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Biogas-fuelled internal combustion engines for micro-scale energy generation: a review of technologies and configurations for systems below 50 kW

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The growing demand for sustainable and decentralised energy solutions drives the development of micro-scale biogas power generation systems using internal combustion engines (ICEs) as prime movers. This paper reviews the technological advances and structural configurations of ICEs designed to burn biogas in generator systems with power outputs of up to 50 kW. The study investigates the adaptation of spark-ignition and dual-fuel engines, optimisation of compression ratios, fuel delivery systems, and ignition strategies to increase efficiency and reliability. Furthermore, the impact of biogas composition on engine performance and emissions is investigated, addressing the challenges of changes in methane and pollutant content. The review provides information on recent innovations, including engine modifications to run lean and integration of advanced control systems to increase efficiency and durability. By synthesising current research and practical applications, this paper aims to guide the selection and development of optimised ICE solutions for distributed microgas power generation.

Key words: *biogas, micro-generation, internal combustion engines, dual-fuel*

1. Introduction

The growing power of decarbonisation, securing access to energy in rural areas, and strengthening the energy supply, through decentralised systems of renewable energy sources. One of the main leads is micro biogas installations (< 50 kW), used in cogeneration and island systems [7, 67].

Biogas, produced by anaerobic digestion of organic waste, produces net GHG emissions and waste from production and storage, which uses electricity [25, 57]. The drive of these installations consists of internal combustion engines (ICE) – scalable systems and economic units.

Operational challenges result from the heterogeneous composition of biogas, corresponding to CH_4 (40–70%), which is responsible for the calorific value, while CO_2, H_2S, and water vapour reduce the occurrence and acceleration of material degradation [12, 70, 71]. This requires, among others, CR modification, ignition calibration, modernisation of the intake/exhaust applications, and the use of pilot fuel dosing in DF engines [16].

With the advancement of gas cleaning and control technologies (e.g., ECU), it is possible to achieve unavailability levels of 35–46% and control above 80% [33, 42]. Lean-burn variants and H_2 enrichment further reduce NO_x, CO, and CH_4 emissions [51, 53].

Biogas-fuelled ICE systems are increasingly vulnerable to combustion and off-grid impacts, increasing their importance in low-emission and waste management strategies [35, 55].

The article presents an overview of biogas micro-installations' technology, properties, and operating parameters ≤ 50 kW. Component types (SI, DF), design adaptations, the impact of fuel composition on performance and emissions, and key challenges and research perspectives are analysed for the benefit of the engineering community and decision-makers in implementing biogas energy systems.

The scientific literature was searched in Scopus, Web of Science, ScienceDirect, and Google Scholar databases to conduct the study. Publications from 2010–2024, reviewed peer-reviewed articles, conference papers, and thematic reviews on biogas engines with a power of ≤ 50 kW were reported. Extreme emphasis on complexity in works on:

- adaptation of SI and DF to biogas
- the impact of biogas composition on operating and emission parameters
- micro-CHP efficiency systems
- micro-installation implementation studies.

There are over 120 literature items, resulting in the final version including over 100 publications that meet the criteria for additional and up-to-date information. Legal acts and technical standards (e.g., EU MCPD, Stage V, Tier 4) were also checked, as well as data from manufacturers of utility and prototype devices.

2. Characteristics of biogas and its impact on engine operation

2.1. Characteristics of engine fuels

Biogas is a renewable fuel of growing importance in the context of energy sources. Produced in the process of anaerobic fermentation of organic waste, it consists mainly of methane (CH_4) and supplied carbon (CO_2), usually automatically in 50–70% and 30–50% [46, 47, 72, 73]. The additive may contain hydrogen sulphide (H_2S), water vapour, nitrogen, oxygen, and trace amounts of silicon, e.g., siloxanes [18, 44]. The composition of biogas is essential for its calorific value and directly affects the emissions and durability of the propulsion system. To illustrate the electrical disconnect between biogas and other gaseous fuels, Table 1 provides the source calorific value of selected energy sources in small-scale engine installations.

Table 1. Comparison of the calorific value of selected gas fuels [2, 9, 22, 42]

Fuel	Main composition	Calorific value [MJ/m³]	Comments
Biogas (raw)	CH_4 (50–70%), CO_2	18–25	Variable value depending on composition
Biomethane	CH_4 > 96%	35–39	After purification, it is comparable to natural gas
Natural gas (CNG)	CH_4 ~95–98%	35–39	Stable properties, high-pressure
LPG (propane-butane)	C_3H_8/C_4H_{10} (mixture)	46–50	Liquefied, very high energy density
Hydrogen (H_2)	100% H_2	10–13	Low calorific value but high gravimetric energy density

As can be seen from the table, raw biogas has a higher calorific value than other natural gases, LPG, or purified biomethane, which directly impacts lower engine power, the need for additional use, or the use of dual fuel. Additionally, biogas composition indicates that the calorific value can be activated over time, making it difficult to operate the drive units stably without advanced control systems.

2.2. The influence of biogas composition on the engine operation

The calorific value of biogas, typically in the range of 18–25 MJ/m^3 (Table 1), depends on the leading share of methane, which determines the power contained in the fuel. The share of CH_4 promotes efficient and fuel-efficient combustion [31], while CO_2 acts as a dissolved agent, reducing combustion temperature, flame propagation velocity, and cylinder pressure [2, 43]. The results of the research by Kovacs et al. [45] show that higher CO_2 content in biogas leads to lower combustion temperature and longer ignition time, which can affect combustion knock and engine starting, but at the cost of reducing usable power

Table 2. The influence of selected biogas components on engine operation and emissions [10, 11, 16, 19, 22, 29, 30, 35, 41, 49, 58, 61]

Component	Impact on engine operation	Impact on emissions
CH_4 enrichment	Increased power, ignition triggering. Higher reliability and power	Loss of CO and HC
High CO_2 content	Lower combustion pressure and temperature. Lower power, larger ignition sizes	NO_x reduction, CO, and HC coefficient
Water enrichment	Improved failure stability, increased efficiency. Better performance, ignition result	Decrease in CO, HC, (sometimes NO_x increase)
H_2S	Corrosion, oil degradation	SO_2 emission
Siloxane	SiO_2 deposits, abrasive wear	No agreement
For water	Intake system erosion	No data
Lowering the intake temperature	Better fuel efficiency with available CH_4	Lower CO, more stable mileage
Injection optimisation	Reduced knock, more power	Lower NO_x, more stable combustion

H_2S and siloxanes are as follows: H_2S causes engine oil corrosion and degradation [11], and siloxanes lead to the formation of SiO_2 deposits on engine mechanical components [44]. Water vapour can be erosive to the intake system [34]. The detailed impact of CH_4 enrichment, CO_2 dilution, H_2S content, siloxanes, and water vapour on both combustion dynamics and emissions is summarised in Table 2.

Table 2 summarises the effects of key biogas components – such as methane, carbon dioxide, hydrogen sulphide, and siloxanes – on engine performance and exhaust emissions. These properties influence combustion quality, ignition behaviour, engine wear, and the emission profile of biogas-fuelled systems.

2.3. Impact on secondary emissions

Biogas as a fuel, discharged to NO_x emissions and used (PM), and its use in cogeneration systems allows for achieving thermal efficiency (Brake Thermal Efficiency, BTE – defined as (1) at the level of 17–30% [10]. However, the CO_2 content can increase CO and HC emissions [32, 66].

$$\mathrm{BTE} = \frac{\mathrm{P} \cdot 10^3}{\mathrm{m_f} \cdot \mathrm{LHV_f} \cdot 10^3} \tag{1}$$

where: P – brake output power [W], LHV_f – Fuel calorific value [MJ/kg], m_f – fuel mass flow (kg/s).

Adding H_2 improves combustion efficiency, ignition acceleration, and CO, HC, and NO_x emissions [16, 17, 22, 23]. However, too much H_2 can increase NO_x [41].

Table 3 shows the emission intensity of biogas compared to other fuels.

Table 3. Functional and emission intensity energy of biogas from other fuels [6, 16, 21, 21, 36, 43, 76]

Fuel	BTE [%]	NO_x	CO	slip CH_4	Comments
Biogas (raw)	17–22	↓ 30–90%	↑	1.5–3%	High CO with lean mixtures
Biomethane	22–28	~ natural gas	~ natural gas	<1%	Comparable to natural gas
Biogas + H_2	25–30	↑ (at >20% H_2)	↓	↓	NO_x boosted but improves performance and load
Diesel oil	27–33	Tall	Short	Lack	High NO_x and PM emissions
Liquefied petroleum gas	25–30	Moderate	Short	Lack	Lower emissions than diesel oil, higher than biomethane
Legend: ↓ – lower than diesel oil; ↑ – higher than reference; ~ – comparable value					

The emission value in Table 3 is qualitative and is marked with symbols: ↓ – use than the reference value (e.g., diesel oil), ↑ – higher, ~ – comparable. The data comes from many literary sources and is adapted. The individual numerical values are presented in Table 7.

Requirements (e.g., EU Stage V, MCPD) often do not consider the specification of units < 50 kW and fuel or variable composition. In practice, this means difficulties meeting the NO_x standard (e.g., < 100 mg/Nm^3 in MCPD) and CH_4 emission limits, especially without using catalytic technologies or fuel refilling systems.

2.4. Biogas purification and standardisation

Efficient removal of H_2S (e.g., by adsorption on carbon monoxide or activated carbon), siloxanes (zeolites, phase-related), and moisture (condensation) is essential for engine protection [18, 68].

Dynamic gas composition [69] and biogas enrichment with hydrogen (up to 20%) support stable engine operation even with variable fuel composition [53]. Increasing attention should also be paid to optimising energy consumption in fermentation processes, including control algorithms and time series analysis [65], which can control the electricity of the entire biogas system.

Effective application methods and fuel quality control are essential to achieve long-term efficiency and performance fuelled by biogas. Raw biogas contains content, primarily hydrogen sulphide (H_2S), water vapour, and siloxanes, which occur due to engine operation, catalytic converters, and exhaust gas start-up systems.

2.5. Technical modifications and operating parameters

Effective use of biogas in combustion engines requires design adaptations and optimisation of operating parameters. Precise compression ratio application, high-energy ignition application, biogas, and pilot fuel dosage (in dual-fuel mode), and control of ignition occurrence and composition of the assembly [10]. Bieniek et al. [13] conducted an experimental adaptation of a high-load Diesel engine to biogas fuelling, determining efficiency and extreme CO and NO_x emissions reductions – the first with a pilot ignition switch.

Electrical time control, necessary for data from the drives and solutions such as ECU, ANN, or fuzzy logic, allows the unit operations to be adjusted to fluctuations in fuel composition and environmental conditions. A comprehensive overview of how selected technical interventions influence both operational and environmental performance is provided in Table 4.

Table 4. The influence of selected technical parameters on operating and emission parameters [2, 15, 20, 26, 37, 60, 69, 77]

Modification	Technical effect	Emission effect
CR optimisation (12–18)	Increased peak pressure and temperature, risk of knock	Decrease in CO/HC, possible increase in NO_x
High energy ignition	Stability of the debris	The fall of HC
Injection optimisation (DF)	Increase in power, decrease in knocking noise	NO_x reduction
Monitoring the composition of biogas	Real-time parameter adjustments	Stability, fuel residue

Table 4 provides a summary of how selected technical modifications, such as compression ratio adjustment, high-energy ignition systems, and biogas composition monitoring, affect engine performance and emissions. These interventions play a key role in maintaining combustion stability and minimising pollutants in variable-fuel micro-biogas engines.

3. Types and configurations that include micro-installations

3.1. Spark ignition (SI) engines

In biogas micro-installations (< 50 kW), the most commonly used are spark-ignition (SI) piston engines, dual-fuel systems of compression-ignition engines, and micro-gas turbines. The choice of technology depends on the expected efficiency, quality of available biogas, and availability.

SI engines are the most commonly used energy sources in micro biogas plants due to their effects and good performance when working with a fuel source. They operate on the principle of releasing a biogas solution from the air initiated by spark ignition.

Thermal efficiency is 22–28%, with modern designs using two-spark ignition and an output frequency pre-chamber [38, 64]. The disadvantage is their sensitivity to changes in biogas composition, including the first CH_4 content.

3.2. Dual-fuel compression ignition engines

In a dual-fuel compression ignition engine, diesel (pilot fuel) and biogas are used simultaneously. There is a higher thermal efficiency (25–32%) and the possibility of operating with biogas quality [6]. This system works well in rural and industrial environments where substrate availability may change.

The disadvantage is the highest NO_x emissions and its use for ignition and fuel proportioning control [28].

3.3. Micro gas turbines

Microturbines are compact, emitting, and quiet, making them ideal for municipal devices and installations with environmental requirements. They are characterised by 25–30% thermal efficiency and reveal NO_x [50].

Their main disadvantage is the high investment cost and limited availability of services, especially in developing countries.

The drive unit selection in biogas micro-installations should include operation, emissions, fuel quality, substrate, service, and integration possibilities.

Spark ignition (SI) engines and dual fuel (DF) systems are used due to their simplicity, availability, and opening up of the biogas packaging. However, low-emission and compact microturbines are characterised by high costs and limited availability.

The engine selection should be correlated with the system operation profile and its connection to cogeneration and energy storage.

4. Performance, emissions, and adaptation challenges of biogas-powered engines

Using biogas as a fuel in high-power combustion engines requires several construction units and supporting technologies. The results are side effects of calorific value, occurrence (H_2S, CO_2, siloxanes), and the presence of composition over time. Effective adaptation of the engine to start biogas allows its operation and emission, and extends the durability of the drive unit and the entire system.

Biogas is an alternative to diesel oil, LPG, and natural gas in micro-scale applications. Once appropriately adapted through dedicated engine configurations, it can offer functional performance (expressed by brake thermal efficiency, BTE) and reduced emissions of pollutants such as NO_x, CO, CH_4, and PM.

Compared to traditional fuels, biogas-powered engines operate under different thermodynamic conditions due to their lower calorific value and the presence of non-combustible CO_2. These factors generally result in lower engine power and BTE values. However, the addition of hydrogen, syngas, or water injection has increased BTE by 2–4%, depending on the combustion strategy and engine type [22, 23, 59].

Regarding biogas emissions, the following are decreasing: lower NO_x and PM levels compared to diesel oil, but CO and CH_4 emissions, especially in spark-ignition engines (Table 5).

Table 5. Thermal efficiency and emissions of selected service functions

Configurable	BTE [%]	NO_x [g/kWh]	CO_2 [g/kWh]	CH_4 [g/kWh]	Comments
Diesel oil (on)	30–40	6–10	0.5–1.0	< 0.1	High efficiency, high NO_x emissions
Dual fuel (biogas)	25–32	3–6	2–5	1.5–3.5	High DF substitution, but CH_4 emissions
~~SI~~ on biogas	22–28	1–3	3–6	4–10	Low NO_x, high methane loss
SI + H_2 (20%)	24–30	2–4	1-3	2-6	Higher efficiency requires ignition control
Liquefied petroleum gas	28–35	2–5	0.3–0.6	<0.1	Low emissions, good combustion parameters
Natural gas	32–38	2–4	0.5–1.0	0.5–2.0	Better emission control than biogas

Emission values (in g/kWh) refer to steady-state engine operation, as reported in the cited literature. Specific test conditions (engine load, speed, and fuel quality) may vary between sources.

While biogas engines offer environmental benefits in terms of lower particulate emissions and potential CO_2 neutrality, their performance must still comply with national and international emission standards, which are often designed for larger or continuously operating systems.

In the micro-generation (< 50 kW) context, meeting the requirements of EU Stage V, MCPD, or EPA Tier 4 regulations is particularly challenging. These standards rarely account for small-scale, intermittently operating units with variable fuel quality. As a result, biogas micro-installations often face difficulties in meeting stringent limits on CH_4 and NO_x emissions. Table 5 summarises reported emission levels for biogas-fuelled engines and highlights the variability between system configurations.

Table 6. Example emission limits for engines <50 kW (EU/MCPD) Sources: EU Regulation 2016/1628; EU Directive 2015/2193 (MCPD); US Environmental Protection Agency (EPA) Tier 4; WHO Guidelines (2021)

Standard	Engine power	NO_x [mg/Nm³]	CO_2 [mg/Nm³]	CH_4 [mg/Nm³]	Comments
EU Stage V (NRMM)	19–37 kW	400	500	–	No CH_4 limit applies to mobile app
EU MCPD	1–50 MW (for gas)	100	100	20–50	Applies to stationary, biogas is subject to exceptions
Level 4 Final (USA)	< 56 kW	400–600	500–600	–	Brake adjustment CH_4; only NO_x and CO
UNDP/WHO (recommendations)	–	< 200	< 500	< 30	For off-grid installations in developing countries

As Table 6 shows, setting emission limits for biogas-fired micro-installations can be problematic, especially for methane (CH_4), which is not always regulated but has a high greenhouse gas potential (GWP = 28–34). Additional problems arise with intermittent operation and variable biogas composition, which affects combustion and uncontrolled emissions.

In the application, compensatory measures are used:

- local emission compensation through cogeneration
- units with cleaning agents (oxidation catalysts, SCR)
- adaptive control systems depending on the biogas composition.

The emission-related limitations in micro-biogas systems highlight the need for targeted technological strategies and regulatory adjustments. In most cases, achieving compliance requires a combination of combustion control techniques, fuel quality optimisation, and selective aftertreatment methods – all of which increase system complexity and cost.

Furthermore, current emission regulations often lack dedicated testing procedures for systems operating under variable loads or hybrid fuel conditions (e.g., dual-fuel with pilot ignition). This creates uncertainty in design and certification, making it difficult for small-scale producers to introduce innovative systems into the market without costly homologation procedures.

To ensure the successful deployment of biogas micro-installations, especially in off-grid and rural areas, it is necessary to promote standardised protocols for low-power systems and offer regulatory flexibility for modular and hybridised units. Support mechanisms, both technical and legal, should reflect the unique operating conditions and environmental benefits of decentralised biogas utilisation.

Numerous technological adaptations have been proposed and tested in micro-biogas systems in response to these challenges. These include advanced ignition control (e.g., high-energy ignition systems, variable ignition timing), hydrogen or water enrichment, and real-time gas composition monitoring. Some setups employ dual-fuel strategies with diesel pilot injection to improve cold-start performance and combustion stability.

Table 7 presents selected examples of such modifications and their effects on thermal efficiency, pollutant emissions, and engine stability. Although most of these solutions improve operational parameters, they also increase system complexity and cost, which must be considered in small-scale applications.

Table 7. Overview of technical biogas adaptations [1, 15, 27, 37, 48, 54, 60, 62, 77]

Adaptation area	Solution description	Technical effects
Compression ratio	CR = 12–13 (SI), CR = 16–18 (DF)	Enhanced regulation, CO/HC reduction, NO_x emission increase
Ignition systems	Twin spark plug, digital, high-energy ignition	Improved ignition performance
Injection system (DF)	Optimisation of injection angle and pressure (250 bar, 26–30° BTDC)	Greater efficiency and cleaner combustion
Biogas purification	Membranes (MMMs), ILs, biomethanation with H_2	Higher purity CH_4, elimination of corrosion
Cogeneration and integration	Micro-CHP, PV hybrid, H_2 production	Overall efficiency > 75%; large-scale system

Design and electrical adaptations are key to the efficient use of biogas in microgeneration. Limited importance: appropriate compression ratio, injection and ignition optimisation, and application of biogas regulation. Integration with cogeneration systems and production of AC for waste, decarbonised, and flexible electricity. An overview of the procedure is in Table 7.

5. Supply and emissions of residues

The use of biogas in micro-scale combustion engines is an alternative to fossil fuels due to its renewable nature, the possibility of starting production, and its relatively low carbon footprint. However, the effectiveness of such an operation is strongly dependent on several factors, including the quality of the biogas, the type of leakage from the engines, and fuel economy and emission control systems. The high content of methane (CH_4) affects the engine's efficiency. It is then supplied from coal (CO_2) as a component to reduce the pressure and flame propagation rate, affecting efficiency [43, 72]. Typical thermal functionality (BTE) in such systems ranges from 17% to 24% [8, 14]. However, in the case of dual fuel, a BTE of 25–28% is possible with diesel oil substitution of up to 90% [6]. Additional biogas supplementation with hydrogen enables further efficiency increases to about 30% while reducing fossil fuel consumption by more than 70% [16, 40, 41]. To fully exploit the potential of biogas as a low-emission fuel, it is necessary to implement alternative adaptive technologies such as control systems, advanced technologies, and advanced gas composition strategies.

Performance values and emissions reported in the literature (Table 5) may vary depending on fuel quality, system type, and operational failures.

All emission values in units of [g/kWh], as a typical range for everyday use. In case of divergence of literature data, average or representative values are used. Available tables (e.g., Table 3) may include qualitative notations (↑/↓) to illustrate trends in terms of the reference design (e.g. Diesel oil).

The presented list allows for determining the available practical applications, thermal, emitted, and fuel type, which is a key element in selecting the optimal configuration of a biogas micro-installation, both under the condition of use and when used.

6. Examples of applications in studies

6.1. Introduction

Biogas micro-installations are important as decentralised energy sources on farms and municipal installations. They come in many forms – from simplified power reactors of spark-ignition engines to connected CHP systems cooperating with PV and energy storage.

Another interesting development direction is the use of biogas in hybrid drive systems. Kovacs et al. [45] (2023) discussed the reasons for the use of a combustion engine powered by biogas in a series set: the power supply was started, and the operational appearance occurred, which caused it to be connected to microgrids and off-grid applications.

The study identified occurrence, key importance, and implementation barriers, including substrate, power sources from other energy sources, and operational and economic system power supply.

Biogas micro-installations are becoming increasingly common as independent energy sources in farms, homes, and municipal installations. Their operation depends on the substrate's quality, the system's scale, the connection with other energy sources, and storage possibilities. Selected practical implementations from various countries and contexts are presented in Table 9, illustrating the diversity of scale, substrates, and integration strategies.

Table 9. Examples of micro-scale biogas installations in various utility contexts [24, 27, 52, 75]

Location/Context	System Type	Effects/Observations
Slovenia – life	CHP, ICE	Profitability depends on scale and substrate additives
Poland – farm	8.1 kW combustion engine	Self-sufficiency, surplus commercial energy to the grid
Vietnam – home life	Bioreactor < 2 m^3	Stable, gas quality, spare parts demand
India – Local Installation	DF + substrate zoo	Good performance, problems with substrate quality, and service
Argentina – Micro-CHP with PV	CHP + PV + energy	Highly available energy, low net CO_2 emissions

Based on the analysed case studies presented in Table 9, several patterns can be identified:

First, both the scale and substrate quality have a direct impact on the profitability of micro-scale biogas systems. Installations using high-quality feedstocks in appropriately scaled configurations demonstrate better energy and economic performance.

Second, while integration with PV panels or storage units may increase system autonomy, it also introduces complexity and a higher risk of operational failures, particularly in low-resource settings.

Moreover, simple systems, such as domestic bioreactors, are commonly employed where electricity demand is modest and grid access is limited.

Finally, key operational challenges such as automation, component wear, and maintenance remain manageable, provided that appropriate control mechanisms and user training are in place.

6.2. Commercial unit and research prototypes

To illustrate the differences between commercially implemented units and research-prototype solutions, selected examples of biogas micro-installations are presented in characteristic tables. Available systems on the market and experimental systems are studied through research studies—comparison of additional types of systems, their costs, and technological status.

Table 10. Examples of commercial and experimental micro-scale biogas systems [3, 27, 52]

Producer/Design	Type/Scale	Status	Comments
Sistema.bio (Mexico)	Bioreactor < 10 m^3	Commercial	Solution for the household
HomepageBiogas (Israel)	Installation 1–2 m^3	Commercial	Easy to use, low heat output
ECN (Netherlands)	Cogeneration 1–10 kW	Prototype	Integrated with PV and battery
IIT Delhi (India)	DF, 5–7 kW	Prototype	Configured on an animal substrate
PV-BIOGEN (Argentina)	Cogeneration + PV + H_2	Prototype	Hybrid, low net emissions

Table 10 presents an overview of selected micro-scale biogas systems, classifying them as commercial or prototype. Commercial systems (e.g., Sistema.bio, HomeBiogas) are characterised by simplicity of operation and investment costs but generally provide limited power and functionality. In contrast, prototype solutions often integrate advanced technologies (CHP, PV, H_2), increasing their efficiency and reliability but also increasing implementation costs and complexity.

Table 11 summarises the technical and economic parameters for three typical configurations of biogas micro-installations. Home systems have the shortest payback time but no electricity supply. CHP units achieve higher efficiency but require biogas and automation – hybrid systems (CHP+PV) discharge energy at the cost of capital and output costs.

These data indicate that electrical decisions in biogas micro-installations require technical parameters, local economic conditions, access to batteries, and the potential for connection to other energy sources. The future of this service lies in solutions that can be applied to specific end-user needs.

The presented data shows that the system selection should be available each time for applications, energy purposes, resources, and institutional support. There is no universal solution – micro-installation success depends on considering the technological and economic configuration.

Research prototypes with higher scope and accessibility, but often at the cost of investment and technical expenses. Commercial solutions with the frequency of risk, but at the cost of efficiency and scalability.

Table 11. Efficiency and profitability of selected micro-installations

System Type	BTE [%]	Investment cost [EUR/kW]	Insurance period [years]	Comments
Homemade bioreactor	–	300–800	1.5–3	No generation
Cogeneration 3–10 kW	25–32	1200–2000	4–7	Automation requirement and burden
CHP+PV hybrid	28–35	1800–3000	6–10	High remaining independence

Analysis of case studies from different regions of the world confirms that biogas micro-installations are a real, technological solution and a solution for decentralised renewable energy. Their key advantages:

- providing power in rural and off-grid conditions
- possibility of use with renewable energy sources (e.g., PV, storage)
- waste utilisation and exhaust gas disposal
- competitive investment profitability, especially in public services.

However, the success of these systems depends on the conscious operation of technology, scale, and parameters defined by the user. Key measures determining and maintaining installations in:

- appropriate selection of technology (SI, DF engines, microturbines)
- optimisation of the substrate and use of the user profile
- possibility of integration with the power grid or energy storage facilities
- access to technical and financial support (e.g., subsidies, green savings).

Conclusions from the general analysis are as follows: biogas micro-installations – general in the case of CHP and DF applications – are technologically developed, are a solution, and are economically feasible. Alternative solution – there is no one universal model of success.

7. Prospects and directions of development

Micro-scale biogas technologies are the result of experiments to be applied. Their nearest future is:

- Standardisation and simplification of installation – through prefabricated CHP modules, plug-and-play turnkey systems, and gas-integrated units. This solution creates cost risk and eases implementation, especially in rural regions [4, 5, 39].
- Integration with RES microgrids – biogas acts as a dispatchable source, unstable PV-wind + storage systems. The effects of such applications have been confirmed, among others, in Bolivia, India, and Cameroon [74, 78].
- AI and predictive systems – machine learning (ANN, LSTM, fuzzy logic) allow for predicting biogas quality, automating combustion, and reducing emissions [56, 69].
- Link to the circular economy – digestate as fertiliser, heat recovery for heating, use of residues as algal substrates, and biogas as a precursor for H_2 production [27, 63].

Micro-scale biogas installations have the potential to become decentralised energy links. Their development depends on eliminating technological and financial barriers, providing support, and using automation and prediction tools. This is not the future – it is already a built foundation for the energy of the 21st century.

In the years, however, the synergy of biogas use with hydrogen technology, photovoltaics, and artificial intelligence may cause the risk of a classic breakthrough. Such hybrid, intelligent micro-installations will become electricity and an active, adaptive participant in micro-networks – algorithmically controlled, functional in terms of losses, and related to variable operating conditions.

8. Conclusions

Biogas, a renewable and locally available energy source, is a real alternative to fossil fuels in micro-energy installations using devices with a capacity of up to 50 kW. The conducted review of literature and studies allows for the following conclusions:

1. Spark ignition (SI) engines and dual-fuel systems are most commonly used in biogas applications. Controlled modifications (compression ratio, ignition system, dosing) can achieve 22–30% thermal efficiencies with limited NO_x and CO emissions.
2. The composition of biogas, which contains methane and CO_2, significantly impacts the combustion process, emission residues, and engine operation residues: poor control and ignition control.
3. Pollutants such as H_2S and siloxanes are used in the engine; therefore, effective methods are used, e.g., adsorption on activated carbon or membrane techniques.
4. Modern control strategies, available on AI and adaptive (ANN, fuzzy logic), enable adjustment of engine operating parameters to the variable biogas composition required and reduce CH_4 and CO emissions.
5. Research shows that micro biogas installations can be available and economically viable, especially in CHP systems and when integrated with energy storage systems and fertiliser management, in the open with other biofuels, labels such as biodiesel, bioethanol or pellets, biogas distinguished by electrical waste production from waste, characteristic for applications (heat, electricity, motor fuel) and net carbon footprint. Its calorific value is lower, and in terms of environmental and functional balance, biogas presents itself as one of the most universal and sustainable energy sources.
6. The challenge includes high operating costs, the need for durability, and the lack of fuel standardisation. Responsibilities may include developing materials resistant to, taking on the role of prosumers, and complying with energy policy.

From an application perspective, the most likely applications for the development directions include:

- the miniaturisation of the CHP switch, biogas switch,
- enrichment of biogas with water.

Moreover, integrating large-scale generators with broadband-connected microgrids and the Internet of Things (IoT) supports energy optimisation.

Nomenclature

ANN	artificial neural network	H_2S	hydrogen sulphide
BTE	brake thermal efficiency	ICE	internal combustion engine
CH_4	methane	IL	ionic liquid
CHP	combined heat and power	LPG	liquefied petroleum gas
CI	compression ignition	LSTM	long short-term memory
CNG	compressed natural gas	MCPD	Medium Combustion Plant Directive
CO	carbon monoxide	MMMs	mixed matrix membranes
CO_2	carbon dioxide	NO_x	nitrogen oxides
CR	compression ratio	PCA	principal component analysis
DF	dual fuel	PM	particulate matter
ECU	electronic control unit	RES	renewable energy sources
GHG	greenhouse gases	SCR	selective catalytic reduction
H_2	hydrogen	SI	spark ignition

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