW as well as for large power plants. The feasibility of the technology requires necessary policy measures and attractive feed-in tariffs. The grid should also be developed to accommodate decentralized generation [43].

It is much easier to modify an Otto engine because they are designed to operate on an air/fuel mixture with spark ignition. The modification involves the provision of a gas-air mixer instead of the carburetor. The engine operation is done by variation of the mixture supply just like the throttle valve position was. Increasing the efficiency of the system may require an increase in the compression ratio. This is necessary to increase the power output of the converted engine, hence leading to lower specific fuel consumption as power density is increased. Unfortunately, the modification is permanent in nature and prevents the operation of original fuel in cases whenever the supply of biogas is limited. The compression ratio is increased by machining off part of the cylinder head sealing surface. In some cases, however, the valves are very close to the piston and may touch the piston at TDC [75].

5.3. Gas Turbines and Microturbines for Electricity. Biogas turbines are generally used for larger power projects, where biogas is produced on industrial scale typically for at least 3 MW and generally more than 5 MW electricity generation capacity. The advantages of biogas turbines include low maintenance requirements and increasing efficiency with an increase in size of installation. Microturbines are smaller in size but can be connected in series and thus offer desirable flexibility in power generation. The main advantage of turbines and microturbines is the fuel quality requirements are not as stringent as in diesel and gas engines because they have a good degree of tolerance to the presence of hydrogen sulfide in biogas [33].

Small biogas power plants are generally used for power output of 30-75 kW, and such units are readily available in the market. These units are relatively expensive, and since they rotate at very high speeds while operating at high temperatures, the gas turbine design, manufacturing, operation, and maintenance are a challenge from both engineering and engineering material point of view making their wide adoption and use in power generation limited [43].

(iv) Design and operation of open-cycle microturbines and gas turbines

Microturbines are small gas turbines, generally with a capacity of 25-30 kW to 350 kW. The working principle of a microturbine is like the gas turbine. The main components of micro and turbines are the combustor, compressor, and turbine. Hot products of combustion enter through the turbine nozzles and expand through the turbine causing conversion of thermal energy to kinetic energy. In the operation of a microturbine, air is taken in by the induction force of the compressor for compression to desired pressure range. In more advanced cycles, the compressed air from the compressor can be directed to a recuperator for preheating by waste heat in exhaust gases before it goes to the combustor. The compressed heated air is supplied to the combustor and mixed with biogas fuel for combustion. In the combustor, the biogas fuel-air mixture burns to produce high-temperature flue gases. The flue gases are directed to a gas turbine where it expands through the stages to perform work that rotates the turbine which is coupled to an electric generator for power generation [60]. Figure 7 shows the general configuration of an open-cycle gas-turbine power plant.

From Figure 7, it is noted that an open-cycle gas turbine which can use biogas as a fuel consists of a compressor, a combustor, and a gas turbine as the main elements of the system. A gas turbine has the advantage of fuel flexibility and can also use biogas as fuel without upgrading and cleaning [47, 60].

(v) Advanced gas turbine cycles

The rotating turbine rotor shaft is coupled to a generator on one side and an air compressor on the other end for compression of combustion air. The gases leaving an open-cycle gas turbine have significant quantities of waste heat which can be recovered to preheat the combustion gases, the fuel, or both before admission to the combustor to improve the combustion efficiency. In larger units, the exhaust gases can be used to operate a Rankine cycle steam turbine for extra power generation by generating steam using a waste heat recovery boiler [60]. A microturbine and turbine can be equipped with an air heater (heat exchanger) through which compressed air is preheated on its way to the combustor where it meets biogas fuel supplied via a gas supply system which can also be equipped with a preheating system [147].

The electricity produced by the turbine and microturbine may or may not be connected to the grid. If it is not connected to the grid, then a battery is connected as an accumulator to store electricity which is incorporated in the system. It is still needed to store energy for use in a startup even for the grid-connected turbines and microturbines.

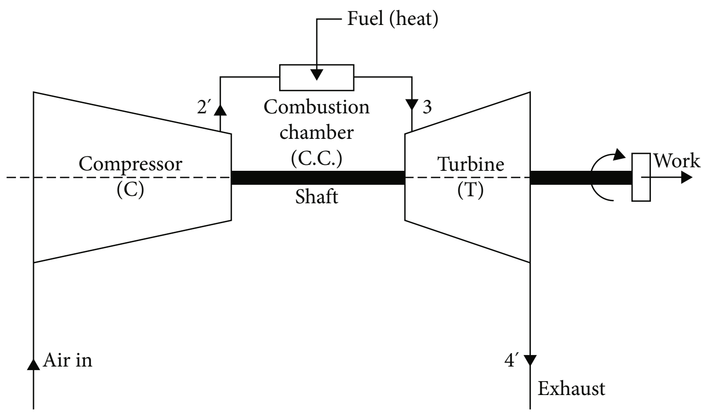

Figure 7: Open-cycle gas-turbine plant [60].

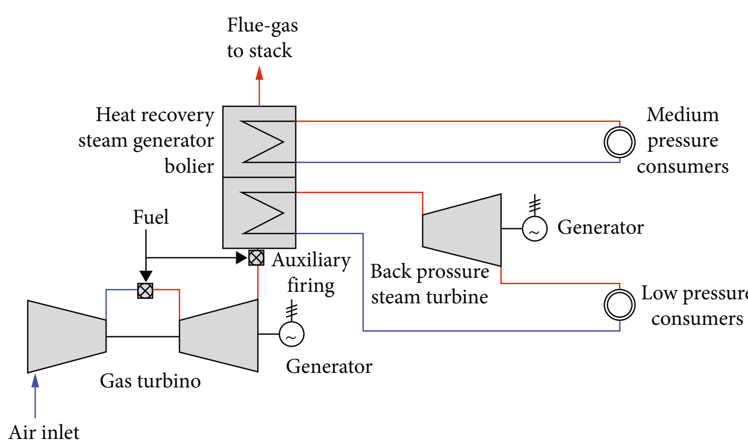

Figure 8: A combined-cycle gas turbine system [60].

The turbines and microturbines can also be used in cogeneration mode where both heat and electricity are put into use. Waste heat from the turbine powered by biogas can be used for thermal application like drying, heating, and other applications on both domestic and industrial scales [147]. Excess gas can be stored and used later through the use of nonporous strong polythene bags [148]. Exhaust gases leaving the gas turbines and microturbines can be used in air conditioning and other thermal applications. Figure 8 shows the general construction of a combined-cycle gas turbine powerplant.

Figure 8 demonstrates the configuration of a combined-cycle powerplant which can use biogas as a fuel. In addition to the basic elements of an open-cycle gas turbine, i.e., the compressor, turbine, and combustor, it is an exhaust/waste heat recovery system which uses excess heat in the flue gases to generate steam which is used to run a Rankine cycle steam turbine to generate extra power. This makes the cycle more efficient than the open-cycle gas-turbine system of power generation [60].

5.4. Combined Heat and Power (Cogeneration). There are various pathways or technologies for the exploitation of biogas energy for both heat and electricity generation [18, 19, 22, 84]. Cogeneration refers to the simultaneous production of both electricity and heat from biogas fuel, which is also called combined heat and power. Biogas can be used in combined heat and power, also called cogeneration for the production of electricity and heat with or without upgrading [26, 47, 48]. In a typical biogas-based CHP technology both heat and electricity plant (BHPP) can be used whereby a combustion engine is used for electricity generation. The produced electricity can be sold to the grid as well as meet local demand. The heat produced by the combustion engine is used for many feasible applications such as in district heating and can be fed to the hot water system [31, 149].

Other generator prime movers that can be used in cogeneration mode with biogas as a fuel are four-stroke engines, dual engines, microturbines, and Stirling engines whose electrical efficiency generally varies between 25 and 45%, based on a specific type of cogeneration setup adopted [150]. The location of the CHP facility is an investment decision, but the CHP unit can be sited near a biogas source, or the fuel which is biogas can be piped or transported to the CHP plant or a district heating unit in the area [26]. The use of heat from biogas instead of fossil fuel sources is very important because of the additional economic and environmental benefits, besides contributing to grid electricity transition for sustainable development [52, 149].

Generally, gas engines are available in sizes of 60 kWe up to more than 2 MWe as single units. In Germany, gas engines have proved to be reliable with over 4000 biogas

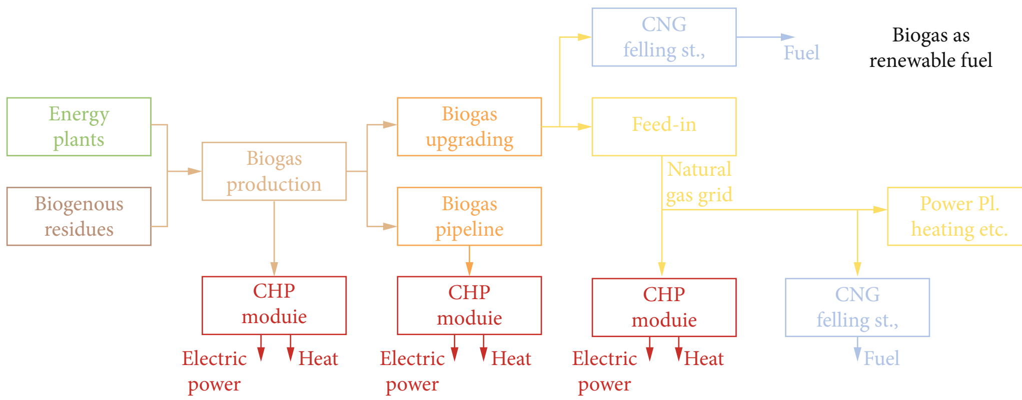

Figure 9: Biogas cogeneration systems and configurations [84].

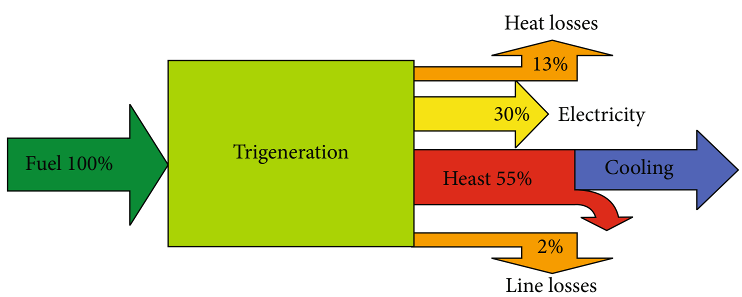

Figure 10: Energy balance in trigeneration [153].

operating with average annual operating hours of over 7500 hrs. The biogas CHP engines can be used in baseload electricity generation [84]. Figure 9 shows the various configurations of biogas cogeneration.

From Figure 9, it is noted that biogas cogeneration can be done under different systems. They include cogeneration with biogas from pipelines, cogeneration with biogas from the digesters, and cogeneration with biogas from the natural gas grids. Biogas for combined heat and power can be used in raw form in onsite power generation, upgraded biogas or biomethane from pipelines, or can also be used in form of compressed biomethane gas.

5.5. Use of Biogas in Trigeneration. The concept of trigeneration generated interest due to concern over fossil-fuel prices and emissions that cause global warming. Trigeneration can be said to be an enhanced form of cogeneration systems where cooling is added to the basic cogeneration system. The main benefits of a cogeneration system are a reduction in fuel use and reduced cost of generation [151], while the use of biogas as heat sources is a way of mitigating greenhouse gas emissions and global warming [26, 32, 152]. The triple application of the same energy input for cooling, heating, and electricity generation is referred to as trigeneration. In a typical trigeneration arrangement, an absorption heat pump, a compression mechanical heat pump, a steam generator, and a heat recovery system can be applied [153]. In such an arrangement, heat at low temperature produced by the absorption chiller is transferred to a mechanical compression heat pump, which receives water at low temperature from the heat recovery plant and heats it up. Biogas is used as a renewable heat source [151, 153].

Figure 10 shows a typical energy balance for a trigeneration system where the main elements of the energy balance or heat distribution are conversion to electricity, line losses, loss to the environment, electricity generation, heating, and cooling.

From Figure 10, it is noted that through trigeneration in a typical setup, heating, cooling, and power generation efficiency of 30% and 55% thermal application including heating and cooling can be achieved. About 13% is lost to the environment with 2% energy lost in the form of line losses. Therefore, up to 85% efficiency can be achieved with conventional technologies.

Therefore, through trigeneration with biogas as a fuel, it is feasible to have simultaneous generation of electricity, provide cooling, and supply heat energies from one input energy. These can also be achieved by recovering powerplant waste heat. Trigeneration with biogas is an effective way to reduce greenhouse emissions, compared to traditional systems like cogeneration and separate applications in heating, cooling, and electricity production [153].

Trigeneration is commonly used in hotels, universities, hospitals, and commercial buildings that need combined heat, cooling, and electricity. For the cooling purpose, absorption refrigerators are commonly used for the generation of cold heat. A refrigerant-absorbent pair consisting of water-lithium bromide is typically used in some applications with operating temperatures of 75–90°C which produce cold water for air conditioners between 12 and

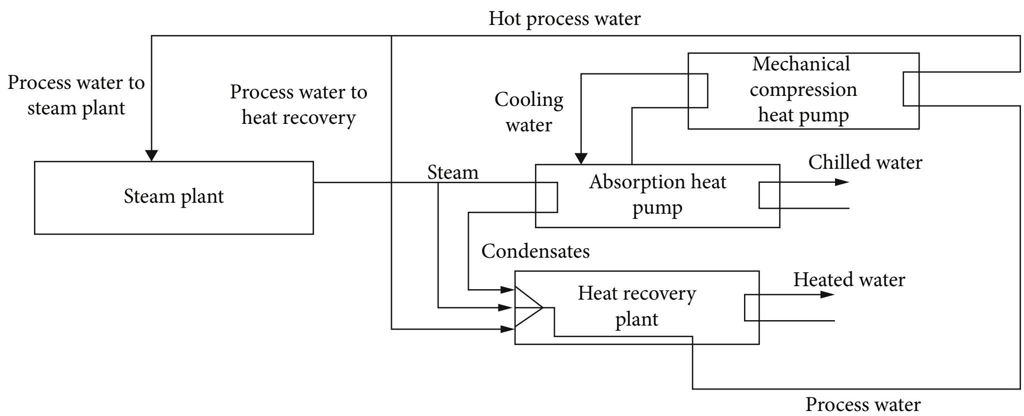

Figure 11: Trigeneration system [153].

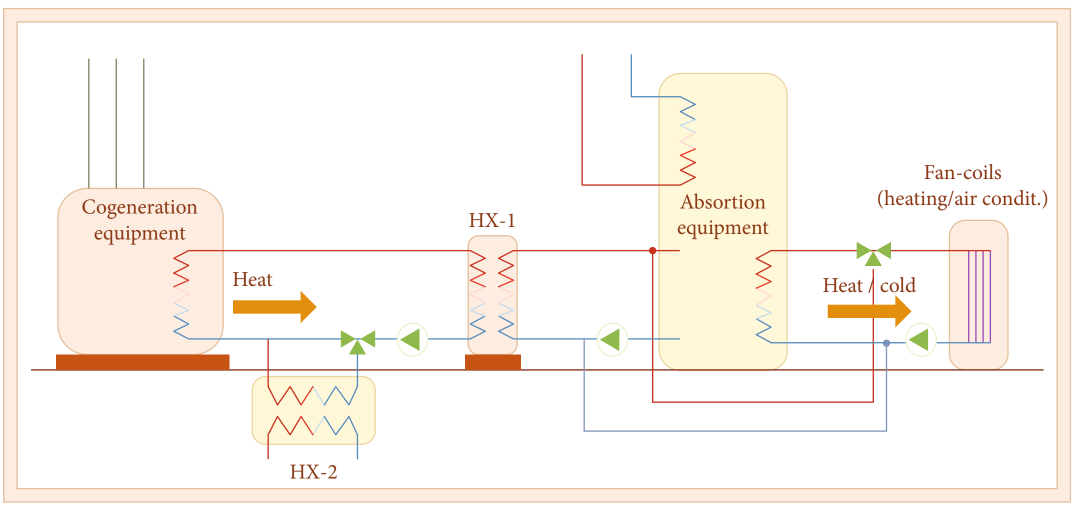

Figure 12: Advanced cogeneration system [154].

7°C. The process of adsorption cooling can produce cold through residual heat, with a low coefficient of performance of 0.3–0.5 and low cooling power per unit volume and weight [154].

Trigeneration systems can be classified into basic and advanced configurations. In basic cogeneration systems, the refrigeration equipment is indirectly activated by heat recovery equipment that generally uses hot water or oil as working fluid. The heat produced is used for applications like space heating, and the operation of an absorption chiller for cooling in a system that combines leading cooling, heat, and power (CCHP), which is also called trigeneration [149]. Figure 10 shows the configuration of a typical basic biogas trigeneration system.

From Figure 11, it is noted that the main elements of a trigeneration plant are the steam plant or steam generator whose role is to produce steam with biogas as a fuel, cooling water which extracts heat from the mechanical compression heat pump, absorption heat pump which is heated by the steam from the steam plant, and heat recovery plant which receives steam, condensates, and hot process water. The absorption heat pump generates chilled water.

The advanced trigeneration systems have direct activation of the refrigeration system without an intermediate fluid through exhaust gases, hot water from a cogeneration engine jacket, or both. This is illustrated in Figure 12.

Figure 12 demonstrates the main elements of the advanced cogeneration system, which consists of the cogeneration unit, absorption equipment, heating and air conditioning unit, and heat exchangers (HX). The system has direct heat exchange to the refrigeration system. Biogas can supply energy to the cogeneration unit with some being directly transferred to the refrigeration system unit.

5.6. Biogas to Hydrogen. Large-scale hydrogen production is by reforming the process of hydrocarbons, particularly natural gas through thermochemical processes. Biogas fuel has got high potential for use as a versatile raw material for reforming processes as a substitute for natural gas. The significance of renewable hydrogen production has increased due to an increase in the pure hydrogen demand, fossil fuel depletion, concerns over greenhouse gas emissions, and global climate change. The availability of capital, the desired hydrogen amount and purity of hydrogen, and the

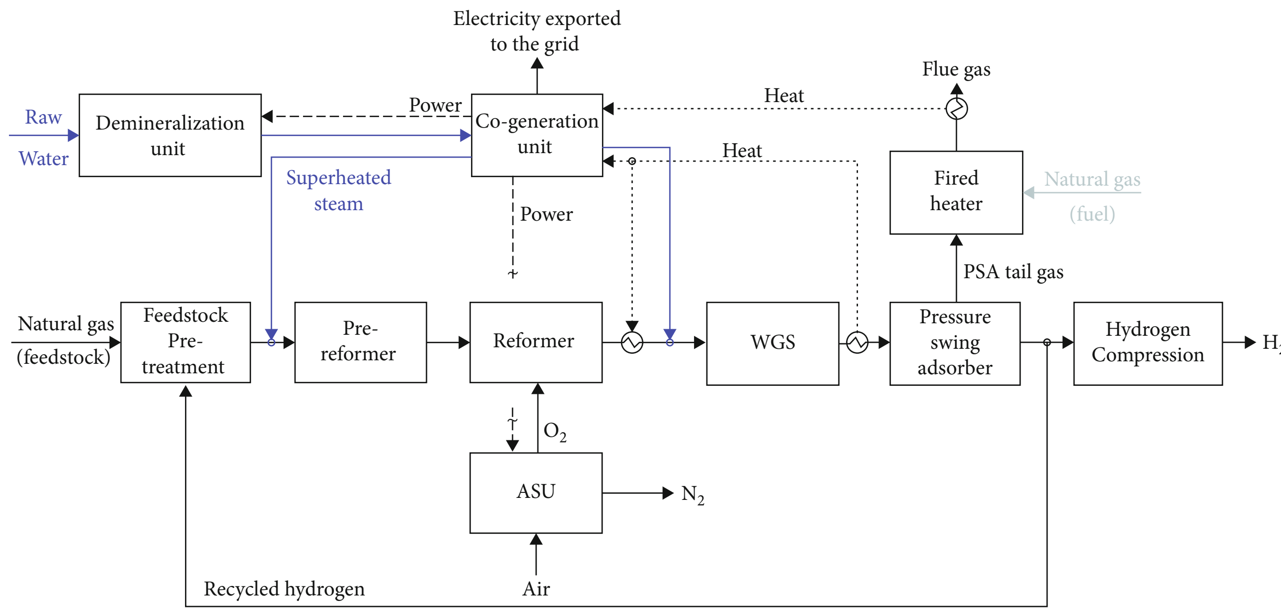

Figure 13: Hydrogen production *via* steam methane reforming; natural gas or biomethane is desulphurized in a pre-treatment section [156].

composition of available biogas will influence the selection of reforming processes [66].

Biogas has sufficient methane content for use as a renewable fuel to substitute imported petroleum in the transportation sector as well as power generation [66]. Biogas has a potential application in fuel cell technologies which are still under development for power generation. Fuel cells can use hydrogen to generate electric power just like batteries as well as fuel for the fuel for powering fuel cars. Fuel cell technology in power generation is emission-free and hence attractive [155]. A potential application of biogas is as a source for renewable hydrogen, for use in stationary fuel cells and to support the fuel cell electric vehicles (FCEVs). Hydrogen-powered FCEVs have no tailpipe emissions except water and hence an extremely clean transport option to petrol and diesel fuel-powered vehicles. Most hydrogen is produced by steam methane reforming (SMR) of natural gas [66].

Energy sustainability can be improved by using it to produce hydrogen for energy-related applications to substitute fossil fuels. The common methods for hydrogen production are electrolysis or methane reforming (SMR) and autothermal reforming (ATR) for syngas production [156]. The technologies can use biomethane, as a substitute for natural gas to provide a lower carbon and renewable hydrogen for transport and power generation. The use of biomethane also provides a hedge against the growing demand for fossil fuels, particularly natural gas, and hence plays a leading role in the energy transition [66].

A combination of using biogas digestate as a fertilizer, and biowaste-based hydrogen fuel reaches net-negative life cycle greenhouse gas emissions even if the process does not apply carbon capture and storage technique. Ultimately, incorporating CCS to the biomethane-based manufacture of hydrogen yields net-negative emissions in all [156]. Figure 13 demonstrates an integrated system of hydrogen production from biomethane or natural gas that can yield net negative emissions.

Figure 13 shows a system that can produce hydrogen fuel and grid electricity from natural gas or biomethane. Biomethane can be used as a substitute for natural gas making the process renewable. Therefore, it is technically feasible to develop an integrated system which produces grid electricity and hydrogen for further electricity production from fuel cells and process applications in a manner that yields negative greenhouse gas emissions. These promises to be a power pathway in the global transition to sustainable energy and electricity as well as sustainable development [66].

Biogas has significant potential for production of hydrogen through a variety of reforming processes whose selection is guided by the composition of biogas, required purity of hydrogen, required volume, process cost, and availability of funding [24]. Of the existing fuel cells, PAFC cells have reached commercialization but face challenges of durability and sensitivity to contaminants. Fuel cells like PEMFC, SOFC, and MCFC are under rapid development and are still in the prototype phase. Raw biogas may not be used as a raw material in reforming processes due to the catalyst poisoning effect of hydrogen sulfide. For partially treated biogas with no H_2S but with 30–45% vol. carbon dioxide, the dry process is appealing as it takes advantage of the carbon dioxide to intrinsically act as an oxidant in dry reforming. If biogas has a CO_2/CH_4 ratio of less than 1, it becomes necessary to supply an alternative oxidant to produce synthesis gas. The addition of oxygen by the DOR method is a potential route for hydrogen production from biogas, aimed at increasing the H_2/CO ratio.

5.7. Biogas Reforming and Application in Transportation as an Energy. The transport sector accounts for about 14% of the global anthropogenic greenhouse gas emissions [157]. Diesel remains the most dominant energy resource used in transportation which calls for a shift to renewable and low carbon sources of energy [25]. The demand for clean non-fossil liquid transport has grown, and biogas to liquid fuel conversion is a feasible method to produce liquid transportation fuels [11, 158]. Common methods used in biogas to liquid fuel conversion include pressurized water scrubbing, dry methane reforming, and Fischer-Tropsch methods with process parameters preferably selected through optimization and sensitivity analysis [158]. Biogas from organic wastes and lignocellulosic biomass can be used to manufacture biodiesel fuel using the Fischer-Tropsch (FT) synthesis process.

Biogas in liquefied form is a feasible source of energy for heavy tracks and power plants. Other than direct use as a fuel, biogas can also be used as a raw material for production of other fuels and chemicals like methanol, dimethyl ether, and hydrogen fuel. Biogas in the form of compressed and liquefied methane is produced from biogas. Biogas can also be used as a fuel in near emission-free fuel cell-powered vehicles. Biomethane on the other hand is currently used as a transport fuel in several countries. Studies involving sensitivity analysis performed for the biogas as an alternative fuel for transport showed that biogas has a lower environmental impact compared to fossil fuels and several other processed transport fuels [159].

Bio-CNG is compressed biomethane which has similar properties to compressed natural gas (CNG) as an alternative automotive in terms of fuel economy and emissions. Production of Bio-CNG needs the removal of impurities such as water, nitrogen (N_2), oxygen (O_2), hydrogen sulfide (H_2S), ammonia (NH_3), and carbon dioxide (CO_2) biogas to get a composition of >97% CH_4 and <2% O_2 at pressure 20–25 MPa. Bio-CNG occupies less than 1% of its volume at standard atmospheric pressure and temperature [62, 159].

Biogas can also be used as a transport fuel in the form of liquefied gas. The conversion can be done at high pressure ranging from 0.5 to 15 MPa.[4]. In the biological or chemical pathways, cleaned biogas mainly consisting of CH_4 and CO_2 is converted to methanol, diesel, liquified petroleum (LPG), and gasoline. Methanol production is achieved through partial oxidation of methane. This method or process of methanol production from methane was first reported in the year 1923. The chemical equation is shown as follows:

$$CH_4 + 0.5O_2 \longrightarrow CH_3OH \quad \Delta H^0 = -128\,\text{kJ/mol} \tag{5}$$

In another method of methanol production, methane is biologically converted to methanol by using methanotrophic bacteria often used in methanol production through the action of a special enzyme, called methane monooxygenase (MMO). This bacterium uses methane as its only carbon source for metabolism at ambient conditions [5].

Methanol can also be produced from methane by reforming methane to syngas then followed by catalytic conversion of syngas to methanol as shown in chemical reactions shown as follows [6]:

$$\begin{aligned} 2H_2 + CO &\longrightarrow CH_3OH \quad \Delta H^0 = -91\,\text{kJ/mol} \\ 3H_2 + CO_2 &\longrightarrow CH_3OH + H_2O \quad \Delta H^0 = -49\,\text{kJ/mol} \end{aligned} \tag{6}$$

Methanol produced can further be converted to gasoline via the methanol-to-gasoline process. Methanol can be produced from biogas or biomethane by means of three main reforming processes, namely, dry reforming, steam reforming, partial oxidation reforming, autothermal reforming (ATR), and the Fischer-Tropsch (FT) process. These processes are explained in the following.

The reforming process leads to synthesis gas (syngas) which is a mixture of hydrogen and carbon monoxide, H_2 and CO. Syngas is a raw material for the production of many long-chain hydrocarbons through fermentation, Fischer-Tropsch fuels, and methanol to gasoline technology conversion. [158]

(i) Dry reforming

In dry reforming, methane (CH_4) reacts with carbon dioxide (CO_2) to produce CO and H_2. This reaction is environmentally attractive because it utilizes two greenhouse gases (CH_4 and CO_2). However, the endothermic reaction minimizes the reduction of CO_2 emissions, because the carbon dioxide (CO_2) emitted by fuel combustion generates the heat required for the reaction needs to be accounted for. Dry reforming also satisfies basic requirements of many processes in Fischer-Tropsch synthesis, as an efficient route for producing synthesis gas production yielding a H_2/CO ratio close to 1 [136].

The main limitation of dry reforming compared with steam reforming is that it produces a lower syngas ratio ($H^2/CO = 1$). The H_2/CO ratio is influenced by water gas shift reaction (WGS), which lowers the ratio because of reverse reaction which converts hydrogen to water. The H_2/CO ratio can be kept between 1 and 2 through partial oxidation of methane as shown in the following equation through feeding water which promotes forward water gas shift reaction. The process also lowers process energy demand since partial oxidation is exothermic [158]. The temperature range for the dry reforming process is 700–1000°C [158].

$$CH_4 + CO_2 \longrightarrow 2CO + 2H_2 \quad \Delta H^0 = 247\,\text{kJ/mol} \tag{7}$$

Since the feed has got lower O/C and H/C ratios, dry reforming tends to form carbon deposition, hence needing to carry out the process at a higher temperature [158].

(ii) Steam reforming and water shift reaction

Steam reforming combines methane in cleaned biogas with water vapor to produce CO and H_2 in the presence of a catalyst. Steam reforming is an endothermic process which takes place between 650 and 850°C, to produce a hydrogen yield of 60–70% [136]. The process takes place at a

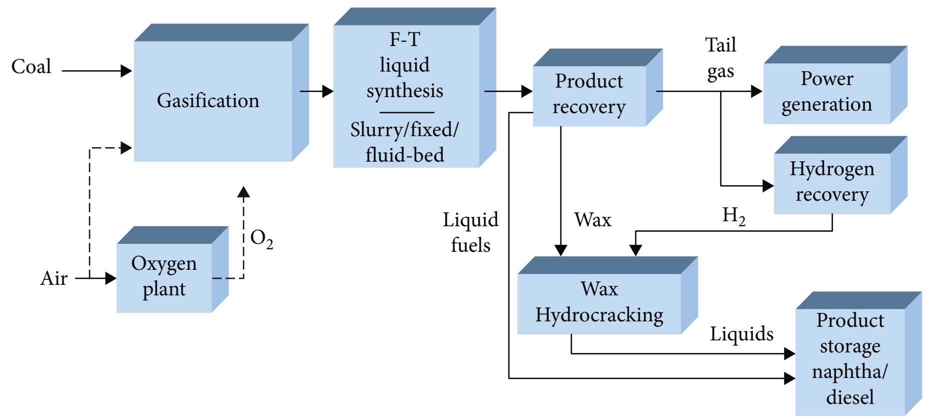

Figure 14: Simplified F-T Synthesis-based Production Scheme [160].

temperature range of between 700 and 900°C. The chemical reaction is demonstrated by a two-step reaction demonstrated in the following:

$$\begin{aligned} CH_4 + H_2O &\longrightarrow CO + 3H_2 \quad \Delta H^0 = 206\,\text{kJ/mol} \\ CO + H_2O &\longrightarrow CO_2 + H_2 \quad \Delta H^0 = -41\,\text{kJ/mol} \end{aligned} \tag{8}$$

The process of steam reforming is often followed by a water shift reaction to improve hydrogen generation.

(iii) Partial oxidation reforming (POR)

The partial oxidation reforming is used to generate hydrogen at reduced energy cost since the process is moderately exothermic as opposed to steam reforming which is highly endothermic. In partial oxidation reforming, methane oxidized partially to H_2 and CO at atmospheric pressure and temperature of 700 and 900 °C. Complete conversion yields a H_2/CO ratio of about 2 and reduced soot formation. A decrease in CO selectivity makes methane react with oxygen to form carbon dioxide (CO_2), hence completing combustion which is strongly exothermic leading to the formation of hot spots in the reactor bed and coke deposition on the catalyst [136]. This process involves oxidation of methane to syngas:

$$CH_4 + 0.5O_2 \longrightarrow CO + 2H_2 \quad \Delta H^0 = -25.2\,\text{kJ/mol} \tag{9}$$

Partial oxidation reforming (POR) is an exothermic reaction. The reduced energy consumption, the process can be combined with either dry reforming or steam reforming which are endothermic.

(iv) Autothermal reforming (ATR)

Internal heating of a reactor is more efficient than external heating, and the exothermal process is more economical. The partial oxidation reaction of methane as in POR is exothermic but the product has lower H_2/CO compared to endothermic steam reforming [136]. Autothermal reforming combines the two processes, i.e., POR and SR, and occurs in the presence of carbon dioxide. In ATR, a thermal zone exists in the reactor where partial oxidation takes place to produce the heat needed for steam reforming in the catalytic zone. The process is efficient as it requires no external heating, while at the same time, it is attractive because of the speed of the reactor stop and restart. The process also has a higher yield of hydrogen and consumes less oxygen compared to partial oxidation reaction. The process also reduces the formation of hotspots; hence, there is no need to deactivate the catalyst [136].

5.7.1. Upgrading Syngas. The syngas from dry reforming has carbon dioxide which must be removed before feeding it to the Fischer-Tropsch reactor. The use of amine absorption is preferred as it has high selectivity for carbon dioxide. This technology has other applications like separation of CO_2 from flue gases and cleaning of natural gas and biogas upgrading on large scale. Other solvents used for absorption include alkanolamines like monoethanolamine (MEA), diethanolamine (DEA), or methyldiethanolamine (MDEA). MEA is the most widely used solvent in low-pressure absorption [11, 160].

5.8. Fischer-Tropsch (FT) Process. Liquid hydrocarbons for use as transportation fuels can be manufactured from syngas and biogas via a catalytic chemical process called Fischer-Tropsch (FT) synthesis, which was named after original German inventors Franz Fischer and Hans Tropsch in the 1920s. This process has been used by Germany during World War II and South Africa which was facing isolation due to apartheid to provide liquid hydrocarbon fuels. Examples of technologies used today include coal-to-liquids (CTL) and/or gas-to-liquids (GTL) based on the source of syngas [11, 160].

Biomethane or natural gas conversion to liquid fuels by Fischer-Tropsch synthesis (FT-synthesis) is established and applicable at an industrial scale [158]. The Fischer-Tropsch (FT) process is used in the conversion of syngas to several useful products like LPG, diesel, and jet fuels. Through this process, syngas can be used to manufacture energy products like ethanol. Other methods related to biological methods are under research and development using genetically engineered microorganisms [160]. Figure 14 shows a

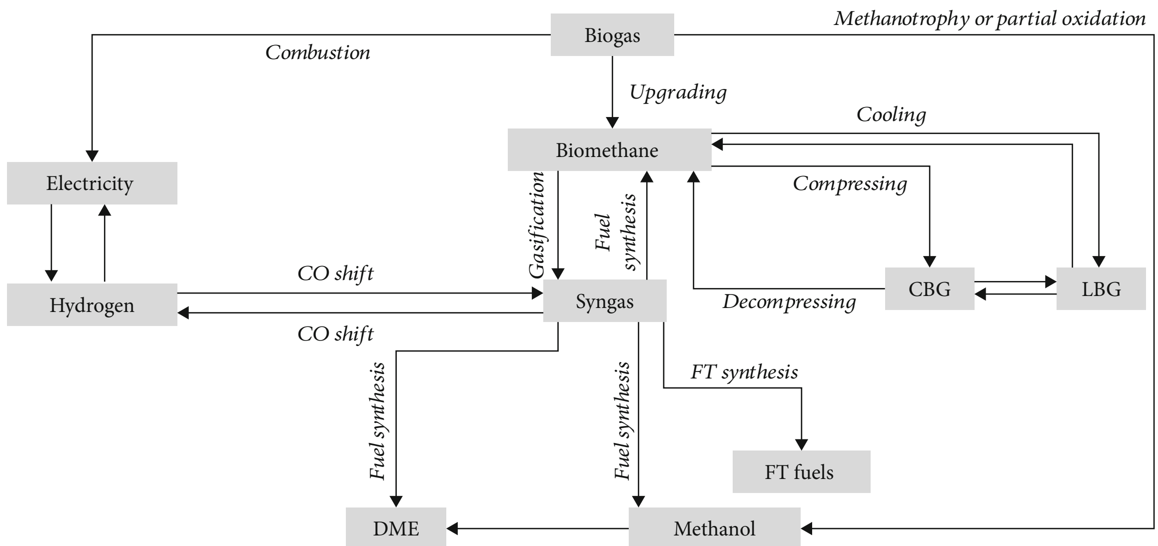

Figure 15: Pathways for biogas conversion to transportation fuels [62].

conventional gasification process for coal which can be modified to use biogas.

Fischer-Tropsch synthesis (FT-synthesis) is used to polymerize the carbon and hydrogen atoms in syngas or biogas to form long-chain molecules. As the process is reverse of methane reforming, it is run over iron or cobalt catalyst at a pressure of 20-30 bar [14] in a process which is overall exothermic that leads to polymerization of CH_2 to long-chain hydrocarbons called Syncrude.

The equations applied in the Fischer-Tropsch process are summarized as follows:

$$\begin{aligned}(2n+1)\,H_2 + nCO &\longrightarrow CnH_{2n+2} + nH_2O \\ 2nH_2 + nCO &\longrightarrow C_nH_{2n} + nH_2O\end{aligned} \tag{10}$$

The reactors used in the process are different in design and include a multitubular fixed bed, circulating fluidized bed, fixed fluidized bed, and slurry reactor. Typical reaction conditions for the slurry reactor are 20-30 bar, 200-300°C, and syngas H_2/CO ratio of 1-1.8 [158, 160]. The fluidized-bed FT reactors are applied for high-temperature FT synthesis and produce hydrocarbons with low molecular weight in the form of gaseous hydrocarbons and gasoline and generally have higher output. The catalysts Fe and Co catalysts are sensitive to sulfur compounds present in syngas [160].

The various processes of converting biogas to transportation fuels are summarized in Figure 15.

From Figure 15, it is noted that biogas can be converted to other forms of fuel for direct use in transport, combined heat and power, or other thermal and cooling applications. Biogas can be combusted directly for heating, cooking, and lighting as well as for power generation. It can also be used for fuel synthesis in the Fischer-Tropsch (FT) process. Upgraded biogas or biomethane can also be used to process methanol fuel. Compressed biogas (CBG) and liquid biogas (LBG) can be reversibly made from biomethane for various direct and indirect applications as fuels and power generation.

5.9. Biofuels from Biogas. Various fuels for transportation and other applications can be processed from biogas. These fuels include compressed biogas (CBG), liquid biogas (LBG), methanol, hydrogen, dimethyl ether, and Fischer-Tropsch (FT) fuels [161]. The two different tracks for production of fuels from biogas are upgrading to biomethane before compressing to make (CBG) or liquefying to make (LBG) or gasification of biogas to produce syngas for fuel synthesis of hydrogen, methanol, DME, and FT diesel. Compressed biogas is currently an economically viable option for small scale applications than other options while liquid biogas has established applications in heavy-duty vehicles and shipping as a replacement for liquid natural gas. Other fuels with potential for production from biogas are hydrogen, ME, and FT diesel but not yet at commercial scales [161].

6. Sustainability of Biogas to Grid Electricity Generation

Sustainability is a major concern today that is a direct result of the serious concerns over climate change, to which electricity is an important contributor [162]. Electricity is a critical product needed to support life, welfare, and sustainable development [163]. Currently, humanity is faced with a significant challenge to realize new sustainable development goals (SDGs) by the year 2030 [60, 163]. Sustainable development and its correlation with energy became a significant global concern and issue at the 2002 Johannesburg world summit on sustainable development [164]. Determination of the most appropriate energy systems in an electricity mix is considered a strategic approach to the realization of sustainable development [165, 166]. Electricity generation systems can be assessed by a five-dimensional approach consisting of environmental, economic, social, technical, and institutional sustainability as a strong measure of energy

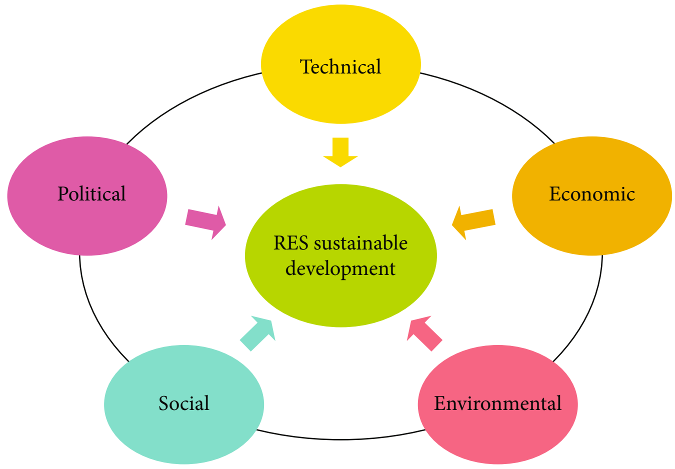

Figure 16: Dimensions of energy sustainability [167].

sustainability [165]. Sustainability in energy development seeks to achieve technical sustainability, political sustainability, social sustainability, environmental sustainability, and economic sustainability which is greatly realized by the development and use of renewable energy resources [167]. Figure 16 illustrates the 5 main dimensions of energy sustainability.

Figure 16 summarizes the main dimensions of energy sustainability, particularly electricity. The main dimensions of sustainability in energy development and consumption are environmental, social, political, economic, and technical sustainability.

6.1. Economic Sustainability of Biogas to Electricity Conversions. The traditional sources of electric power face challenges like fuel price and supply fluctuations, seasonal variability of rainfall for hydropower, and low reliability of power supply with persistent risk of power cut intermittency of wind and solar energy resources as well as scarcity and long project delivery periods for geothermal and high security and risks associated with low carbon nuclear power plant generation [52, 79]. Important economic indicators for economic and financial sustainability of biogas to electricity conversions are guided by parameters and indicators like the profitability, investment costs, cost of generation, feed-in tariffs, electrical energy sales value, operation, maintenance costs, net present value (NPV), the internal rate of return (IRR), the levelized cost of energy (LCOE), and payback period [33].

Operation and maintenance costs are associated with technical or engineering personnel, raw material cost, and other basic power plant services. These cost elements are classified into fixed and variable costs which can be valued based on the project investment cost. For biogas, plant operation and maintenance costs are generally taken as 7.4% of the overall investment [33]. The levelized cost of power is used as a basis of comparing different power generation technologies in terms of economic viability. The levelized cost of electricity refers to the cost of electric power generation during the plant lifespan in (USD/kWh). Investment cost includes interest and total cost of all auxiliary equipment including electrical infrastructure given as USD/kWh; O&M used is the operation and maintenance cost for one year while time used in the computation of levelized cost is the useful or design life of the powerplant given in USD/kWh. Internal rate of return (IRR) is a quantitative measure and represents the highest interest rate that an investor is ready to pay with minimum risk. The payback period (PBP) is the period over which the project cost is fully recovered [33].

Generating electricity from biogas could reduce the costs of electricity and increase access to many, especially where the source of biomass is abundant and cheap. Electricity access is directly linked to the general improvement in people's quality of life, and biogas being a locally available resource to many can play a leading role in the improvement of the majority's socioeconomic wellbeing as a source of secure energy [33]

6.2. Social Sustainability of Biogas to Electricity Conversion. The main social impact of biogas technology is that it creates employment opportunities for skilled and unskilled persons. Specific skilled trades include plumbers; civil engineer agronomists get employment in a well-organized biogas development program [82, 149]. More employment opportunities are created in the design, manufacture, operation, and maintenance of biogas equipment and appliances as well as construction. An active biogas development initiative will also promote research and development activities leading to new products and efficient systems with more social benefits besides fully engaging researchers in the biogas supply chain. In employment, China has over 90,000 people working directly or indirectly in biogas-related jobs while Germany and India have 85,000 and 50,000, respectively.

The use of biogas minimizes the environmental impact of organic wastes which can be a source of conflict among neighbors and hence negatively affect social relations and wellbeing [40]. Women and children in rural areas of most developing countries spend long hours looking for firewood while forests which are a critical element of the carbon cycle are cleared to burn charcoal and harvest firewood. The use of bright biogas lamp light is a direct boost to school children who can have a clean source of affordable light to do their studies and homework [168].

Other socioeconomic benefits of biogas include the following:

(i) It saves expenditures on fuel sources

(ii) Saves time to utilize in other income generation activities

(iii) Increases soil productivity

(iv) Reduces consumption of chemical fertilizers due to the use of bioslurry

(v) It helps in the reduction of health expenditures related to smoke-borne diseases

(vi) Biogas sector generates direct and indirect job opportunities to the local population and households [47, 149]

In general, the social acceptance of biogas is often affected by negative environmental and health concerns. The main greenhouse gases (GHG), produced by biogas use are carbon dioxide (CO_2), methane (CH_4), and nitrogen oxide (N_2O) [169].

6.3. Environmental Sustainability of Biogas Energy Resources. Biogas has significant environmental benefits as a substitute of fossil fuels in heat and electricity. Besides mitigation of greenhouse emissions, biogas guarantees the security of energy as it is both renewable and uses locally available materials as feedstock [18, 19, 51]. Biogas production provides a controlled waste decomposition that avoids the natural emission of methane and provides an alternative route of disposal to combustion for agricultural and municipal solid waste while producing useful digestate for use as a fertilizer in place of chemical fertilizers which are often expensive and are produced using polluting industrial processes. This has both environmental and socioeconomic benefits combined. The use of biomethane instead of natural gas can be a sustainable way of supply to natural gas grids and a transport fuel substitute for vehicles [169].

Biogas can be used as a viable route in the disposal of organic wastes. The process does not add to the carbon dioxide load in the atmosphere because it is offset by either the carbon dioxide consumed by the biomass or by avoided fugitive methane production from open waste deposits. This makes biogas a “green” sustainable energy resource and has a very important role in transition to a decarbonized society [149]. Biogas production landfills and other waste systems can be used to improve the quality of the environment and reduce health risks to both personnel and nearby towns and other settlements [33]. The environmental benefits of biogas can be stated as follows:

(i) Biogas provides a sustainable source of energy and fertilizer for soil enrichment and hence sustainable agriculture resources source from the digestate

(ii) Biogas production and use is a sustainable way of treating or sterilizing wastes from pathogens

(iii) It is an economical way of organic waste recycling which minimizes disposal costs and space requirements for landfills

(iv) Biogas production minimizes the environmental impacts of greenhouse gas emissions, mainly through avoided use of fossil fuels and smoke from incineration facilities

(v) Biogas supports agriculture by providing a disposal route to organic farm wastes, hence reducing pressure on land space [168]

Biogas has significant health benefits as it avoids the direct burning of biomass sources like charcoal and wood which produce smoke-borne diseases like headaches, eye infections, and respiratory tract infections. The use of biodigesters improves sanitation in homes through toilet connection with biodigesters, soothless and ashless combustion, and reduced burning accidents [37]. With about two million deaths a year globally from pneumonia, lung cancer, and chronic lung diseases, associated with indoor air pollution from combustion of traditional fuel sources, biogas will significantly reduce these deaths [168].

6.4. Technical Sustainability of Biogas Electricity and Fuels. There are streams of excess organic biodegradable materials, previously regarded as waste, from industrial processes, human activities, crop husbandry, and animal husbandry and processing that can be readily converted to biogas and biomethane with available biogas technology [106, 122, 170]. These wastes can be channeled to biogas digesters and converted to useful energy. Biogas has got wide applications for cooking, lighting, cooling, engine combustion fuel, and gas mains supply for domestic and industrial applications and thermal and process applications [25].

As a fuel, biogas is more efficient than fuel wood, and cow dung; hence, a better choice for rural household energy use burning at an efficiency of about 60% compared to wood whose burning efficiency is just 5–8% in Openfire while dung burns with efficiency close to 60% of that of fuelwood efficiency. Biogas also offers a reliable source of electricity as well as transport fuel and can be used in many crucial operations like water pumping which need electricity [168]. Biomethane can be used as a direct substitute for natural gas in many domestic and industrial applications. This can make biomethane a technically feasible alternative to natural gas. Biofertilizer from biodigesters supports sustainable agriculture and livelihoods by a supply of cheaper alternative manure with about 10% higher ammonia content than the fresh manure [82, 128]. The bioslurry is easier to apply to the farm and crops than fresh manure because it is less viscous and less lumpy than traditional manure. It is also richer in phosphorus which is the most expensive fertilizer and as well as potassium. Biogas technology also creates both skilled and unskilled job opportunities for both skilled and unskilled labor to various professionals like engineers,

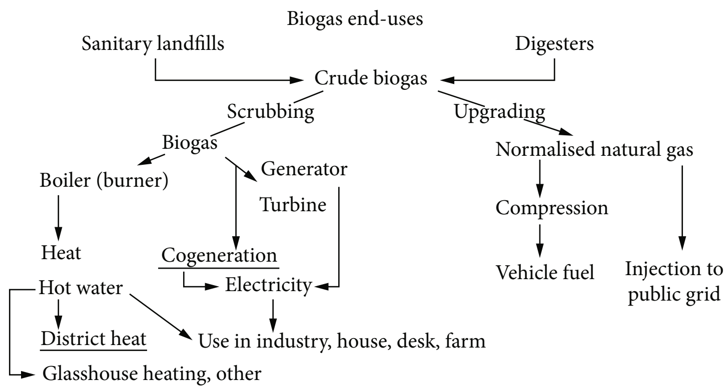

Figure 17: Summary of biogas applications in the energy transition.

agronomists, building technicians, and plant designers [168]. All these together make biogas energy renewable and technically sustainable.

The growth and spread of biogas technology have encountered mixed results of success and failure. The technical requirements for the operation and maintenance of biogas plants require training and availability of skilled personnel and skills which may be scarce in many rural areas of developing countries [3, 122]. This has led to operational failure of many biodigesters which is an indicator of lack of sustainability. State incentives are often required to motivate investment in biogas technology with measures like attractive electricity feed-in tariffs for electricity from biogas, investment reliefs, tax incentives, and grants to promote investment in biogas technology. Such incentive measures have been successfully tried in India, China, and Germany which have a successful biogas industry. Research into efficient biogas production and conversion technology also holds the key to the future success and sustainability of biogas technology [30]. These technologies include biomethane production, biogas fuel cells, and biogas to hydrogen conversion [15, 21].

Overall sustainability of biogas systems will be increased through multiple applications like electricity generation, fertilizer production, biofuel production, and trigeneration among others [28, 53, 171]. These will make the systems economical, cleaner, technically sustainable, and socially acceptable for wider adaptation [43, 134]. Economic analysis of several biogas power generation systems is contradictory or inconsistent but generally gives payback periods of 1.5–2.5 years. This makes biogas electricity comparable to the price of grid electricity and bottled LPG for biomethane [3, 18, 19, 43, 105].

6.5. Institutional and Political Sustainability of Biogas Energy. There is a need to develop an institutional and policy framework to encourage biogas production and use. Countries can encourage large-scale and small-scale manufacturing fuels from biomass and biowaste through tax measures like tax exemptions and encouraging biogas research and development [23, 82, 106]. As a good example, Germany is a leading producer of biogas in Europe, with over 8000 biogas plants in operation, having electricity installed capacity of 4 TWh. As a success story, while the world was facing a global economic crisis in 2010, biogas production expanded rapidly and contributed to rural economic development in Germany because of a deliberate government policy to promote the use of biogas as a renewable energy resource [7].

7. Results and Discussion

7.1. Summary of Applications of Biogas. Biogas is used in its raw form or is upgraded to biomethane or bionatural gas. The applications for biogas are summarized in Figure 17.

Biogas can be used directly for cooking, and lighting as well as for power generation, but can also be used for the production of Fischer-Tropsch (FT) fuels. Fuel upgraded biogas/biomethane which can also be used to process methanol fuel. Compressed biogas (CBG) and liquid biogas (LBG) can be reversibly made from biomethane for various direct and indirect applications as fuels and power generation. Biogas can be used in processes like combined heat and power generation from biogas (CHP), compression to bio-CNG, and bio-LPG for cleaned biogas/biomethane. Fuels are manufactured from biogas by cleaning, and purification before reforming to syngas, and partial oxidation to produce methanol which can be used to make gasoline. Syngas is used in the production of alcohols, jet fuels, diesel, and gasoline through the Fischer-Tropsch process.

7.2. Status and Progress of Biogas to Electricity/Energy Conversion. Methane is not toxic, but it can cause death by asphyxiation if not well handled. Therefore, biogas should be handled carefully. Methane is also a greenhouse and is more than 20 times more potent than carbon dioxide. This implies that leakages by means of accidents or emissions from uncontrolled anaerobic digestion have a significant environmental impact which cannot be neglected in sustainability assessment.

Biogas can also be used in the manufacture of chemical fuels and substances like hydrogen and methanol which can further be processed to gasoline via the methanol-to-gasoline process. Other than production of fuels, biogas can also be used as a raw material for production of chemicals whose production process would have led to severe environmental impact. On the negative side, biogas has trace elements like hydrogen sulfide and carbon dioxide which reduce its quality as a fuel. Additionally, biomethane from biogas upgrading has high operating costs and energy consumption which needs to be addressed

Well-designed and built biogas digesters and wider applications and efficient biogas to electricity, biogas to heat, and biogas to value-added chemicals and products will combine to ensure that biogas plays a leading and sustainable role in the energy transition. Electricity from biogas can be used directly which avoids or limits electricity imports from the grid while excess generated electricity can be exported to the electricity grid by using various prime movers like gas turbines and internal combustion engines. It is also possible to make direct conversion from biogas to electricity in fuel cells. Biogas can also be converted to hydrogen fuel for wide renewable applications. This study has identified several pathways for use of biogas in the sustainable energy transition. They are summarized in Table 10.

From Table 10, it is noted that various conversion technologies with varying characteristics and processes are available for exploitation of biogas in thermal and electricity generation and application. They include cogeneration, trigeneration systems, and open conversion systems. Devices or equipment used includes diesel engines, petrol gasoline engines, gas turbines, fuel cells, and Stirling engines. Feasible energy products for other multiple applications include biomethane and hydrogen fuels.

Biogas has a double role to play in reducing emissions from the transport sector which account for close to 14% of all anthropogenic greenhouse gas emissions. Biogas or biomethane can be used as a direct fuel in place of fossil fuels in transport and can also be used to produce biofuels/chemicals through processes like the Fischer-Tropsch (FT) process to produce jet fuel, diesel and gasoline, and reforming processes (dry reforming, steam reforming, partial oxidation reforming, and autothermal reforming) to produce hydrogen and methanol which can be used as a fuel in fuel cells and chemical substitutes as well as direct combustion fuel with very minimum carbon value. Biogas-derived transport fuels have very low emissions and, in some cases, have a negative carbon value.

Although biogas has less environmental impacts, it is still associated with some greenhouse gas emissions mainly CO_2, CH_4, and N_2O with the level depending on the technology used or the source of biogas. Therefore, a positive role of biogas in the sustainable energy transition is dependent on the selection of conversion technology used and the source of biogas. The production of electricity from biogas is quite limited in developing countries like Africa [43]. Anaerobic digestion is used to produce byproducts that are used and hence reduce the negative environmental impact and pollution potential of biogas production. Several benefits of anaerobic digestion are realized by individuals, the human environment, and the whole community [114, 144, 172].

7.3. Challenges of Biogas to Electricity Generation. Several challenges limit the wider use of biogas in grid electricity generation as well as thermal applications among others. These limitations include low technical capacity to operate and maintain biogas systems, especially in the rural areas as well as the availability of spare parts for biogas systems [13]. This is because most components are sourced from foreign countries with little or no technical support from investors, especially for developing countries. Building local capacity and more local content will improve the technical sustainability of biogas systems [43, 101]. According to [101, 114], low feed-in tariffs and low capacity of grids to absorb small distributed electricity sources are another limitations to the wider use of biogas to electricity systems. Other limitations are lack of on-grid generation opportunities, high upfront costs in terms of feasibility studies, financial barriers, design capacity, construction, operation, and maintenance; legal and policy barriers and relatively high costs of production and maintenance in comparison with fossil fuels energy systems and changing and short-lasting regulatory frameworks that do not support biogas programs all combined make the development of grid-connected biogas systems difficult to implement [36, 80, 118].

Monopolistic structures in the energy sectors of many developing countries prevent healthy competition and benefits like customer and product focus; absence of clear rules for gas-grid access; protective structures and stakeholders in the waste business; absence of biogas pipeline grid to facilitate wide distribution and use of biogas; lack of highly efficient heavy-duty biogas engines to compete against conventional engines; insufficient knowledge among end-users about economic advantages of using biogas instead of fossil fuels, low electricity demand to sustain continuous generation and operation of the biodigesters; inability to pay for electricity and other related costs to operate the plants; difficulties in operation and maintenance of the systems; limited knowledge of biogas technology and electricity generation; seasonal variability in demand for fertilizer from biodigester; weak biomass supply chain to sustain the operation of digesters and generators; and lack of economies of scale in operation of the schemes, hence higher unit costs of power and other products [57, 124, 173, 174].

7.4. Measures to Promote On-Grid Biogas Electricity Generation. For biogas to play a leading role in the energy transition, several measures are proposed for the benefits of anaerobic digestion to accrue to individuals, environment, and community as a whole [114, 144, 172]. The diversified application of biogas plants will make economic sense for small biogas installations [101]. Compared to fossil fuels, anaerobic digestion technology reduces greenhouse gas emissions by consuming locally available biowaste. Additionally, the byproduct of biogas production also called digestate can be used as a high value for sustainable agricultures [7, 58, 117, 122].

7.5. Policy Implications and Recommendations. Various factors are necessary for successful biogas to grid electricity development and other high-tech application. These factors among others include the following:

(i) Appropriate institutional reforms and arrangements to encourage biogas to electricity investment

Table 10: Summary of biogas to electricity conversion systems and technologies.

	Method/process	Device/technology	Application	Remarks
1	Chemical-electrical	Fuel cell	Generation of electricity	Very efficient, reliable but expensive
2	Chemical-electrical	Hydrogen	Generation of electricity and process chemicals. Hydrogen 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
3	Chemical	Biomethanenation	Biomethane can be fed to natural gas supply and fuel for vehicles and fuel natural gas powerplants	Renewable replacement of fossil natural gas
4	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
5	Thermal-electrical	Gas/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
6	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
7	Thermal-mechanical-electrical	Gas turbine	Can be used as open-cycle or combined-cycle plants for electricity and heat applications. Micro, small, medium, and largescale turbines can be used based on fuel source and application	Turbines are versatile and can use raw biogas in uncleaned form. They are light and simple in construction, easy to operate but need skilled manpower
8	Thermal-mechanical-electrical	Cogeneration	Cogeneration is 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, hydrogen, and fuel cells can all be operated on cogeneration mode
9	Thermal-mechanical-electrical	Trigeneration	Trigeneration is simultaneous generation of electricity with both heating and cooling	Trigeneration is the most efficient conversion system but more complex and expensive

by smallholder farmers and other rural communities

(ii) Effective and reliable technology with respect to local needs and conditions

(iii) Carry out community sensitization awareness programs on biomass and decentralized generation

(iv) Put in place proper digester and power system maintenance for reliable biogas production and electricity generation.

(v) Access and provision of financial subsidies for plant and equipment for the biogas and energy/electricity systems

(vi) Development of local expertise

(vii) Attractive feed-in tariff to the electricity grid to make investment feasible and sustainable

(viii) Exemptions from limiting legal and regulatory obstacles [13, 38, 80, 89]

It is necessary to put in place facilitating legal and policy framework if biogas electricity generation must develop because of various technical and economic challenges in a competitive market. In Germany, biogas power generation is profitable just because of grid connection and attractive feed-in tariffs. It is noted that output-oriented support schemes as opposed to investment-oriented financial support are more effective and successful in promoting biogas power generation [3, 80, 82, 122].

To promote biogas electricity generation, it is necessary to put in place subsidies and public financial support measures to support the installation of biogas power plants. Developing appropriate feed-in tariffs stimulates the construction of efficient power plants and their continuous and efficient operation. Several other factors that should be put in place to encourage biogas electricity generation are as follows.

(i) Create awareness of biogas power generation opportunities and incentives

(ii) Mitigate against high investment costs through tax incentives and access to cheap and readily available finance

(iii) Develop local capacity in power plant project design, construction, operation, and maintenance

(iv) Through the promotion of decentralized generation, small-scale biogas producers should be allowed to operate as prosumers who sell and consume electricity based on circumstances. This can be realized through the extension of smart grids to rural areas and attractive feed-in tariffs [28, 119, 171]

8. Conclusions

Biogas technology is a promising venture globally mainly because of the existence of mature production technologies and applications as well as promising future technologies. Biogas technology is viable and sustainable due to the abundant supply of cheap feedstocks and availability of a wide range of biogas applications in heating, power generation, use as fuel, and raw material for further processing and production of sustainable chemicals including hydrogen and carbon dioxide and biofuels. The flexibility of biogas production in terms of size from small-scale to large-scale industrial size digesters and a wide range of feasible feedstock allows to produce biogas anywhere globally. Biogas production and use is growing globally and is promising to be a leading economical alternative to produce renewable bioenergy.

Biogas is a versatile fuel as it generates less greenhouse gas emission, it is renewable as it is generated from renewable sources, and its production can be used to treat and reduce the organic waste quantity for disposal while disinfecting pathogens in biomass and has a wide portfolio of energy applications in electricity, heat, and cooling applications. Biogas yield from biomass can be increased by appropriate pretreatment of the substrate and monitoring of digestion parameters like C/N ratio, temperature, and substrate dilution. Various biogas to many electricity conversion technologies are available, but trigeneration and combined heat and power show higher conversion efficiencies while fuel cells have the highest level of system reliability. Other technologies identified and proposed include small gas turbine and microgas turbine diesel engines, gasoline engines, Stirling engines, fuel cells, biomethane conversion, biofuel processing, and hydrogen production. Biogas as a fuel presents significant opportunities for direct and indirect use in electricity and heat production in the sustainable energy transition. By application in power generation and fuel production, biogas acts as a substitute for fossil fuels in electricity generation and thermal applications. Through grid electricity generation and supply, biogas has a special role to play in decentralized generation and where investors are both producers and consumers also called prosumers, and hence, biogas energy has a significant role to play in the economic sustainability of the global energy transition.

On the environmental sustainability of the energy transition, biogas use reduces global greenhouse gas emissions and the threat of global warming and climate change. Biogas use helps keep the environment clean by preventing harmful environmental and health impact from the huge agricultural wastes available globally. Therefore, biogas provides financial, economic, environmental, and health benefits for the critical mass of humanity who rely on agriculture for subsistence as well as cash. On social energy sustainability, planned investment in biogas plants utilizing agricultural wastes will help in job creation and generation of extra income streams, hence reducing unemployment while improving the income and hence sustainability of smallholder agriculture and incorporate farmers in the transition to low carbon and green electricity and energy future while leaving a huge positive impact to the society. It is notable that over two-thirds of humanity globally rely on agriculture for their entire livelihood while crop and animal husbandry supply all mankind with the food they need for survival. Through decentralized generation, locally available biomass will be used in grid power generation using biogas and hence transform rural economies and stabilize power systems and effectively help in the realization of goal 7 of the sustainable development goals.

Sustainable exploitation of biogas energy resources requires investment and promotion of both biogas production through investment and technology and creating demand through measures that encourage consumption of biogas in a competitive energy market that has cheaper nonrenewable options. This calls for an institutional framework where deliberate policy and legal measures are put in place to encourage both investment in production and consumption of biogas energy resources. Biogas can be converted to electricity using various available technology options which include diesel engines, petrol engines, use of Stirling engines, and gas turbine technology with micro, small, medium, and large turbines in open or combined-cycle configurations. Others are conversion to hydrogen and fuel cell application which constitute a renewable source of electricity generation. Biomethanation or conversion of biogas to biomethane is another pathway for direct use in heat and power generation as a fuel which can be injected to natural gas pipeline as renewable gas. Biogas engines are made by modification of the conventional compression ignition and spark ignition engines. Full and partial conversion can be done. Microturbines can be used to generate electricity from biogas in small scale and large scale using larger gas turbines in open- or combined-cycle configurations with the advantage of ability to use biogas with less stringent quality requirements compared to internal combustion engines. However, they are more technical and complex to operate and maintain.

Indirect biogas application pathways include converting biogas to transport fuels and electricity generation. The processes include direct heat and power generation from biogas (CHP), compression to CNG and LPG for cleaned biogas, cleaning, and purification before reforming to produce syngas, partial oxidation to produce methanol and gasoline, and the use of the Fischer-Tropsch process to manufacture a variety of chemicals, gasoline, diesel, and jet fuels. This will greatly reduce emissions from the transport sector which accounts for close to 14% of the total greenhouse gas emissions. Various fuels for transportation and other applications can be processed from biogas. These fuels include compressed biogas (CBG), liquid biogas (LBG), methanol, hydrogen, dimethyl ether, and Fischer-Tropsch (FT) fuels. The two different tracks for production of fuels from biogas are upgrading to biomethane before compressing to make (CBG) or liquefying to make (LBG) or gasification of biogas to produce syngas for fuel synthesis of hydrogen, methanol, DME, and FT diesel. Compressed biogas is currently an economically viable option for small-scale applications than other options while liquid biogas has established applications in heavy-duty vehicles and shipping as replacement for liquid natural gas. Other fuels with potential for production from biogas are hydrogen, ME, and FT diesel but not yet at commercial scales.

This study showed that it is feasible to generate grid-connected power from smallholder farms but policy initiatives like tax relief, access to credit, technical support, and development of smart grids to facilitate decentralized generation and development of microgrids. Attractive feed-in tariffs would also promote investment in grid-connected biogas electricity generation from farmers and other small-scale investors with agricultural farm residues and wastes in rural areas by promoting decentralized power generation and microgrid technologies or more advanced smart grid technologies which enhance uptake of variable renewable to the power grid. Development and adoption of efficient conversion technologies and equipment are a key strategy for wider adoption and use of biogas in the future energy transition to green and low carbon sources. The main challenges facing biogas as a fuel are varying quality of output, existence of impurities like hydrogen sulfide which are corrosive to engine parts, low level of technological progress in promising application like hydrogen and fuel cells, and high costs of biomethane production and handling. We therefore conclude that biogas to electricity and biofuel conversion provide sustainable pathways in the global energy transition and realization of the Paris climate and emission targets.

Abbreviations

AD: Anaerobic digestion
ATR: Autothermal reforming
CHP: Combined heat and power
CBG: Compressed biogas
CH_4: Methane
FT: Fischer-Tropsch
kWe: Kilowatt electricity
kWh: Kilowatt-hour
kWth: Kilowatt thermal
kJ: Kilojoule
LBG: Liquid biogas
MPa: Megapascal
Mj: Megajoule
MSW: Municipal solid waste
MWe: Megawatt electricity
MWh: Megawatt-hour
TOE: Tons of oil equivalent
VS: Total volatile solids
ODM: Organic dry matter
POR: Partial oxidation reaction
RNG: Renewable natural gas.

Data Availability

The research has provided all data and information used and did not use any undeclared data and information. However, any datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request

Additional Points

Highlights. (i) There is global commitment by all countries to low carbon and renewable energy resources. (ii) Biogas has an important role to lay in the sustainable energy transition as a renewable energy resource for electricity generation and transportation fuel and as a raw material for processed renewable fuels. (iii) Biogas can be used in the hydrogen transformation as a renewable source of hydrogen for power generation and other thermal applications. Hydrogen can also be used in the manufacture of fuels and industrial chemicals. (iv) Biogas can also be used in fuel cells for direct electricity production with higher conversion and reliability of over 99.99% in electricity generation.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Authors' Contributions

The first author wrote the draft under the guidance of the second author on the theme and content of the paper.

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