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REVIEW

A conceptual review of sustainable electrical power generation from biogas

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Abstract

High-energy demand with rapid industrialization and mechanization combined with environmental pollution due to the burning of fossil fuels has driven a shift toward renewable energy. Biogas derived from biomass is a potential renewable energy source that can be used in different sectors such as transportation sector, electricity generation, heat production, combined heat and power (CHP) systems, and fuel cells. Moreover, the upgraded biogas can be applied as transportation fuel via an internal combustion chamber (for internal combustion engine (ICE) vehicles), and electricity station (for electric vehicles). In the present work, a conceptual review of biogas-based electrical power production systems is presented. It is clear that the conventional types of biomass contain a high amount of pollutants and unwanted constituents, which lower the lower heating value (LHV) of biogas fuel. Moreover, the energy and exergy efficiencies of biogas applications

The contribution of the authors is the same.

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are influenced by these components. Consequently, several biogas-upgrading technologies have been elaborated to increase the LHV of biogas fuel by removing biogas pollutants. So, the energy and exergy analyses of biogas-driven plants are discussed in this regard. Also, the economic analysis of biogas-fueled systems is measured through the connection between biogas production, purchased electrical power, and selling of an additional amount of biogas. Biogas represents an important source of renewable energy as shown before, and it helps in waste management and W-to-E (waste to energy) conversion, which allows utilizing huge amounts of wastes instead of disposal or landfill procedures. However, handling of biogas from production to utilization has an impact on the environment. Therefore, the assessment of the environmental impacts of biogas plants is presented. In addition, a combination of the biogas energy with other sources, especially renewable energy sources (eg, solar-biogas, geothermal-biogas, wind-biogas, CHP, CCHP, and concentrated photovoltaic-biogas), and reusing waste energy for other tasks (eg, employing the waste heat from a gas turbine) are examined.

KEYWORDS

biogas, electrical applications of biogas systems, exergetic modeling, power generation, sustainability

1 | INTRODUCTION

Fossil fuels, such as coal, crude oil, and natural gas, provide much of the world's growing energy supply. In 2018, primary energy consumption grew by 2.9%, which is twice the annual average energy consumption since 2010.^{1,2}

China, United States, and India are responsible for more than two-thirds of the rise in energy demand, which is expected to lead to fossil fuel scarcity over time.^{3,4} In 2018, the use of renewable energy has grown by 14.5% over ten years, but it was lower than expected.⁵ Renewable energy sources accounted for more than 25% of the total world electricity generation in 2018, mainly hydroelectric, wind, and solar energy.^{6,7}

In this regard, sustainable and clean electricity production is a promising approach to satisfy multifaceted objectives. The use of renewable energy can be a solution in providing desirable conditions (both economic and environmental) in the production of electrical power.^{8,9} The detection of resources, investments, and industrial knowledge has crucial roles in promoting renewable and sustainable energy trends in developing countries, while the existence of a logical balance between performance parameters is a critical condition.^{10,11}

Renewable energies are essential to achieve sustainable and clean electricity generation. Among all conventional methodologies for renewable power generation, just about

8.3% of the renewable energy resources belong to bioenergy units.^{12,13}

One of the most influential factors in sustainable power generation is based on the type of fuel. Based on the literature,¹⁴ biogas is an important fuel in producing clean and sustainable electric power. Assessing sustainability entails going further than the conventional environmental life cycle assessment and combining the study of economic aspects with social performance.^{15,16} Regardless of the presence of various renewable resources and green perception for electricity generation, the production rate of electrical power from biogas needs to be effectively recognized and calculated. Life Cycle Assessment (LCA) is a functional approach employed to quantify the environmental sustainability of energy systems.^{17,18} The incorporation of various environmental and economic assessment indicators, through standard scopes and models, further broad insights into the sustainability of the biogas system would be provided.¹⁹⁻²¹

Sustainable power generation through biogas is impacted by biogas production, directly. The sustainability of biogas production is not determined by regional yield but rather by nutrient recovery and operational factors.²² The biogas plants' feedstock and their availability demonstrate the potential of biogas production for utilization as an alternative fuel for sustainable electricity generation.²³ It also has dependency based on the demands

for biogas-based electricity and other energy markets for biogas, for example, the transport sector where the willingness to pay is often higher.

Among renewable energy sources, biogas is more adaptable and flexible in comparison with wind and solar energy, and more economical as it requires less capital investment and operational cost (which may vary depending on geographical location).^{14,24} It features a high energy value, easy storage, and offers dependency regarding the geographical location and season.²⁵

Biogas is produced from different feedstock such as wastewater treatment plants, organic waste, municipal solid waste, or food residues (generally the organic wastes).²⁶ Traditionally (specifically in Asia), biogas was employed for cooking and lighting houses as a low-quality energy source.

The main reason for replacing conventional fuels with biogas is to decrease global warming and provide a renewable energy source. The combustion of biogas produced from waste materials or biomass results in a variable flame temperature, which depends on the amount of methane contained in the biogas. This gives an advantage for using the flue gases from the biogas combustion to provide energy for industrial processes depending on the heat source temperature.²⁷

Nowadays, upgraded biogas has drawn attention because it can be produced when required, easily stored and used in the transportation sector as vehicle fuel.²⁸ Upgraded biogas can also improve energy distribution,²⁹ electricity generation (10% generated from renewable energy sources), heating, and refrigeration separately or simultaneously through combined heat and power (CHP) or combined heat, power, and cooling (CHPC) systems.³⁰⁻³⁴

Recently, biogas is often upgraded to biomethane to be injected into gas grid lines and can be used in fuel cells, or used as feedstock for chemicals

production.^{30-32,35,36} Various sources can be used for biogas production by anaerobic digestion, for instance, municipal solid waste, food, and agricultural and vegetable products such as *Panicum virgatum*, wheat straw, and maize (these three feedstocks provide high yields in methane production).³⁷

In the United States, it has been estimated that under the current circumstances and the use of available sources, biogas has the potential to generate energy equal to 17,000 metric kilotons of oil equivalent. Meanwhile, it allowed reducing greenhouse gas emissions by 4.33 million metric tons of carbon dioxide in 2018, which could be accounted for one of the main environmental benefits of biogas.³⁸

Figure 1 shows the use biogas from 2000 to 2019, where the highest consumption of biogas occurred in CHP systems (in USA). Next, the utilization of biogas for power production has shown that it experienced a steady increase from 2000 to 2013, after which it has grown at slower rate. Since 2017, natural gas and compressed natural gas production based on renewable energy have grown.³⁸

Anaerobic digestion, which happens in the absence of oxygen, is a process consisting of breaking down biodegradable materials. The four main steps of this phenomenon are hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

If the feedstock is available and cheap, biogas production will be usually economically viable. Much research has been done to date on increasing the efficiency of methane production, improving digestion, optimizing the operating conditions and process design, and selecting feedstock.³⁹⁻⁴²

Carbon dioxide and methane are the main components of biogas. Other components in the biogas cause corrosion in the heat exchanger components and reduction in heat transfer. Depending on the type of feedstock, other

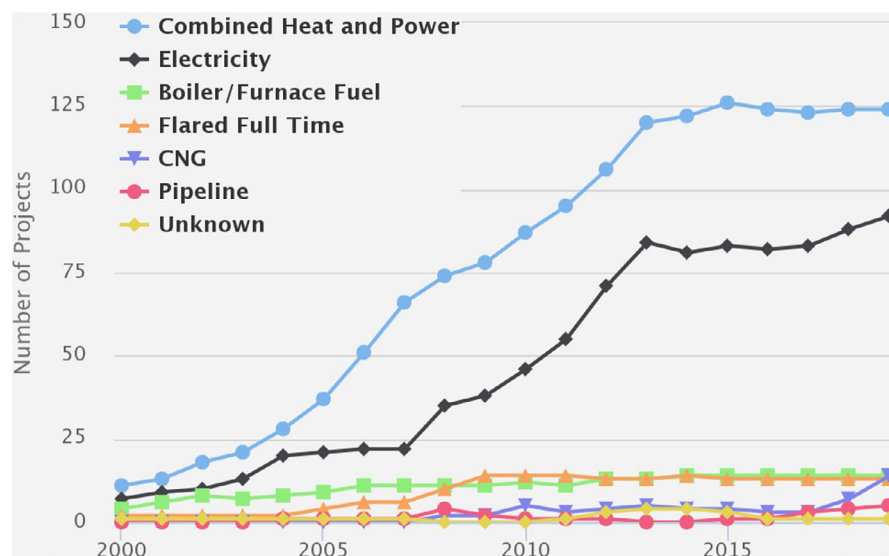


FIGURE 1 The trend of biogas consumption for various applications in the USA from 2000 to 2020³⁸

impurities such as siloxane, ammonia, and hydrogen sulfide exit in the produced biogas.⁴³ Compositions of natural gas, landfill biogas, and anaerobic digestion biogas are tabulated in Table 1.⁴⁴

In this article, a review of biogas applications for electricity production is reported. Recent developments of installed biogas production and utilization plants are presented. A comprehensive study is performed on biogas-driven electrical power production plants. An in-depth overview of energy and exergy analyses of biogas-fueled plants is provided. Table 2 summarizes previous works related to the use of biogas in generating electric power.

2 | BIOGAS-FUELED ELECTRICAL POWER PRODUCTION

Electricity generation from biogas is still relatively novel in the world, but in industrialized countries, this application is more common. Due to the environmental impacts of fossil fuels, applications of biogas for electricity production such as gas turbines in different capacities and usages as fuel in internal combustion engines are gaining more interest.⁴⁷

A comprehensive investigation on the utilization of biogas systems suggesting the utilization of biogas can be categorized into four subcategories based on the final use⁴⁸ as:

- Electricity generation from power plants, CHP units, and fuel cells.
- Production of heat using a boiler.
- Heat from power plants, CHP systems, and fuel cells.
- Transportation fuel via internal combustion engines (for ICE vehicles), and electricity station (for electric vehicles).

Outcomes of a research work (Hakawati et al.⁴⁸ in 2017) revealed that for the biogas systems based on anaerobic digestion facility and biogas composition the energy efficiency could vary from 8% (steam reforming of methane) to 54% (upgrading of biogas to biomethane) for electricity generation, 16% to 83% for heat production, and 18% to 90% for the CHP system. This study clearly showed that the application of biogas systems was more attractive for CHP usages (in comparison with other fuels). So for this reason, the application of this renewable energy is more appropriate in this field.

Barzegaravval et al.⁴⁹ performed an exergy-economic evaluation of a gas turbine with a preheater driven by biogas with different methane contents (Figure 2). This study showed the methane volume fraction of the biofuel

decreased from 0.95 to 0.6, and the gas turbine total cost increased by about 1%, hence the electricity production cost increased. Furthermore, by changing the output power of the gas turbine from 1 to 10 MW, the electricity generation cost varied from 0.05 \$/kWh to 0.18 \$/kWh.

2.1 | Micro gas turbine system

Applications of biogas for CHP production in different locations with different biogas resources have been studied in many research works. In these studies, different aspects of energy, exergy, produced electricity, heat, cost of electricity (COE) generation, and cost of heat (COH) production were examined.^{14,50,51} Kang et al.⁵² performed an economic assessment on the gas turbine for CHP that used natural gas and biogas mixture (Figure 3). The results of this study showed that COE and COH increased with the increase in the natural gas ratio. The heat sales ratio and the mixing ratio had a significant impact on the payback period. This survey also estimated that the COE was 0.1436 \$/kWh, and COH was 0.0738 \$/kWh for the CHP system.

Kim et al.⁵³ used biogas to run a micro gas turbine (MGT), which is combined with an organic Rankine cycle (ORC) as shown in Figure 4. The biogas of this system was provided by sewage sludge and food waste. The results revealed that the annual thermal energy produced by an MGT in the case of CHP plant was 7.4 MWh per year, while it was 9.0 MWh per year for the combination of ORC and MGT.

Similarly, a thermoeconomic analysis of biogas-fueled MGT with an ORC was investigated. This research concluded that the system economy could be competitive, depending on the methane ratio in biogas; while a higher methane ratio is more beneficial.⁵⁴ The economic feasibility of the gas cycle fueled with biogas for CHP (Figure 5) and combined cycle (CC) (Figure 6) was examined. The results of this study showed that the CHP system was more beneficial than the CC system based on several economic parameters.⁵⁵

2.2 | Fuel cell

Saadabadi et al.⁵⁶ conducted a comprehensive study on the application of hybrid anaerobic digestion (AD) unit and solid oxide fuel cell (SOFC) (Figure 7). Furthermore, an outline for the benefits and difficulties of the hybrid integration of AD and SOFC systems was examined to measure the performance of this system for electricity generation and usage of heat produced by SOFC. The outcomes showed that the high temperature produced

TABLE 1 Compositions of natural gas, landfill biogas, and anaerobic digestion biogas adapted from^{45,46}

Component	Natural gas	Landfill biogas	Anaerobic digestion biogas
Carbon dioxide (%)	0.7–1	25–47	30–50
Methane (%)	81–89	30–65	53–70
Oxygen (%)	0	<1–3	0–5
Nitrogen (%)	0.28–14	<1–17	2–6
Hydrogen (%)	NA	0–3	NA
Higher hydrocarbons (%)	3.5–9.4	NA	NA
Ammonia (ppm)	NA	0–5	<100
Hydrogen sulfide (ppm)	0–2.9	30–500	0–2000
Siloxane (%)	NA	<0.3–36	0.08–0.5
Overall chlorines (%)	NA	0.3–225	<0.25

heat by the SOFC unit could increase the volume of biogas production, which resulted in increasing the total efficiency.^{56–59}

A new configuration of the hybrid combination of SOFC and MGT fueled by biogas was proposed by Wongchanapai et al.⁶⁰ The key concept of this research was the application of the internal reformation unit in SOFC for the internal transformation of methane into hydrogen. A comprehensive set of data was obtained and reported in this study.⁶⁰

The achievements of hybrid integration of a molten carbonate fuel cell (MCFC) and MGT fueled by natural gas and biogas for power production (Figure 8) were analyzed by Huang et al.⁶¹ It was found that the output power of the MCFC-MGT system increased from 39.0% to 42.0% due to the increase in the biogas flow rate. Moreover, the hybrid MCFC/MGT power system was easy to operate and stable with power variation. Finally, this hybrid MCFC/MGT system could be applied for power generation of a network at a micro-scale.^{61–63}

2.3 | Internal combustion engine (ICE)

The low speed of the ignition process, severe back burning, and high temperature of the flue gas are the main drawbacks of biogas engines.⁶⁴ In this case, the speed of combustion process using CH₄ was 37.3 cm/s, while the presence of CO₂ reduced this value down to 23 cm/s. Therefore, the burning continued in the stack (post-combustion) and associated combustion quality reduced correspondingly.⁶⁵ In response to the flame high temperature, spontaneous

combustion is a rare process in these engines with burning biogas as fuel.

The achievement of a diesel engine was inspected for different fuels consisting of diesel fuel, natural gas, mixture of methane with biogas, and stand-alone biogas by Chandra et al.⁶⁶ The outcomes showed that the generated power of the engine was decreased by 31.8% for compressed natural gas, 35.6% for methane-enriched biogas, and 46.3% for raw biogas relative to diesel fuel. Moreover, it was found that the methane-enriched biogas and compressed natural gas were similarly based on thermal efficiency, power output, and specific gas consumption.

The chemical properties of biogas such as purity and composition significantly affect IC engine performance.⁶⁷ It is worth mentioning that compressed natural gas (CNG) and biogas have similar compositions, making the use of biomethane as the source of energy in vehicles possible. Table 3 shows the compositions of biogas and CNG.

The use of biogas as a fuel in engines has even more merits in comparison with other fuels. The main advantages of this energy source are economic, environmental friendly, and ecological. Utilization of biogas reduces exhaust emissions of carbon dioxide (up to 70%), sulfur compounds (up to 25%), carbon monoxide (up to 90%), hydrocarbons (up to 80%), and nitrogen oxides (50–86%) (in comparison with CNG).^{69,70} The degree of purity of biogas is dependent on the process utilization. Requirements to eliminate gaseous species based on the biogas application given in Table 4.

Yingjian et al.⁷² analyzed the energy balance and assessed the achievement of the power generation by IC engine when biogas was used as the working fuel. The thermal energy dissipated from the engine exhaust was the highest of all, which was about 40.34%.

Qian et al.⁷³ stated that consuming biogas in a dual-fuel approach was an improved method to attain the optimal use of biogas. Associated with diesel engines, the CO and HC productions of the dual-fuel mode by biogas were enhanced; nonetheless, the soot and NO_x released were reduced. Cacho et al.⁷⁴ developed a spark-ignited internal combustion (SIIC) engine propelled by biogas-gasoline for which the experimental results revealed that the maximum power was 5.97 kW at 3600 rpm for 8:1 compression ratio. An experimental examination of the ignition and flue gas descriptions of dual-fuel combustion (biogas/biodiesel) of the compression ignition (CI) engine was performed by Yoon et al.⁷⁵ For the dual-fuel approach, the highest heat removal for biogas and biodiesel fuels were marginally less than the amount of biogas–diesel. Dobslaw et al.⁷⁶ studied the influence of various types of IC engines and adjustments of the working constraints of the engine on the emission spectrum.

TABLE 2 Comparative analysis of biogas surveys for electric power generation

Ref. no.	Country	Biogas sources	Energy scenario	Economic study	Environmental impact	Bio-power generation	Challenges in biogas generation	Type of study
12	Thailand	Green waste	✓	✓	×	✓	✓	Case study
12	China	Municipal solid waste	✓	✓	✓	✓	✓	Case study
3	Iran	Animal waste and agriculture residues	✓	×	✓	✓	✓	Case study
4	Benin	Solid waste and agriculture biomass	✓	✓	×	✓	✓	Case study
5	Indonesia	Cattle dung	✓	✓	✓	✓	✓	Case study
6	China	All	✓	×	×	✓	✓	Review
7	Turkey	Animal manure	×	✓	×	✓	×	Case study
8	South Africa	Human wastes	×	✓	×	✓	×	Case study
9	Pakistan	Biomass wastes	✓	✓	✓	✓	✓	Review
10	Brazil	Vinasse	✓	✓	×	✓	×	Case study
11	Brazil	Vinasse	✓	✓	✓	✓	✓	Case study
12	Bangladesh	Organic waste	×	×	✓	✓	×	Case study
13	Germany	All	✓	✓	×	✓	✓	Case study
14	Indonesia	Fruit waste	×	×	✓	✓	×	Case study
15	Ukraine	Agricultural residues and industrial waste	✓	✓	×	✓	✓	Case study
16	Ukraine	Animal manure	✓	×	✓	✓	×	Review
17	India	Biomass wastes	✓	✓	×	✓	✓	Case study
Present study		All	✓	✓	×	✓	✓	Review

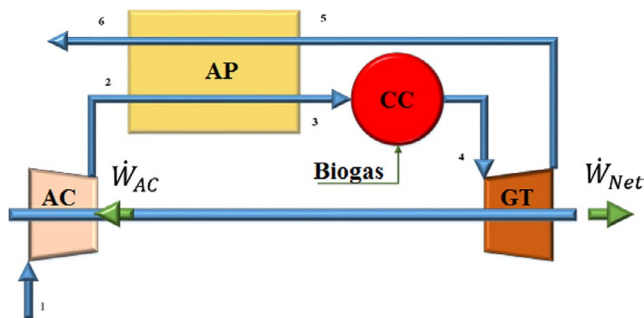


FIGURE 2 Flow diagram of gas turbine cycle with a preheater for power production⁴⁹

Technical and economical evaluations of a multi-generation system based on biogas have been reported by Khan et al.⁷⁷ In these systems, energy conversion stages were examined for various combustion variables. Moreover, the levelized cost of electricity (LCOE), gas for cooking purposes, and freshwater production (by membrane distillation) in terms of energy and economics have been analyzed.

3 | ENERGY ANALYSIS OF BIOGAS-FUELED SYSTEM

The presence of CO_2 and N_2 in biogas influences the energy and exergy efficiencies. Consequently, several biogas-upgrading technologies have been elaborated to increase the LHV of the fuel by removing biogas pollutants. As shown in Figure 9, these technologies include chemical scrubbing, membrane separation, pressure swing adsorption (PSA), and pressured water scrubbing (PWS). The water scrubbing technology has been proved to be one of the simplest and cheapest technologies because of its high efficiency and low CH_4 loss, as well as the possibility of hydrogen sulfide (H_2S) removal.^{14,78,79}

For CO_2 removal, Xu et al.⁷⁸ calculated the energy efficiency of three biogas-upgrading techniques namely ionic liquid scrubbing (ILS), pressured water scrubbing (PWS), and monoethanolamine aqueous scrubbing (MAS). Their study also involved methane (CH_4) recovery ratio calculation along with the specific energy consumption, and the CO_2/CH_4 selectivity.

The methane recovery ratio (MRR) can be written as⁷⁸:

$$\text{MRR} = \eta_{\text{CH}_4} \frac{v_{\text{out}} \cdot C_{\text{out}}}{v_{\text{in}} \cdot C_{\text{in}}} \cdot 100\% \quad (1)$$

where v_{in} denotes the biogas volumetric flow rates (m^3/h) and v_{out} stands for the volumetric flow rates of produced gas (m^3/h), C_{in} represents the concentration of the methane in

biogas, and C_{out} represents the methane concentration in produced gas.

The specific energy consumption (SEC) in kWh/m^3 CH_4 is obtained in terms of the total energy consumption (TEC) rate (kW) as⁷⁸:

$$\text{SEC} = \frac{\text{TEC}}{v_{\text{out}} \cdot C_{\text{out}}} \quad (2)$$

The energy efficiency (η_i) of gas separation technology can be expressed by the following equation⁷⁸:

$$\eta_i = \frac{Q_{\text{out},p}}{Q_{\text{in},f} + Q_{\text{in},u} + \frac{E_{\text{in},u}}{\sigma}} \quad (3)$$

where $Q_{\text{in},f}$ is the feed gas lower heating value, $Q_{\text{out},p}$ is the produced gas lower heating value (MWth), $Q_{\text{in},u}$ is the required heat of the solvent regeneration, heating, and evaporation processes (MWth), $E_{\text{in},u}$ is the electrical energy required by the driving machines in the process (MWh), and σ is the conversion efficiency of steam to electricity (about 20–40%).⁷⁸

The solvent selectivity S is calculated in terms of H_{CH_4} and H_{CO_2} , which are the Henry constants of CH_4 and CO_2 , respectively, at a specific temperature, as follows⁷⁸:

$$S = \frac{H_{\text{CH}_4}}{H_{\text{CO}_2}} \quad (4)$$

The theoretical energy consumption is the minimum energy demand for the separation of CO_2 and CH_4 , which is expressed as⁷⁸:

$$E_{\text{theor}} = nRT \left[x_{\text{CO}_2} \ln \left(\frac{1}{x_{\text{CO}_2}} \right) + x_{\text{CH}_4} \ln \left(\frac{1}{x_{\text{CH}_4}} \right) \right] \quad (5)$$

Figure 10 shows that the ILS and PWS energy consumptions were about 50% lower compared to MAS technology due to the fact that the ILS and PWS are physical absorption processes in which the absorbed CO_2 demands less energy when released with air stripping. Meanwhile, MAS is a chemical-absorption process where heating is needed for solvent vaporization.

European Union suggested that a major part of the energy generation could be supplied by biogas sources, and therefore, its consumption in energy generation is likely to increase. In this context, some researchers have focused their study on the efficiency of using biogas as fuel. Brizi et al.⁸¹ have conducted research aiming at comparing the usage of biogas and natural gas for a cogeneration system.

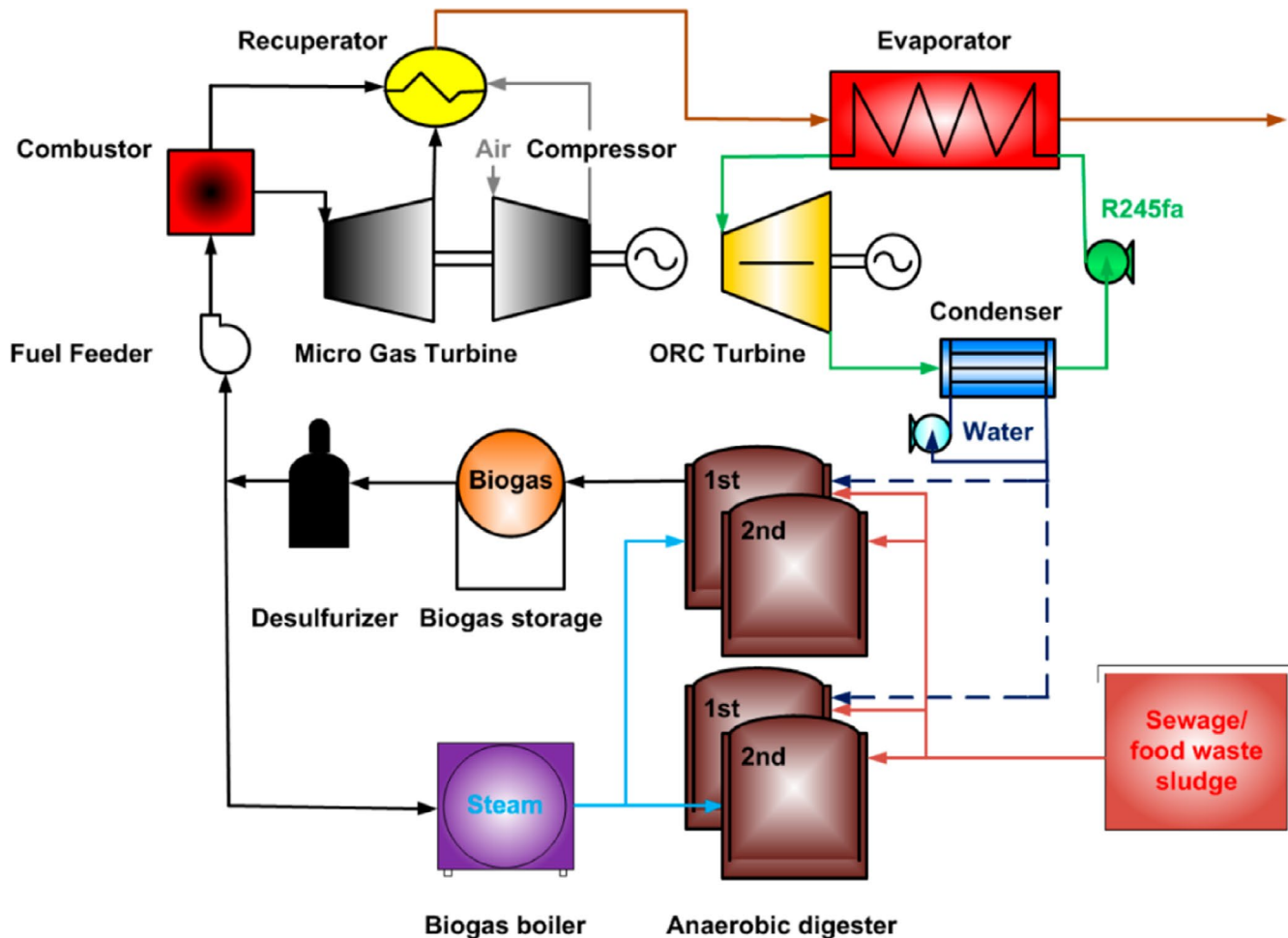


FIGURE 4 Combination of MGT with a biogas production unit and ORC⁵³

The system thermal efficiency is written as⁸⁶:

$$\eta_{thermal} = \frac{n_{H_2}^{out} \cdot LHV_{H_2} + n_{CO}^{out} \cdot LHV_{CO}}{n_{CH_4}^{in} \cdot LHV_{CH_4} + Q_R + n_{Steam}^{in} \cdot \Delta H_L} \quad (7)$$

$$Q_R = H_T^{out} - H_T^{in} \quad (8)$$

$$H_T^{in} = \sum_{i=1}^{N_1} n_i^{in} h_{T,i}^{in} = \sum_{i=1}^{N_1} n_i^{in} \left[h_{298,i} + \int_{298}^T c_{p,i} dT \right] \quad (9)$$

$$H_T^{out} = \sum_{i=1}^{N_2} n_i^{out} h_{T,i}^{out} = \sum_{i=1}^{N_2} n_i^{out} \left[h_{298,i} + \int_{298}^T c_{p,i} dT \right] \quad (10)$$

where LHV denotes lower heating value (kJ/mol) and ΔH_L is the latent heat enthalpy change (kJ/mol). Q_R is the net variation in total enthalpies of inlet and outlet reformer streams (kJ/mol). $h_{T,i}^{out}$ and $h_{T,i}^{in}$ are the specific enthalpies of constituent i th of the outlet and inlet streams at temperature T (kJ/mol), respectively. $H_{298,i}$ is the molar enthalpy of component i at 298 K (kJ/mol) and $c_{p,i}$ is the component of i heat

capacity (kJ/kmole). The outcomes of the system modeling are presented in Figures 11 and 12. For a CH_4/CO_2 ratio from 45/55 to 80/20, the energy efficiency of the reforming process is between 92.4 and 91.5%. The energy required per mole of biogas was found to be between 109 kJ and 179 kJ. The authors concluded that the product gas of biogas steam reforming obtained from various feedstock could be used as a fuel for SOFC and produce an electrical power up to 158 kW for 40% of methane and 280 kW for 80% of methane.

Furthermore, for high-efficiency power plants, researchers have examined multi-generation systems driven by hybrid technologies with biogas integration. Mosaffa et al.⁸⁷ focused on a multi-generation process conducted by a solar-biogas hybrid system as heat and power source to produce hydrogen and methanol. The system was composed of solar-based biogas-steam reformer, PSA unit, carbon capture, and sequestration unit Rankine and organic Rankine cycles, gas turbine cycle, and methanol synthesis unit. The thermoeconomic analysis showed a 15% decrease in energy efficiency with a 200 K increase in the temperature. Rostamzadeha et al.⁸⁸ also conducted a study on a multi-generation technology driven by a

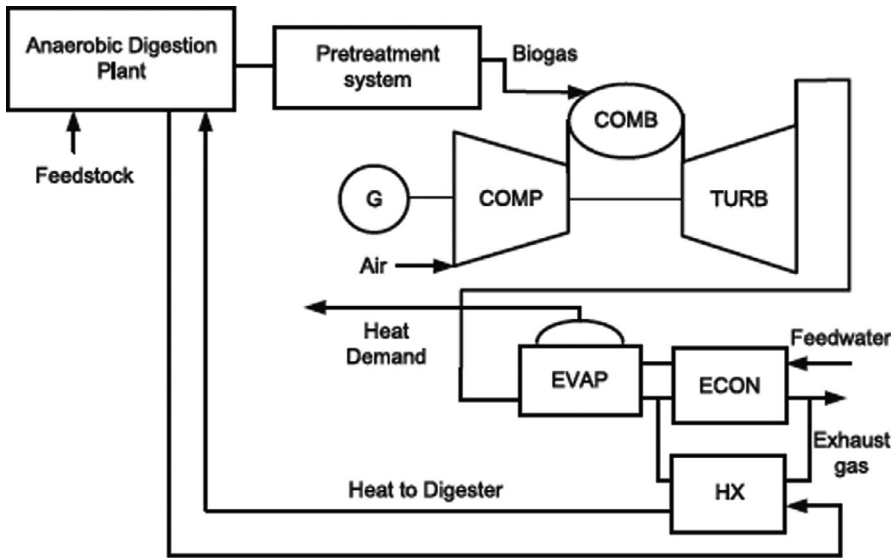


FIGURE 5 An illustration of CHP system configuration powered with an anaerobic digestion plant (case 1)⁵⁵

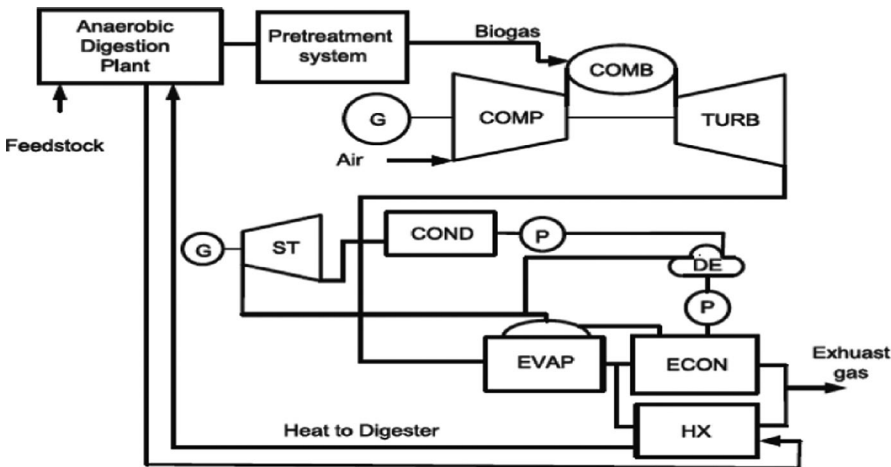


FIGURE 6 An illustration of combined cycle configuration powered with an anaerobic digestion plant (case 2)⁵⁵

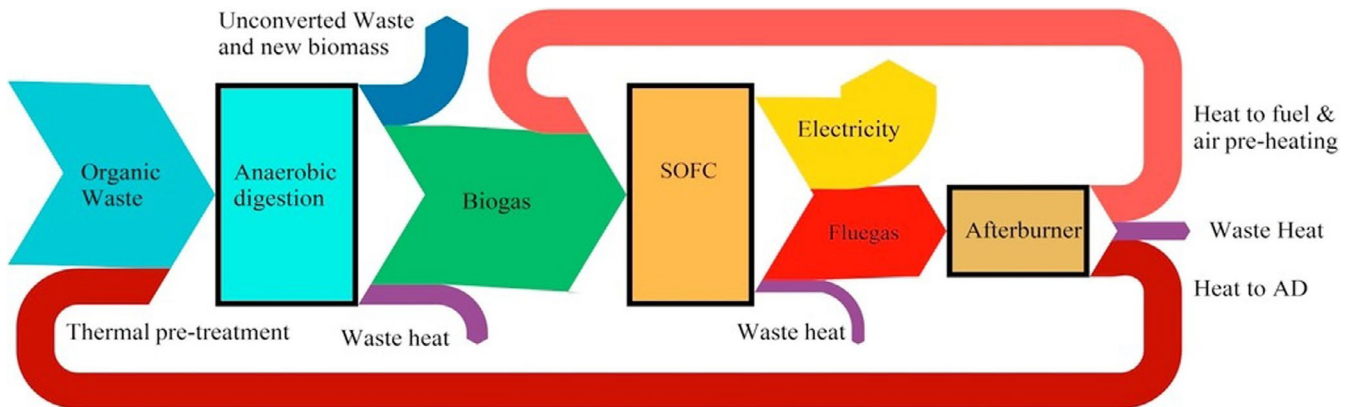


FIGURE 7 AD-SOFC system energy flow diagram⁵⁶

biogas-geothermal hybrid system as a heat source, where they performed a comparison to the single-generation system, which showed a considerable improvement in the thermal efficiency up to 62.3%. Moreover, the multi-generation system produced an overall heating power of 538.1 kW, a cooling capacity of 1799 kW, a net output

power of 443.4 kW, a mass flow rate of produced hydrogen 0.26 kg/s, and 367.9 L/h of freshwater. Bamisilea et al.⁸⁹ modeled a multi-generation system powered by renewable energy sources, which are wind, biomass, and solar using a wind turbine, biogas, and concentrated photovoltaic/thermal (CPVT). Various case studies such as

FIGURE 8 Schematic diagram of hybrid MCFC/MGT power system for power production⁶¹

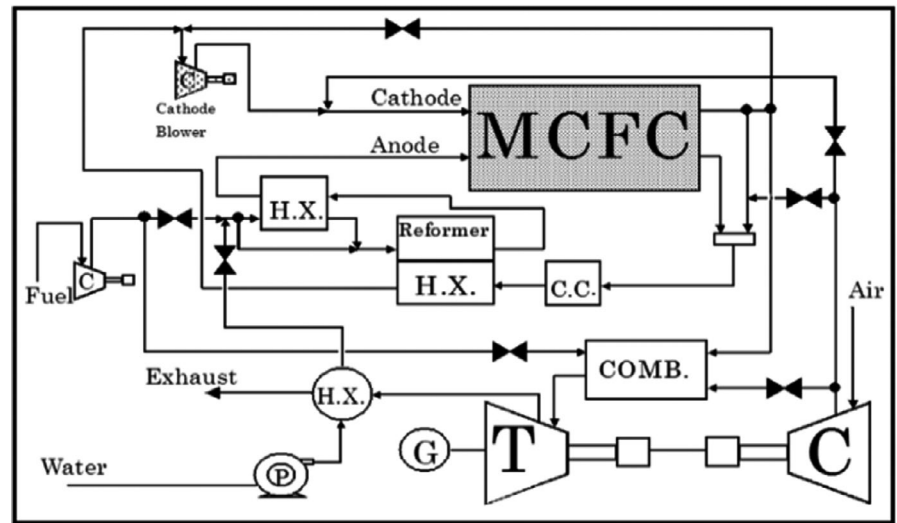


TABLE 3 Comparison of compositions (%) of biogas and CNG⁶⁸

Component	Biogas (high purity)	CNG
CH ₄	55–75	97.4
CO ₂	25–45	0.07
H ₂ O	1–5	-
O ₂	0.1–0.5	-
C ₃ H ₈	-	0.22
Noble gases	-	0.13
N ₂	0–0.3	1.22
H ₂ S	0–3	-
C ₂ H ₆	-	0.94

CPVT-wind, CPVT-biogas, wind-biogas, and stand-alone biogas were evaluated and compared. The system energy efficiency was expressed as follows⁸⁹:

$$\eta_{en,power} = \frac{\dot{W}_{net,power}}{\dot{Q}_{in,solar} + \dot{Q}_{in,WT} + \dot{Q}_{in,biogas}} \quad (11)$$

where $\dot{W}_{net,power}$ is the net output power (kW), $\dot{Q}_{in,solar}$ is the input solar energy rate (kW), $\dot{W}_{in,WT}$ is the input wind turbine power (kW), and $\dot{Q}_{in,biogas}$ is the input heat rate to the biogas system (kW), which can be calculated as follows⁸⁹:

$$\dot{Q}_{in,biogas} = \dot{m}_{biogas} \times LHV \quad (12)$$

where \dot{m}_{biogas} is the mass flow rate of the biogas (kg/s) and LHV is the lower heating value (MJ).

The results of this study showed that systems with biogas integration were the most efficient. Energy efficiency up to 71.1% and 67.8% was obtained for CPVT/biogas integration and wind/biogas integration technologies,

respectively. In contrast, corresponding values of 69.9%, and 64.9% were achieved for the CPVT/wind integration and stand-alone biogas technologies, respectively.

Conventional steam Rankine power plants fueled by biomass are capable of producing power output less than 50 MW,⁹⁰ for which the electric efficiency is ranging between 15% and 35% depending on the installed capacity. At low operating temperatures (less than 300°C), ORC power plants can be used using biomass with efficiency less than 25% and power output capacity less than 2 MWe.⁹¹

Internal combustion engines and Stirling engines running by biogas produced from biomass gasification process are capable of producing about 100 kWe and 20 MWe, respectively.⁹² Thermodynamic models are not enough to maximize the efficiency of power plants running by biofuels. Hence, to promote the biomass utilization efficiency in Rankine power plants, a supercritical Rankine power plant is implemented, where the steam is heated above its critical temperature and pressure, that is, 374°C and 22 MPa.

4 | EXERGY ANALYSIS OF BIOGAS-FUELED SYSTEMS

Exergy is introduced to determine the most possible available work which could be obtained through a process that is reversibly in mechanical, chemical, and thermal equilibrium with its surrounding at reference state of temperature, pressure, and chemical potential.^{93–95}

The specific exergy with chemical composition change is defined as^{93,94}:

$$e_i = (h_i - h_o) - T_o (s_i - s_o) + i \sum x_i (\mu_i - \mu_{io}) \quad (13)$$

Utilization	H ₂ O	CO ₂	H ₂ S	Siloxane
Vehicle fuel	Affirmative	Optional	Affirmative	Negative
CHP engine	No-condensation	Negative	<500 ppm	Negative

TABLE 4 Gaseous removal from biogas for different purposes⁷¹

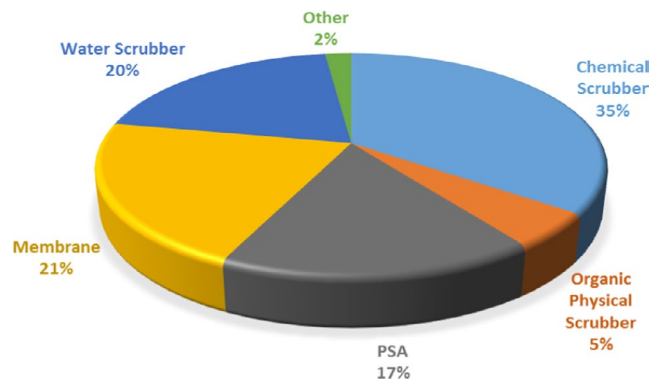


FIGURE 9 Distribution of current technologies for biogas-upgrading methods around the world⁸⁰

where h is the specific enthalpy (kJ/kg), s is the specific entropy (kJ/kg K), T is the temperature (K), x is the mole fraction, and μ is the chemical potential (kJ/kg). T_o (K) and p_o (kPa) are the reference environment conditions, respectively.

The useful work of a steady-state open system is^{93,94}:

$$\dot{W}_{useful} = \sum_i \dot{n}_i e_i + \sum_j \left(1 - \frac{T_o}{T_j} \right) \dot{Q}_j - T_o \dot{S}_{gen} \quad (14)$$

where \dot{Q}_j (kW), T_j (K), \dot{n}_i and \dot{S}_{gen} (kW/K) are the heat transfer rate, and the temperature at which heat is exchanged, molar flow rate, and rate of entropy generation, respectively.

The specific exergy is expressed as^{93,94}:

$$e_i = (h_i - h_o) - T_o (s_i - s_o) + e_{ch} \quad (15)$$

where the specific chemical exergy, e_{ch} , is^{93,94}:

$$e_{ch} = \sum_i (x_i e_{ch}^o + RT_o x_i \ln x_i) \quad (16)$$

where e_{ch}^o (kJ/kg) is the standard chemical exergy for which the values are published in literature.^{93,94}

Exergy efficiency, which is defined as the proportion of the produced power to the reversible power (maximum), can be written as^{93,94,96-99}:

$$\eta_{ex} = \frac{\dot{W}}{\dot{W}_{rev}} \quad (17)$$

Exergy analysis was used as an efficient thermodynamic technique to improve the performance of SOFC.¹⁰⁰ The exergy analysis has been presented on the SOFC system consisting of the evaporator, preheater, reformer, and afterburner. The results showed that a 73% improvement occurred in exergy efficiency for 600% theoretical air.¹⁰⁰

The performance of SOFC using sugar cane bagasse as a source of biogas has been presented using exergy analysis.¹⁰¹ The total exergy efficiency was 35% at a temperature of 1023 K and an air factor of 0.2. A detailed thermodynamic analysis has been conducted showing that a great proportion of the exergy destruction (lost work) was within the gasifier, which contributed to about 80% of the total exergy loss.¹⁰¹ SOFC system has been investigated thermodynamically using exergy and economic analyses.^{102,103}

SOFC has been integrated with steam-injected gas turbine and gasifier using woodchips as a biogas fuel source for the fuel cell.^{102,103} The exergy efficiency of the combined plant was about 43%, which is much higher than that of conventional plants using biomass as fuel.^{102,103} An anaerobic digester (AD) has been used to produce biogas for SOFC,¹⁰³ and the results showed the AD-SOFC system exergy efficiency was reduced with the growth in the current density. Moreover, the effects of SOFC operational conditions, for example, pressure, fuel consumption, and air stoichiometric ratio on the exergy efficiency, have been discussed.¹⁰³

Exergy analysis of SOFC using different gaseous fuels produced from biomass gasification unit has been presented.¹⁰⁴ The SOFC was integrated with the internal reforming unit. Three gasifiers, namely, dual, circulating, and bubbling fluidized beds, have been used to produce syngas products¹⁰⁴ for the use in the SOFC, which was combined with the ORC and an absorption chiller. This integration system resulted in 50% exergy efficiency.

The performance of SOFC using biogas as fuel has been optimized using exergy analysis.⁸⁵ For this purpose, a simulation code THERMAS has been used to analyze the effects of temperature and fuel composition on the system performance. The system in question consisted of the preheater, SOFC, reformer, and burner. The results of the simulation indicated that low methane fuel was the ideal option from an exergy efficiency standpoint. The most important result obtained in the analysis⁸⁵ was that the temperatures of the fuel cell and the reformer should be the same and above 1000 K in optimal conditions.

FIGURE 10 Demonstration of ILS, MAS, and PWS unit energy consumptions and circulating solvent flow rates⁷⁸

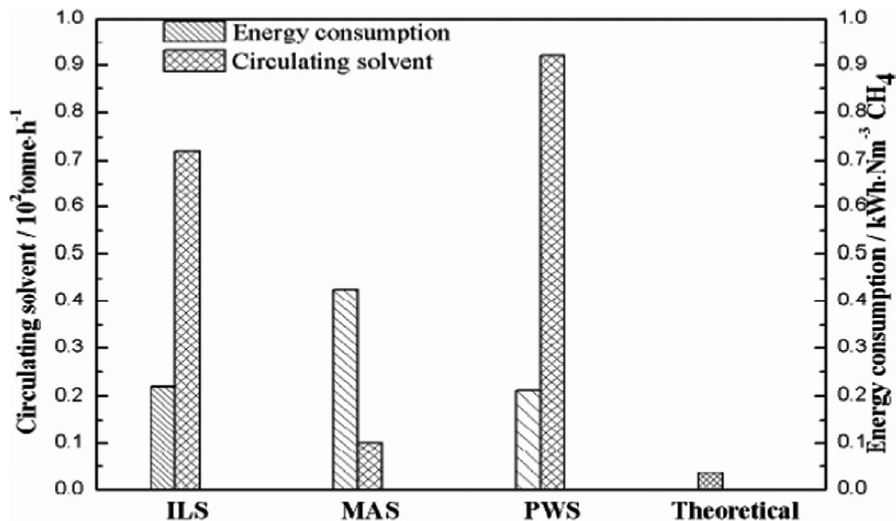


TABLE 5 Typical energy quantities and efficiencies of three various biogas utilization systems⁸⁴

System	Net electricity output (MJe/day)	Net heat recovery (MJth/day)	Net electric efficiency (%)	Net heat efficiency (%)	Energy efficiency (%)
Biogas-improvement	-	-	-	-	46.5
Biomethane-CHP plants	4139.8	5202.5	13.8	16.6	30.4
Biogas-SOFCs	5286.5	3530.6	20.4	12.5	32.9

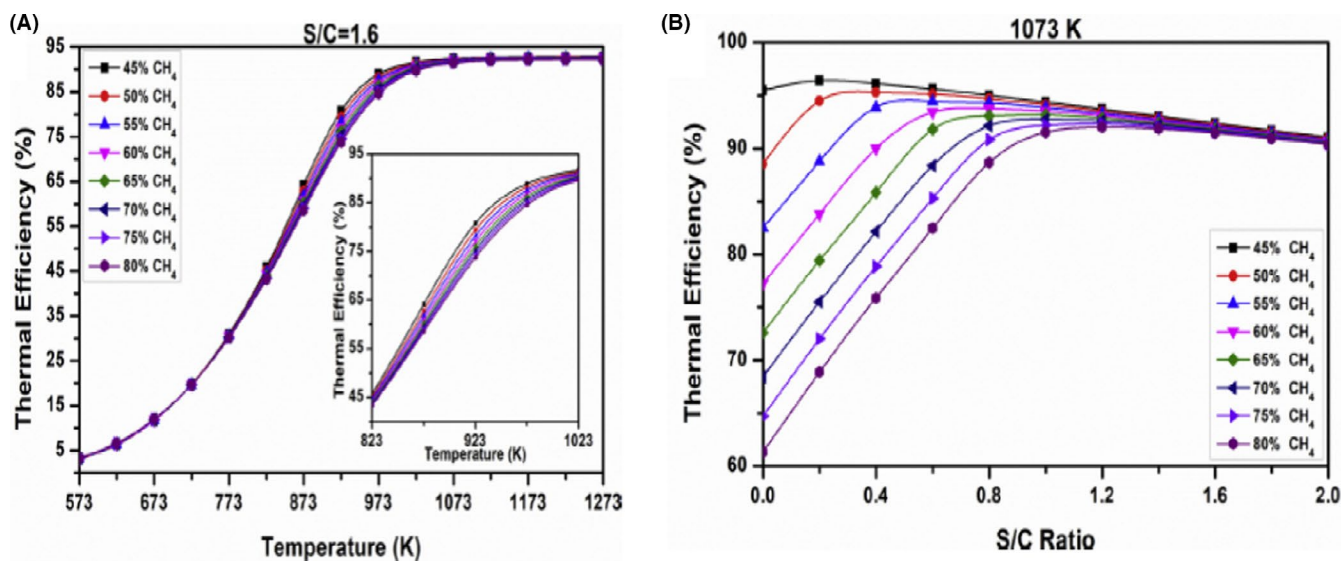


FIGURE 11 Thermal efficiency variations for different biogas compositions.⁸⁶ (A) Temperature effect at constant S/C = 1.6 and (B) S/C effect ratio at constant temperature of 1073 K

A comparison between SOFC integrated with reformer and SOFC fed with upgraded biogas obtained from CO₂ separation membranes has been presented based on exergy analysis.¹⁰⁵ Exergy analysis of an integrated plant containing biomass gasification unit, gas expanders, SOFC, and Kalina cycle has been proposed.¹⁰⁶ In this

hybrid system, a carbon dioxide capture unit has been implemented. It has been stated that the use of exergy analysis to determine the exergy destruction of each sub-unit of the hybrid system was an effective tool to improve the system performance.¹⁰⁶ The effects of biomass moisture content and dry biomass mass flow rate have been

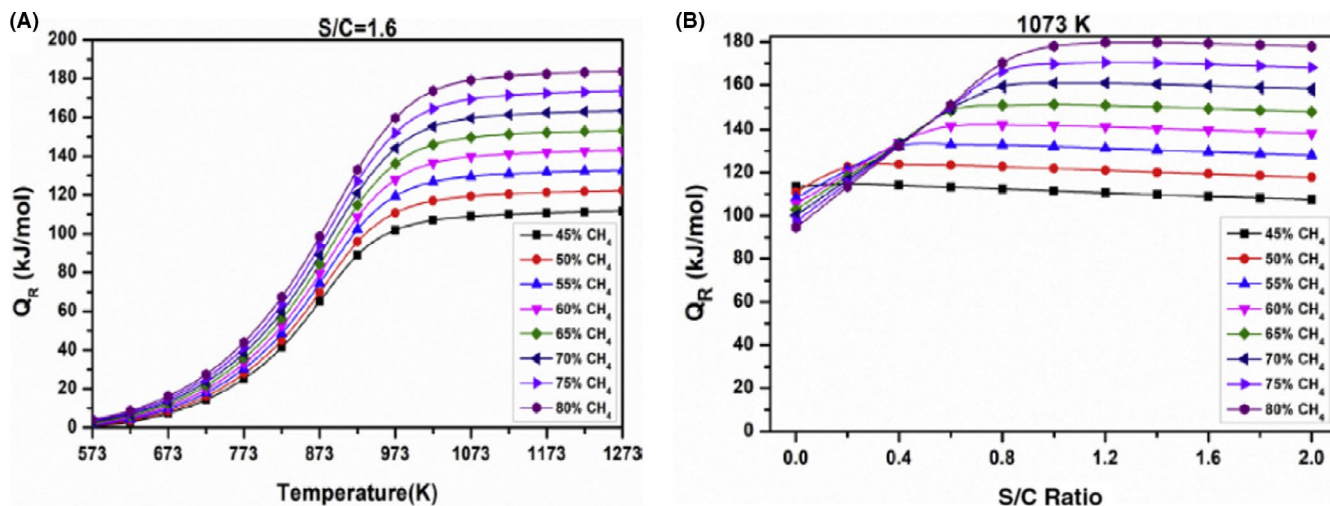


FIGURE 12 Energy requirement for different biogas compositions.⁸⁶ (A) Temperature effect at constant S/C = 1.6. (B) S/C effect at constant temperature of 1073 K

TABLE 6 Chemical reactions and thermodynamics properties at standard conditions (25°C and 100 kPa) for SOFCs using biogas

Electrochemical reaction	Δs° (kJ/mole)	Δh_f° (kJ/mole)	Δg_f° (kJ/mole)	Chemical reaction
$\text{CH}_4 + \text{CO}_2 \leftrightarrow 2\text{CO} + 2\text{H}_2$	256.542	247.023	170.535	MDR
$\text{CO}_2 + \text{H}_2 \leftrightarrow \text{CO} + \text{H}_2\text{O}$	42.045	41.138	28.602	RWGS
$\text{CH}_4 \leftrightarrow \text{C} + 2\text{H}_2$	80.73	74.6	50.53	MP
$\text{H}_2 + 0.5\text{O}_2 \leftrightarrow \text{H}_2\text{O}$	-44.42	-241.8	-228.6	HOR
$\text{CO} + 0.5\text{O}_2 \leftrightarrow \text{CO}_2$	-86.466	-283	-257.2	CMOR
$\text{CH}_4 + \text{CO}_2 \leftrightarrow 2\text{CO} + 2\text{H}_2$	214.5	205.885	142	MDR
$\text{CH}_4 + \text{H}_2\text{O} \leftrightarrow \text{CO} + 3\text{H}_2$	172.45	164.075	113.33	MSR
$\text{CH}_4 + 2\text{H}_2\text{O} \leftrightarrow \text{CO}_2 + 4\text{H}_2$	175.812	172.42	120	MFSR
$\text{C} + \text{CO}_2 \leftrightarrow 2\text{CO}$	133.767	131.3	91.4	CDCG
$\text{C} + \text{H}_2\text{O} \leftrightarrow \text{CO} + 2\text{H}_2$	170.076	-35.94	-86.65	SCG
$\text{CH}_4 + 0.5\text{O}_2 \leftrightarrow \text{CO} + 2\text{H}_2$	-5.233	-802.557	-801	MPOX
$\text{CH}_4 + 2\text{O}_2 \leftrightarrow \text{CO}_2 + 2\text{H}_2\text{O}$	89.346	-110.54	-137.18	MFOX
$\text{C} + 0.5\text{O}_2 \leftrightarrow \text{CO}$	340.631	329.3	227.739	COX
$\text{CH}_4 + 3\text{CO}_2 \leftrightarrow 4\text{CO} + 2\text{H}_2\text{O}$	91.722	90.147	62.8	MFDR
$\text{C} + 2\text{H}_2\text{O} \leftrightarrow \text{CO}_2 + 2\text{H}_2$	11	15.547	12.27	SFCG
$2\text{C} + 2\text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{CH}_4$	186.8	187.97	132.274	CFSM

Reaction abbreviations: COX = carbon oxidation, CFSM = carbon full steam methanation, CSM = carbon steam methanation analysis to ensure SOFC safe functioning, CDCG = carbon dioxide carbon gasification, CMOR = carbon monoxide oxidation reaction, HOR = hydrogen oxidation reaction, MP = methane pyrolysis, MFSR = methane full steam reforming, MSR = methane steam reforming, MFOX = methane full oxidation, MPOX = methane partial oxidation, MFDR = methane full dry reforming, MDR = methane dry reforming, SCG = steam carbon gasification, RWGS = reverse water-gas shift, SFCG = steam full carbon gasification.

discussed. The results indicated that the power efficiency of the integrated system increased as the moisture content decreased (less than 20%) and the biomass mass flow rate decreased below 20 kg/s. In another work,¹⁰⁷ it has been shown that the use of biomass containing 20% moisture content at 65 kg/s mass flow rate of biomass was needed to produce 120 kW electric power from SOFC integrated with a gasifier using orange peels with steam/air to produce the biofuel.

Based on the above-mentioned references, there are many electrochemical reactions taking place in SOFC and the systems integrated with SOFC.¹⁰⁸ Table 6 shows a list of some electrochemical reactions for SOFC operating with biogas as fuel.

Exergy analysis can help in finding the most efficient component in a system and what type of feed fuel to SOFC should be used. Moreover, the analysis gives clear guidance about what type of components should be integrated

with SOFC at operating temperature and pressure. CO₂ capture unit should be used as an integrated unit with SOFC to improve the overall exergy conversion efficiency. The exergy destruction decreases by reducing the temperature of the reformer; however, the exergy efficiency decreases at lower reformer temperature. Therefore, a balanced operating reformer temperature should be found.¹⁰⁹ The exergy destruction in SOFC is significantly high due to the release of heat within SOFC. To reduce this exergy destruction rate, it is recommended to employ this waste heat in a gas turbine to improve the exergy efficiency.¹¹⁰ One of the effective factors in causing exergy destruction in SOFC is the overpotential. Over potential of SOFC depends on the electrochemical reactions and their operating temperature as well as the material of electrolyte. The overpotential should be decreased to improve SOFC efficiency.¹¹¹ For example, the selection of optimum operating conditions was empirically found to be 900°C as operating temperature for SOFC, 45/55 CH₄/CO₂ as bio-gas feed composition, and higher than 25% as fuel utilization for tubular SOFC.¹¹²

Energy and exergy investigations were applied to reveal the best possible performance of a hybrid system made-up of ORC and ejector refrigeration cycle (ERC) powered by a diesel engine operating with biogas.⁹² The presented hybrid system was able to generate electrical power, heating, and cooling loads. In this study, the diesel engine was operating with different biogases to provide heat for the bottoming cycles by the aid of exhaust gases of the diesel engine. The biogas investigated in that study was sunflower biodiesel blend, B10 blend, and canola B30 blend. The results showed that the energy efficiency was the highest for canola B30 when the engine was running at full load and 2400 rpm, whereas the optimum exergy efficiency was achieved for full load operating conditions of the diesel engine at 1700 rpm using canola oil. Similarly, energy and exergy studies were employed to investigate the performance of supercritical steam power plants powered by biomass for combined heating and power, district heating, and space cooling.¹¹³ The heat produced from this power plant was used to provide heat for pulp and paper industry as well as the aluminum industrial process. The results presented that the exergy destruction was maximum for the combustion chamber and steam heat generation unit, which was about 67–80% and 13–16% of the total exergy destruction of the whole combined power plant, respectively. The findings also showed that the exergy efficiency combined heat and power was always greater than that of combined power, heat, and cooling in the aluminum industrial process for the identical capacity of heating potential of the regarded district.

The exergy efficiency of electricity production, CHP, and CCHP can be expressed, respectively, as¹¹³:

$$\eta_{ex,e} = \frac{P_{e,net}}{\dot{E}_f} \quad (18)$$

$$\eta_{ex,CHP} = \frac{P_{e,net} + \dot{E}_h}{\dot{E}_f} \quad (19)$$

$$\eta_{ex,CCHP} = \frac{P_{e,net} + \dot{E}_h + \dot{E}_c}{\dot{E}_f} \quad (20)$$

where \dot{E}_h (kW) is the summation of exergy rates of the high- and low-pressure stream flows, \dot{E}_c (kW) is the exergy rate of the cooling load produced in the absorption chiller, \dot{E}_f (kW) is the fuel exergy rate, and $P_{e,net}$ (kW) is the net electrical power output.

Exergy analysis of an ORC using toluene as a working fluid, powered by the heat of the flue gases produced from biogas combustion, has been analyzed.¹¹⁴ The ORC in this study was implemented for electrical power and heat production. The results exposed that the exergy efficiency was maximum when the temperature of the biogas at the combustion chamber exit was 355°C at a pinch temperature difference of 10°C for the condenser and evaporator. The results also showed that increasing the heat source input temperature for the ORC resulted in a growth in the exergy efficiency, which could be explained by producing more useful work owing to the more efficient utilization of high-quality thermal energy. An exergy study has been applied to evaluate the performance of a geothermal-biogas hybrid system for producing electricity, cooling, heat, and freshwater.^{88,115} The main outcome of these studies was the increase of exergy efficiency as a result of increasing the molar ratio of carbon or decreasing the molar ratio of CO₂/CH₄. Exergy analysis of a fluidized bed boiler used to provide the required heat for ethanol production plants has been investigated using biogas as fuel for the boiler.¹¹⁶ The obtained data indicated that the exergy efficiency of de-aerator, pump, soft water tank, evaporator, and heat exchanger was 66.3%, 61.4%, 54.4%, 46%, and 29%, respectively.

A multi-generation system consisting of biomass digester, open Brayton cycle, ORC, absorption chiller, heat recovery, and water separation plant has been analyzed using exergy analysis.²⁷ The multi-generation system was used to provide electricity, cooling load, heat, and freshwater. The findings exposed that the maximum exergy efficiency of the combined system was obtained as 30.4% and the highest exergy destruction was in the combustion chamber representing 65% of the total exergy destruction of the multi-generation system.

Three CH₄ compositions (93%, 84%, and 75% by volume) have been used in a dual-fuel mode for the CIE. The results presented that using the three compositions of biogas resulted in increasing the exergy destruction from 59.6% for diesel operation to 61.4%, 64.2%, and 64.6% for the three CH₄ compositions, respectively. Moreover, the results indicated that the exergy destruction rate of the combustion chamber decreased with increasing CO₂ concentrations in the biogas. The best biogas according to the results of this work was for methane composition of 93% with 26.9% exergy efficiency.¹¹⁷

5 | ECONOMIC ANALYSIS OF BIOGAS-FUELED SYSTEMS

It must be admitted that the economic analysis is an inseparable topic in system performance investigation. Economic characteristics are measured through the connection between biogas production, purchased electrical power, and selling of an additional amount of biogas.¹¹⁸ If the produced biogas becomes inadequate to address the needs for energy in the farm, excess power can be obtained (at around 10 cents/kWh).¹¹⁹ If the amount of produced biogas becomes higher than the considered demand, two scenarios will happen. First, based on the local situations, generated power can be sold to the electrical grid (slightly more than 8 cents/kWh). In another case, the extra amount can be combusted, so that the corresponding GWP (global warming potential) will be 21 times lesser in comparison with methane.¹²⁰ Typically, the rate of tariff for biogas as an alternative energy resource is around 0.13 €/kW.¹²¹

With the intention of the economic assessment, different strategies can be considered. One of the most popular approaches is net profit estimation by summing the whole revenues and expenditures for the considered system.¹²² Consequently, production, operating, and maintenance expenses for the treatment procedures would be included. Furthermore, the cost of fuel and obtained profits from the finalized products are involved in the economic assessment. In the case that a novel treatment technique brings an organic by-product, then capital expenditures for this route must be included.¹²³ Solid remainders from AD would be utilized as fertilizer, comparable with manure, while it has a similar content of useful nutrients. This causes extra profits by diminishing the application of chemical fertilizers in farms, dropping nutrient waste, and avoiding methane productions. In this case, the profitability will be soared dramatically.¹²⁴

Biogas production capital cost consists of entire expenses involving the construction and equipment of AD. The plant provision, construction resources, and biogas

equipment are involved in the investment cost. The labor impression is through the wages and stated as USD per unit volume of produced biogas during the system lifetime. Commonly the lesser value of the labor charges per each unit of volume for produced biogas will result in more improvements for the biogas plant.¹²⁵ The investment cost of household-scaled digester varies based on the model, resources accessibility, size, and site. The investment costs of tubular models in Latin America vary between 100 and 700 USD. In specific countries, like Bolivia, Costa Rica, and Nicaragua, low-density polyethylene is mostly utilized for the plastic bag, allowing investment costs between 100 and 200 USD (eliminating labor charges).¹²⁶

Gozan et al.¹²⁷ accomplished a techno-economic analysis of a biogas production plant using palm oil. The results revealed that the payback period was 6.6 years and the cost of electricity production was 0.06 USD per kWh. Boldrin et al.¹²⁸ evaluated an independent biogas plant in terms of energy, emissions, and economic, where the viability was an influential parameter in economic aspects. Based on the results, the associated size of the plant was not an important factor for environmental and energy evaluation. On the contrary, it was a key parameter for economic analysis. Scarlet et al.¹²⁹ investigated the economic viability of AD plants by considering local detailed factors. Stürmer et al.¹³⁰ investigated the impacts of the technical parameters in the biogas plant performance on the end-product cost. The associated costs with the substrate were primarily influenced by the types of equipment in cultivation, harvesting, and transportation in addition to land accessibility. Riva et al.¹³¹ compared the economic aspects of three scenarios for biogas production fed by energy crops, manure, agro-industrial, and organic fraction of municipal solid wastes (OFMSW). OFMSW brought a high cost in the management and maintenance section (around 0.155 € per each m³ of biogas), while EC (energy crops) revealed a high range of charges for feedstock supply (0.130 € per each m³ of biogas). Walla and Schneeberger¹³² studied the most optimum size for biogas plants based on their energy and economic restrictions. The results indicated that by increasing the electricity production by 1000 kWh, the long-run average cost fell steadily as shown in Figure 13. Moreover, the associated costs with the biogas and electricity production were included while the transportation cost was excluded.

Díaz-Trujillo et al.¹³³ optimized a biogas production chain in terms of environment and economics. By considering the discount rate as 10% and while the project lifetime was 10 years, the economic and environmental parameters used by the optimization model were provided. Based on this work, increasing GHG savings would result in a drop of the profits gradually as can be seen from Figures 14 and 15. In a comparative study, Lask et al.¹³⁴

explored the economic life cycle calculation of biogas production from perennial wild plant mixtures and maize. Economic analysis of 1 kWh power generation was considered, by the used of biogas produced from three diverse systems: maize, stand-alone wild plant mixture cultivation (WPM E1), and a mixture of maize undersown with biennial and perennial wild plant species (WPM E2).

The economic study initiates with summing the investment charges and operating and maintenance costs, which is essential to achieve biogas production. Further and even more interesting in economic analysis is related to the related parameters such as net present value, profitability index, internal rate of return, and levelized cost of electricity.¹³⁵ In this case, Net Present Value (NPV) can be calculated as:

$$NPV = \sum_{t=0}^n \frac{B_t - C_t}{(1+r)^t} \quad (21)$$

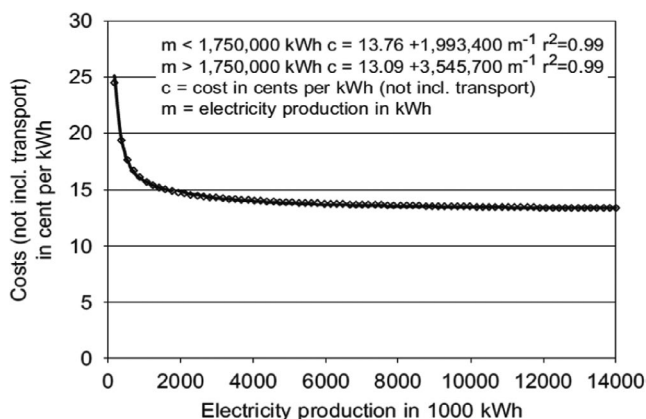


FIGURE 13 Cumulative cost for power and biogas production¹³²

where B is the revenue per year, C is the outgoings per year, and r is the real interest rate. Moreover, the Internal Rate of Return (IRR) can be estimated as:

$$0 = \sum_{t=0}^n \frac{B_t - C_t}{(1+IRR)^t} \quad (22)$$

For calculating the Profitability Index (PI), Equation (23) has been presented:

$$PI = \frac{\sum PV_{Proceeds}}{PV_{Initiate}} \quad (23)$$

$$LCOE = \frac{\sum_{t=0}^n \frac{C_t - M_t}{\left(1 + \frac{r}{100}\right)^t}}{\sum_{t=0}^n \frac{E_t}{\left(1 + \frac{r}{100}\right)^t}} \quad (24)$$

where C_t is the capital cost in year t (USD), M_t stands for the operating and maintenance cost (USD/year), r is the discount rate, and E_t is the electricity power demand (kWh/year).

Another parameter of an investment cost of the project performance calculation is the Life-cycle net present value (LCNPV), which will be estimated based on the cash-flows in a specified period in consideration of the environmental concerns. The LCNPV assessment is studied in a typical method; however, the cash flow contains entire defined environmental charges and benefits.¹³⁶ LCNPV is defined as:

$$LCNPV = \sum_{t=1}^n \frac{CF_t}{1+r^t} \quad (25)$$

where CF_t is the cash flow for t th year, and n stands for the number of years for which cycle lifetime is considered.

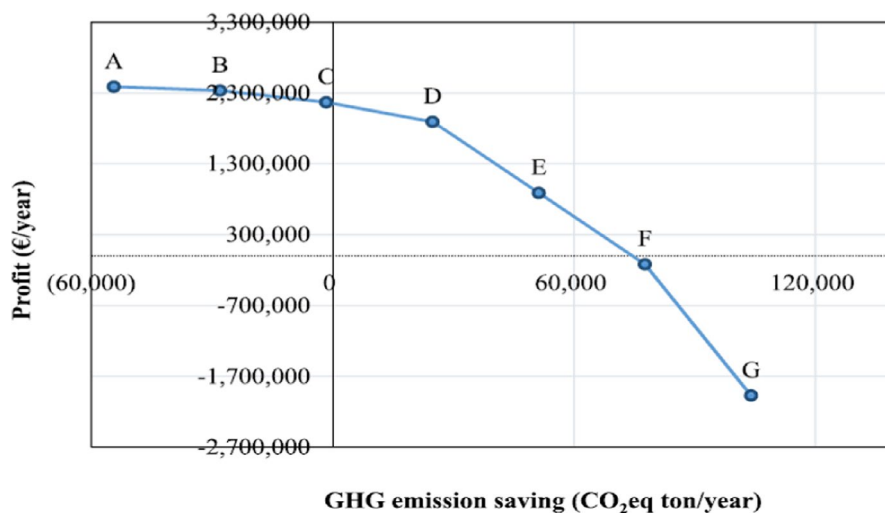


FIGURE 14 Pareto frontier for the profit by considering the greenhouse gas emission saving¹³³

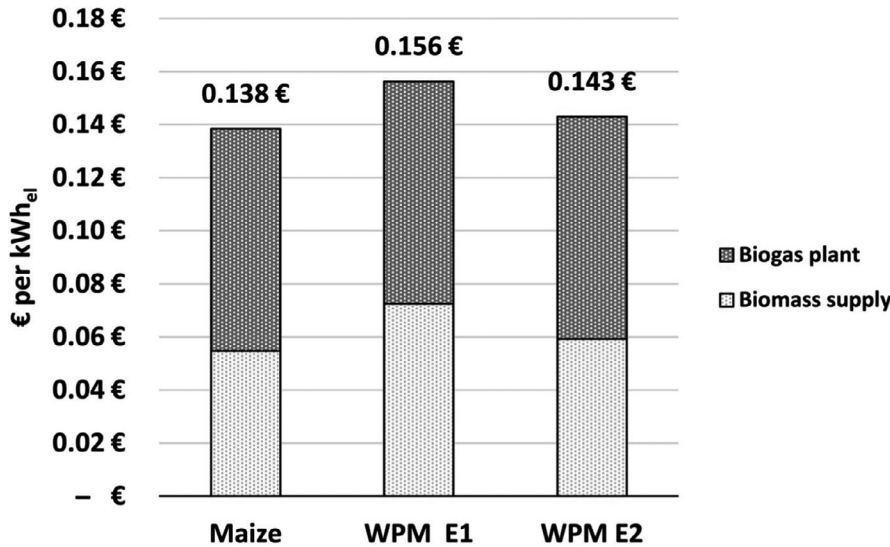


FIGURE 15 Energy cost of biogas plant with different resources for Maize, WPM E1, and WPM E2¹³⁴

To analyze the economic parameters, consideration of the investment and associated operating and maintenance costs is necessary.

The model of income is established on the motivation structure. The configuration of costs is separated into capital investment, operating and maintenance expenses, and devaluation for mechanical and electrical tools. This structure varies each year by the influence of the inflation rate.¹³⁷ The investment cost and the generic variable cost are expressed as, respectively:

$$C_{inv}^{1s} = C_{inv}^{u,1s} \times S_{biogas} \quad (26)$$

$$C_{gv,t+1} = C_{gv,t} \times (1 + inf) \quad (27)$$

where C_{inv}^{1s} is the investment cost, $C_{inv}^{u,1s}$ is the unitary investment cost, S_{biogas} is the size of the biogas plant, C_{gv} is the generic variable cost, and inf is the rate of inflation.

6 | ENVIRONMENTAL ANALYSIS

Biogas represents an important source of renewable energy as mentioned before, it helps in waste management and W-to-E (waste to energy) conversion, which allows utilizing huge amounts of wastes instead of disposal or landfill procedures. However, the handling of biogas from production to utilization has an impact on the environment. An environmental impact assessment study must be conducted for which many parameters such as air emissions, industrial process wastewater, hazardous materials, and noise should be considered.¹³⁸ The environmental impact assessment is done in all stages of any biogas project that starts from the planning phase to the production phase and ends with the safe disposal of hazardous wastes

produced.¹³⁹ Table 7 shows the steps in environmental impact assessment. For short-run biogas plants, a rehabilitation phase must be involved.

Air emissions include greenhouse gases such as carbon dioxide and nitrous oxides, and particulate matters (ie, dust from solid biomaterials are also one major air pollution from biogas plants). N_2O emissions from biogas production cause a significant contribution to global warming.¹⁴⁰ The total greenhouse gases emission from energy production from biogas are calculated within the range of 0.10 and 0.40 kg CO_2/kWh .^{14,141,142}

The NO_x emission for biogas is more than for natural gas engines: The averaged emission factor is 540 g NO_x/GJ ,¹⁴³ which is more than three times the rate of natural gas engines. When the emission factor is reported to methane consumption, an emission factor of 0.63 g $NO_x/Nm^3 CH_4$ can be assumed for flaring.¹⁴⁴

A previous work¹⁴⁵ estimated a significant control improvement of 10% of NO_x emission in 2020 in California (USA); however, the study included biogas and biomass combustion. It is important to mention that the type of raw material affects the nature and amount of air pollutants from the biogas industry.¹⁴⁶ CO_2 , NO_x , CO, hydrocarbons, and particles can differ by a factor of 4 among ley crops, straw, sugar beet, liquid manure, wastes from the food industry, and municipal waste. On the other hand, differences by a factor of up to 11 can be observed in SO_2 emissions, as a result of the high variability of H_2S in the biogas products.¹⁴

The use of scrubbing units produces a huge amount of wastewater which may leak from storage containers.¹⁴⁷ Hazardous materials involved in the production and treatment of biogas such as acids need special handling, storing, and disposal procedures. The perfectly sealed storage of the gas is highly recommended, as the greenhouse gases and ammonia fugitive emissions are even more important than

TABLE 7 Environmental impact assessment (EIA) for biogas plant¹³⁸

Stage	Negative impacts	Positive impacts	Mitigation measures
Construction	<ol style="list-style-type: none"> 1. Disruption of fauna and Flora 2. Wildlife will flee because of noise 3. Disruption of the ecosystem by tree cutting and brush clearing 4. Dust emissions during Construction 5. High levels of noise during construction 6. Exerts pressure on the available land 	<ol style="list-style-type: none"> 1. Construction of access Roads (infrastructure) 2. Creation of settlement Area 3. Development of area due to structural buildings like clinics, shops, and schools as well as dams 4. Migration of people to seek for work 	<ol style="list-style-type: none"> 1. Selective clearing of Areas 2. Isolation of the area being constructed 3. Using dampening effect instruments to minimize vibration which will affect the wildlife 4. Personnel working should wear protective clothing like ear muffs
Operation	<ol style="list-style-type: none"> 1. High level of noise crushing equipment 2. Air quality is affected because of dust 3. Rapture of machinery in particular fluidized bed separator 	<ol style="list-style-type: none"> 1. Employment creation 2. Continual development of the area 3. No production of tailings, thus minimal/no pollution to the rivers 	<ol style="list-style-type: none"> 1. Provision of earmuffs 2. Use of bag filters to minimize emissions into the air 3. Stringent control on the equipment with safety trips and alarms
Decommissioning	<ol style="list-style-type: none"> 1. Idle buildings 2. The inability of the land to be rehabilitated 	<ol style="list-style-type: none"> 1. Equipment can be sold to give salvage money 2. The buildings can be sold or leased for the same purpose of mining or another line of work 	<ol style="list-style-type: none"> 1. Continuous rehabilitation by backfilling of the gangue to the mined areas since the gangue is chemically inert (no chemical usage in the process)

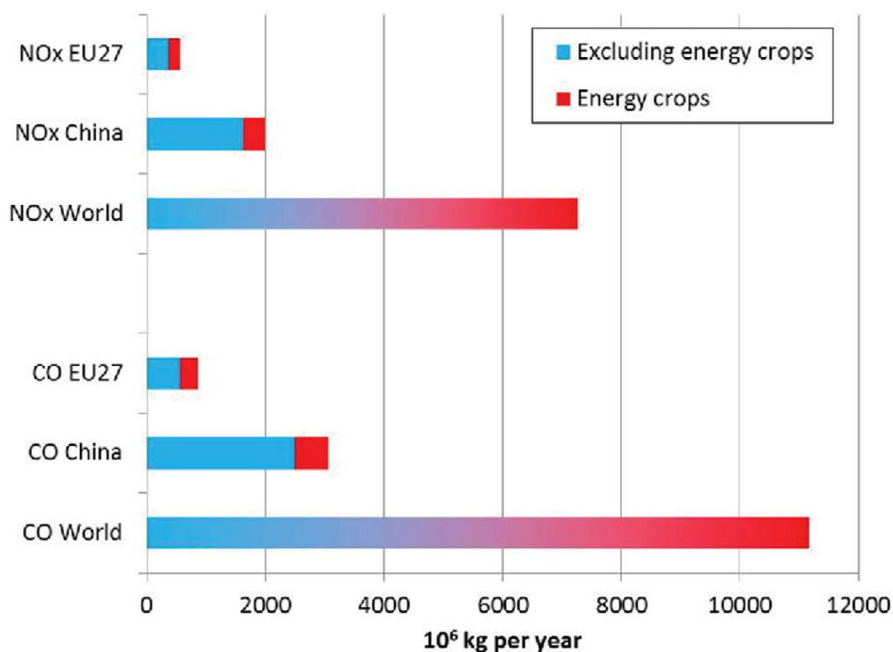


FIGURE 16 Illustration of comparative emission potential of biogas plants for NOx and CO¹⁵¹

those coming from fertilizers.¹⁴⁸ Thus, avoiding leakage and using very well-sealed containers are ways to minimize significantly the global warming impact of biogas plants.¹⁴⁹

The use of machines in production plants such as turbomachines and conveyors belts causes noise pollution that has a direct effect on the environment, human health,

and sustainability.¹⁵⁰ The gas emissions from biogas plants are shown in Figure 16 (for NO_x and CO).¹⁵¹

All of the above-mentioned considerations require the presence of special units such as air filters, wastewater treatment plants, personal protection equipment, and chemical treatment units.

Another environmental matter related to biogas production is the slurry produced during the treatment phase. This slurry can be used as fertilizer; however, the uncontrolled or un-careful procedure to produce it can cause surface water and soil pollution.¹⁵² The underground water as well can be polluted as a result of leachate that can diffuse through the soil to reach deep water. It should be mentioned that the properties of slurry change during the fermentation process. The concentration of ammonium nitrogen increases. This slurry is also the source of unpleasant odor being caused by the presence of many gases such as methane, hydrogen sulfide, and ammonia (although, after fermentation, the slurry is less malodorous than undigested manure). These problems can be solved by a controlled and well-planned fermentation process.¹⁴

The location of biogas plants should be selected carefully so as not to affect the nearby residencies. The location of the plant should be suitable for feedstock transportation. Transportation of raw materials to the plant and transportation of possible wastes from plant to disposal site must be considered. A procedure and instructions for waste transportation, waste packaging, and labeling must be ready for safe handling of such wastes. A manifest system is highly recommended and inventories for raw materials and wastes must be prepared.

7 | CONCLUSION

One of the most promising methods is the utilization of biogas. The biogas industry capacity increased by over 90% between 2010 and 2018. This is due to its energy quality, cheapness in production and operation, availability, ease of being stored, and lower GHG emissions by 60–80% than gasoline.

Nowadays, the majority of the applications is in generating electricity (by using internal combustion engines, gas turbine, micro-gas turbines or on-site turbines), generating heat (by using boilers as in farms/agricultural application), and generating a combination between these two, that is, CHP, to maximize the benefit of the biogas. Based on the anaerobic digestion, the biogas efficiency in generating electricity, heat, and CHP are 8–54%, 16–83%, and 18–90%, respectively. Although this work is mainly considering the use of biogas in electricity generation, it shows other applications for biogas include transportation (used as vehicle fuel), refrigeration, and cooling power plants. Moreover, biogas is a valuable feedstock to produce hydrogen, which can be employed to generate energy, electric power, and fuel for fuel cells.

This work represents the updated methods to produce biogas and electricity production from biogas. This

will open the door for others to work on other methods of improvement. For example, biogas can be improved by converting it to biomethane which is used in heating, powering a generator, or compressed natural gas.


The biogas is mixed with other fuels to improve biogas process efficiency and to reduce the released gases from the fuel, for example, mixing biogas with diesel or biodiesel reduces the emissions of burning diesel fuel, while it reduces the heat disposal and back burning of biogas, and the ignition issue associated with the biogas. Several mixtures/systems were proposed in literature including diesel-biogas, biodiesel-biogas, biogas-green plant, biogas-natural gas, MCFC-MGT (molten carbonate fuel cell and micro gas turbine)-biogas, SOFC (solid oxide fuel cell)-methane-hydrogen, AD (Anaerobic digestion)-SOFC, AD-SOFC-ORC, SOFC-injected gas turbine and gasifier, and biogas-SOFC-MGT.

The exergy destruction rate in an energy conversion operation is significantly high, with the greatest exergy destruction rate occurring in the combustion chamber followed by the gasifier and the steam generator. Several studies have been accomplished to improve biogas system energy and exergy efficiencies. These outcomes were achieved by removing biogas pollutants, combining the biogas with other sources, especially renewable energy ones (eg, solar-biogas, geothermal-biogas, wind-biogas, CHP, CCHP, and concentrated photovoltaic-biogas), and reusing waste energy for other tasks (eg, employing the waste heat from a gas turbine).

Biogas as an alternative fuel supports the sustainability of modern cities. Modern cities are crowded and transportation is used heavily. This work focused on showing the reduction in greenhouse and toxic gases reduction incorporated with the use of biogas as a fuel or in producing alternative fuels. This will encourage the research to improve the processes of producing such fuel and encourage the governments to adopt policies to depend more on renewable energy resources, mainly in big cities where the electricity consumption is high with a big demand for power sources.

This work presents an introduction on how to manage projects of storing, treating, processing, and safe disposal from its wastes. Moreover, steps of environmental impact assessments are shown and environmental pollution that might be solutions for them have been presented. Examples from the world on how policies relevant to biogas management can improve the social, economic, and environmental situation provided a comprehensive perspective. The triple bottom line of sustainability can be satisfied by just applying laws to support the biogas management and handling from the real case studies from countries such as Sweden and Germany.

NOMENCLATURE

B	Revenue per year (USD)	n_i^{in}	Moles of component i in inlet stream (mol)
C	Outgoings per year (USD)	n_i^{out}	Moles of component i in outlet stream (mol)
CF	Cash flow (USD)	n_{Steam}^{in}	Moles of steam in inlet stream (mol)
C_{in}	Methane concentration in input biogas (-)	$P_{e,net}$	Net electrical power output (kW)
C_{in}^{ls}	Investment cost (USD)	P_o	Reference pressure (kPa)
$C_{inv}^{u,ls}$	unitary investment cost (USD/m ²)	r	Real interest rate (%)
C_{gv}	generic variable cost (USD)	S_{biogas}	Size of the biogas plant (m ²)
C_{out}	Methane concentration in produced gas (-)	\dot{Q}_i	Inlet heat rate (kW)
$c_{p,i}$	Heat capacity of i th flow (kJ/mol K)	$\dot{Q}_{in,biogas}$	Input heat rate by the biogas system (kW)
C_t	Capital cost (USD)	$Q_{in,f}$	Input feed gas energy (MWh)
E_{Cold}	Produced cold water energy (kWh)	$Q_{in,u}$	Input heat required for the solvent regeneration (MWh)
E_{El}	Electrical energy produced (kWh)	$\dot{Q}_{in,solar}$	Input solar energy rate (kW)
$E_{HotWater}$	Produced hot water energy (kWh)	$Q_{out,p}$	Produced gas energy (MWh)
$E_{in,e}$	Required electrical energy of driving machines in the process (MWh)	Q_R	Net change in total enthalpies (kJ/mol)
e_{ch}	Specific chemical exergy (kJ/kg)	R	Characteristic gas constant (kJ/kg K)
e_i	Specific inlet exergy (kJ/kg)	s	Specific entropy (kJ/kgK)
\dot{E}_c	Exergy rate of cooling load produced in absorption chiller (kW)	S_i	Solvent selectivity (-)
\dot{E}_h	Summation of exergy rates of the high- and low-pressure steam flows (kW)	\dot{S}_{gen}	Rate of entropy generation (kW/K)
\dot{E}_f	Fuel exergy rate (kW)	SEC	Specific energy consumption (kWh/m ³)
E_t	Electricity power demand (kWh/year)	t	Year
E_{theor}	Theoretical energy consumption (MWh)	T_o	Standard temperature (K)
Inf	Rate of inflation (%)	TEC	Total energy consumption rate (kW)
h	Specific enthalpy (kJ/kg)	v_{in}	Volumetric flow rate of input biogas (m ³ /h)
H_{CO_2}	Henry constant of CO ₂	v_{out}	Volumetric flow rate of output product gas (m ³ /h)
H_{CH_4}	Henry constant of CH ₄	\dot{W}_{rev}	Reversible power (kW)
ΔH_L	Latent heat of steam in the feed (kJ/mol)	\dot{W}_{useful}	Useful work rate (kW)
$h_{T,i}^{in}$	Molar enthalpy of i th component in the inlet stream with temperature T (kJ/mol)	$\dot{W}_{in,WT}$	Input wind turbine power (kW)
$h_{T,i}^{out}$	Molar enthalpy of i th component in the outlet stream with temperature T (kJ/mol)	x	Mole fraction
h_T^{in}	Total molar enthalpy of inlet stream at temperature T (kJ/mol)	Greek letters	
h_T^{out}	Total molar enthalpy of outlet stream at temperature T (kJ/mol)	σ	Conversion efficiency of steam to electricity (-)
$h_{298,i}$	Molar enthalpy of i th component at a temperature of 298 K (kJ/mol)	η	Energy efficiency (-)
LHV	Lower heating value (kJ/kg)	$\eta_{thermal}$	Thermal efficiency (-)
LHV _{CH₄}	Lower heating value of methane (kJ/mol)	η_{biogas}	Energy efficiency of biogas system (-)
LHV _{CO}	Lower heating value of carbon monoxide (kJ/mol)	$\eta_{en,power}$	Energy efficiency of power production system (-)
LHV _{H₂}	Lower heating value of H ₂ (kJ/mol)	η_{ex}	Exergy efficiency (-)
MRR	Methane recovery ratio	$\eta_{ex,CCHP}$	Exergy efficiency of combined cooling and heat and power system (-)
\dot{m}_{biogas}	Mass flow rate of biogas (kg/s)	$\eta_{ex,CHP}$	Exergy efficiency of combined heat and power system (-)
M_t	operating and maintenance cost (USD/year)	$\eta_{ex,e}$	Exergy efficiency of electricity production (-)
n	Number of years (years)	μ	Chemical potential (kJ/kg)
$n_{CH_4}^{in}$	Moles of methane in inlet stream (mol)		
n_{CO}^{out}	Moles of carbon monoxide in outlet stream (mol)	ORCID	
$n_{H_2}^{out}$	Moles of hydrogen in outlet stream (mol)	Abolfazl Ahmadi  https://orcid.org/0000-0003-2652-6011	
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