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CREATION OF A DISTRIBUTED ENERGY SYSTEM FOR THE PRODUCTION OF THERMAL AND ELECTRIC ENERGY

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The object of the study is the distributed generation (DG) system for remote areas where extending power lines is challenging or impossible. The study demonstrates how integrating electrical and thermal energy modules based on renewable energy sources (RES) into a common DG bus can ensure continuous energy supply. This approach provides both heat and electricity to consumers, independent of weather conditions an advantage over traditional systems reliant on variable sources like wind and solar energy. Numerical assessments suggest that the proposed system can improve local renewable resource utilization by approximately 20–30 % compared to single-source renewable setups. This enhanced efficiency results in a more stable power output, with fewer interruptions caused by low wind speeds or reduced solar irradiance. Economically, reducing dependence on diesel generators by about 15–25 % can translate into substantial fuel cost savings. In addition, shifting energy production away from non-renewable sources may cut greenhouse gas emissions by an estimated 10–20 %, contributing to environmental protection targets. In this research received lies in its solution for off-grid energy delivery in rural areas, which generally rely on expensive and frequently unreliable centralized energy infrastructure. By leveraging renewable energy sources and implementing a cogenerative DG system, the study significantly reduces reliance on traditional energy grids and enhances energy independence for remote facilities. The research highlights the practical value of the proposed solution, particularly for rural areas far from power lines and with limited access to traditional electricity systems. The suggested system not only provides continuous energy, but it also coincides with worldwide trends toward sustainable and decentralized energy solutions

Keywords: cogeneration distributed generation, renewable energy sources, off-grid energy, biogas, electrical and thermal energy

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1. Introduction

To cover the energy needs of geographically remote regions from large cities, large-scale introduction of affordable alternative energy sources into this area is required. Since it is impractical, and sometimes impossible, to carry out various types of power transmission lines to these regions, the optimal way to ensure energy supply to these regions is to use RES for this purpose. Such renewable energy sources can be suns, wind and biofuels.

Ensuring reliable, cost-effective, and sustainable energy supply in remote and off-grid areas remains a critical challenge in the modern energy landscape. According to the International Energy Agency (IEA), approximately 759 million people worldwide still lack access to electricity, representing roughly 10 % of the global population. This situation not only undermines socioeconomic development but also conflicts with the international commitment to achieve universal access to affordable, reliable, and sustainable energy – a key target of the United Nations Sustainable Development Goals.

In contemporary conditions, conducting scientific research on cogenerative distributed generation (DG) systems is necessary for several reasons [1–3]. First, as global economies strive to reduce greenhouse gas emissions and limit the adverse effects of climate change, decentralized energy solutions become increasingly relevant. By integrating multiple renewable sources – such as wind, solar, and biogas – into one cohesive energy framework, it is possible to enhance operational flexibility, maintain stable energy outputs, and reduce reliance on fossil fuels. Studies show that implementing such hybrid systems can improve the utilization of local resources by up to 20–30 %, minimizing overall costs and improving energy security [4, 5]. Moreover, integrating advanced storage technologies and intelligent control algorithms can increase system efficiency, ensuring continuous energy delivery even in the face of variable environmental conditions [6].

From a practical perspective, the results of these studies can yield substantial benefits. For instance, implementing cogenerative DG solutions can reduce operational costs associated with diesel generation by an estimated 15–25 % in remote communities, leading to more affordable and reliable energy access [7]. Improved energy availability, in turn, supports local industries, agricultural production, and public services – factors essential for economic development and social well-being. Policy makers can utilize the research findings to design supportive frameworks and incentives that encourage decentralized energy systems, while engineers and investors can rely on evidence-based strategies to optimize system design and resource allocation [1, 8].

Furthermore, making energy systems more flexible with better optimization methods and long-term planning, helps manage uncertainties in demand and resource availability [3]. Research indicates that combining different renewable energy sources with advanced controls can lower costs and reduce environmental impact. Forecasting capacity factors, aids in planning so that renewable-based distributed generation (DG) systems can meet the real needs of isolated communities without wasting resources [9].

In essence, the relevance of current scientific research in cogenerative DG stems from its potential to address global energy disparities and support the transition to a sustainable energy future. By integrating renewable resources, enhancing system flexibility, and improving cost-effectiveness, cogenerative DG research can help reduce the percentage of the global population without electricity, moving closer to universal energy access and contributing directly to tangible environmental, economic, and social improvements.

2. Literature review and problem statement

The paper [1] presents the results of research on improving full-chain process synergy in multi-energy complementary distributed energy systems through cascade storage and initiative management strategies. It is shown that by coordinating various energy carriers and storage solutions, system flexibility and operational efficiency can be enhanced. However, there were unresolved issues related to the scalability and economic justification of these integrated strategies in remote or isolated regions. The reason for this may be the complexity inherent in balancing multiple energy vectors and ensuring stable, continuous supply under diverse operating conditions. A way to overcome these difficulties can be found by combining proactive management with advanced storage technologies, although such approaches require validation in more constrained scenarios.

This approach was partially employed in [2], where integrated energy system modeling incorporating demand response, heat pumps, and thermal storage improved the adaptability and robustness of the system. Nevertheless, unresolved issues persisted concerning the translation of these methods to standalone or islanded conditions, as well as optimizing thermal and electric output simultaneously. The reason for these lingering difficulties may be the absence of a comprehensive framework that accounts for variable demands, resource intermittency, and local climatic factors, limiting the applicability of the proposed models.

The paper [3] considered the optimal planning of islanded integrated energy systems with solar-biogas supply. It showed that coupling different renewable sources could improve autonomy and resilience. Yet, there were unresolved issues related to effectively handling uncertainties in load variations and ensuring consistent thermal-electric generation. These challenges may stem from insufficient strategies to dynamically adjust energy flows in response to fluctuating conditions, especially when both electric and thermal demands must be met concurrently.

A potential solution is reflected in [4], where a two-stage approach for efficient power sharing within energy districts was examined. The study demonstrated that coordinated operation among distributed units could enhance resource utilization. However, unresolved issues remained regarding the complete synchronization of thermal and electric energy production for remote applications. The underlying reason might be the fundamental difficulty of achieving a cost-effective, fully integrated system that reacts seamlessly to variable inputs and outputs across different energy carriers.

In [5], a comparative review of energy storage systems highlighted their critical role and potential impacts on future power systems. Although it is shown that appropriate storage selection can mitigate variability, unresolved issues persist in selecting optimal storage configurations for conditions where both thermal and electric energy must be generated and delivered reliably. The reason could be the cost implications and technological constraints associated with deploying a unified storage and control solution across diverse energy forms.

The research in [6] addressed planning distributed generation resources and storage within a virtual power plant, considering load uncertainty. While this work demonstrated that accounting for unpredictability could improve system performance, unresolved issues arise in extending these frameworks to isolated, off-grid conditions where both thermal and electric outputs must be optimized. The difficulty lies in creating robust algorithms that handle variable demand patterns and complex resource mixes without significant cost overruns or reliability trade-offs.

The approach taken in [7] tackled the integration of hydrogen production and thermal energy recovery in renewable microgrids, showing that introducing alternative fuels and recovery processes can boost efficiency. However, unresolved issues remained regarding the comprehensive management of multi-vector energy systems that supply both heat and power. Such complexity, and the associated infrastructural costs, may limit the practicality of the solution in certain remote contexts.

Finally, [8] investigated an integrated hybrid thermal dynamics model and energy-aware optimization for grid-interactive residential building management. This demonstrated improved local load management and energy utilization. Still, unresolved issues are evident when attempting to scale such building-level solutions into a fully-fledged distributed system that ensures stable thermal and electric supply at a district or regional level. The reason might be that local solutions do not straightforwardly aggregate into a system-wide approach without sophisticated coordination mechanisms and cost controls.

The paper [9] presents research on agro-energy-environment synergy-based distributed energy planning in rural areas. It is shown that integrating agricultural activities with energy production can enhance the sustainability and efficiency of distributed energy systems. However, there were unresolved issues related to the optimization of resource allocation and the economic viability of such integrated systems in diverse rural settings. The reason for this may be the variability in agricultural outputs and the limited financial resources available in rural areas. A way to overcome these difficulties can be the development of adaptive planning models that can dynamically adjust to changing agricultural and energy demands.

This approach was partly addressed in [10], where a flexible multi-objective optimization planning method was proposed to enhance the operational flexibility of distributed energy systems by considering both long-term and temporary objectives. Nonetheless, integrating such flexible planning methods with agro-energy systems in rural areas requires further exploration to ensure economic and operational feasibility. This suggests the necessity of conducting studies focused on adaptive and flexible optimization techniques tailored for agro-energy integrated distributed energy systems in rural contexts.

The paper [11] investigates community-based virtual power plants' technology and circular economy models in the energy sector through a techno-economy study. It is shown that virtual power plants can facilitate the efficient management of distributed energy resources and promote circular economy practices. However, unresolved issues exist regarding the seamless integration of circular economy principles with virtual power plant technologies, particularly in terms of scalability and economic incentives. The reason for this may be the lack of standardized frameworks and incentives to support the widespread adoption of such integrated models. A way to overcome these difficulties can be the establishment of policy frameworks and economic incentives that encourage the adoption of circular economy practices within virtual power plants.

This methodology was explored in [12], which focuses on carbon neutrality and hydrogen energy systems. However, integrating hydrogen energy systems into community-based virtual power plants while maintaining circular economy principles remains a complex challenge. Consequently, it is advisable to conduct comprehensive studies that develop integrated techno-economic models incorporating both virtual power plant technologies and circular economy practices to enhance the sustainability and scalability of distributed energy systems.

The paper [13] offers a systematic review towards integrative energy management of smart grids and urban energy systems. It is shown that integrative energy management can significantly enhance the efficiency, reliability, and sustainability of urban energy systems by leveraging smart grid technologies. However, unresolved issues pertain to the interoperability of diverse energy management systems and the scalability of integrative approaches in large urban settings. The reason for this may be the heterogeneous nature of urban energy infrastructures and the high costs associated with upgrading existing systems to smart grid standards. A way to overcome these difficulties can be the development of interoperable standards and cost-effective technologies that facilitate the seamless integration of diverse energy management systems.

Despite significant advancements in distributed energy systems, ensuring the reliable and simultaneous production of both thermal and electric energy in remote and off-grid regions remains a critical challenge. The complexities of integrating multiple renewable energy sources, optimizing energy storage, and managing variable energy flows under diverse environmental conditions contribute to the difficulty. Additionally, economic constraints and the scalability of existing solutions hinder the widespread adoption of effective distributed energy systems. There is a pressing need to develop comprehensive, cost-effective, and scalable solutions that seamlessly integrate renewable resources, advanced storage technologies, and adaptive control algorithms to achieve sustainable and autonomous energy provision for remote areas.

3. The aim and objectives of the study

The aim of the study is to develop a technology for creating a modular cogenerative hybrid energy system based on renewable energy sources, providing continuous electric and thermal energy and independent of the vagaries of the weather.

To achieve this aim, the following objectives are accomplished:

– to design and develop a cogenerative distributed generation (DG) system integrating wind, solar, biogas turbines, and batteries, ensuring reliable electrical and thermal energy supply for remote consumers;

– to identifying the experimental dependences of electricity generation by a wind-solar installation on wind speed;

– to conduct experimental studies of electricity and useful heat from the volume of biogas.

4. Materials and methods

The object of this research is the distributed generation (DG) system designed to produce both electrical and thermal energy for consumers in remote regions. This system integrates multiple renewable energy sources (RES) including wind turbines, solar panels, and biogas-powered gas turbines, alongside energy storage solutions such as batteries and thermal accumulators [14]. The primary focus is on creating a modular hybrid power system that ensures reliable and uninterrupted energy supply irrespective of external weather conditions.

The main hypothesis of this study is that a cogenerative distributed generation system, which harmoniously integrates multiple renewable energy modules and employs advanced energy flow management strategies, can provide a stable and continuous supply of both electrical and thermal energy to remote consumers. This system is expected to overcome the limitations posed by the intermittency of individual renewable sources, thereby enhancing energy reliability and economic viability in off-grid settings.

In this study, it is assumed that the target remote regions have enough wind and solar resources to run wind turbines and solar panels effectively. Let's also assume a steady supply of organic waste for biogas production, ensuring reliable fuel for the gas turbine engines. The local energy demand is considered stable and predictable, enabling better planning and management of energy flows. Additionally, all system components – including wind turbines, solar panels, biogas generators, and energy storage units – are assumed to work reliably under the given environmental conditions [3–7].

To make the modeling and analysis more manageable, several assumptions were made. First, the models consider the modules operating under steady-state conditions, ignoring any rapid changes in environmental factors or energy demand. Second, each module's energy conversion efficiency is treated as constant, without accounting for changes due to wear or maintenance. Third, the DG system is modeled as isolated, with no interactions or dependencies on external grids. Finally, the control algorithms focus only on basic energy distribution and synchronization, without advanced predictive or adaptive functions. These simplifications help maintain clarity and keep attention on the core goal of developing a reliable, efficient cogenerative DG system for remote areas.

Theoretical Methods. The theoretical investigation of the proposed cogenerative distributed generation system employed several analytical approaches. Mathematical modeling and simulation techniques were used to represent each power module – the wind-solar hybrid, the gas turbine engine, and the biogas reactor – through sets of equations derived from fundamental physical, thermodynamic, and biochemical principles. System-level multi-energy flow analysis was conducted by integrating these individual models into a unified framework of equations governing electrical, thermal, and fuel flows, enabling simulations of their interactions and overall performance under varying operating conditions. Sensitivity and parametric studies were performed to assess how changes in input parameters, such as wind speed distributions and biogas production rates, influenced system robustness and efficiency. Comparative evaluation against established benchmarks and single-source generation models provided a reference point, allowing the validation of theoretical improvements and confirming that the chosen modeling methods and assumptions were appropriate.

Justification of methods. The creation of a modular cogenerative hybrid energy system having four modules: a module using solar energy using solar panels and a module producing electricity and thermal energy, a module using wind energy to generate electricity and a module using biofuels to generate electricity and generate fuel energy of the type of gas will ensure uninterrupted energy generation for the needs of these regions regardless of weather conditions.

Therefore, the creation of low-power hybrid energy systems for locally remote regions is in demand. Such an energy system, as already noted, should have a modular design. The socio-economic aspects of this issue should not be forgotten here.

The main advantages of a modular hybrid power system compared to "pure" solar technologies are:

– low dependence of the potential of the generated type of energy on weather conditions, i. e. high reliability;

– economic profitability.

Experimental conditions. The proposed cogenerative DG system integrates a gas turbine engine (GTE), hybrid wind-solar power plants, and biogas production. The experimental setup demonstrated the capability to simultaneously produce electrical and thermal energy efficiently. The following results were observed:

– the GTE has dimensions of 30×14×14 cm, weighs 10 kg, and generates 3.3 kWh of electricity and 3500 kcal of heat per hour when fueled with 1 liter of biogas. The thermal battery used in the system measured 2×2×3 meters;

– a hybrid wind turbine with a blade diameter of 4.7 meters and a solar panel of 1 m^2 produced combined electrical energy through its coils and solar panels, contributing to the overall power generation.

5. Results of the cogenerative distributed generation system experiment

5. 1. Results of design and development of the cogenerative distributed generation system

Initially, derived for each of the four integrated modules proposed in the system:

1. Hybrid Wind-PV module (module 1).

Module 1, depicted in Fig. 1, is a hybrid wind-powered installation integrated with photovoltaic (PV) components, theoretically modeled using aerodynamic equations, electromagnetic induction principles, and photovoltaic conversion formulas. Structurally, it includes a mast (1), solar panels (2), magnetic blades (3), an asynchronous motor (4), an induction coil (5), and a controller (6) [15].

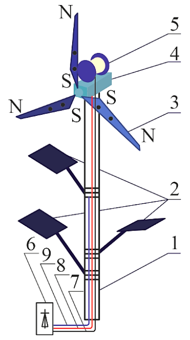


Fig. 1. Hybrid wind power plant (wind turbine) (Patent of the Republic of Kazakhstan for utility model № 7391)

Under the influence of wind, the magnetic blades 3, generating an alternating electric current 7 using an asynchronous motor 4, and creates a magnetic field around itself, which, crossing the windings of the induction coil, generates an induction current 8. Direct current 9, generated on solar panels 2 through the controller 6, is transmitted to the micro network (Fig. 2).

By combining these principles, Module 1 can produce both alternating and direct current outputs from a single, integrated unit. Multiple such hybrid wind-PV modules can be connected to form a microgrid, ensuring that generated electrical energy is efficiently delivered to the DG bus [16]. This integration of aerodynamic, electromagnetic, and PV modeling elements underpins the stable and flexible operation of the module, effectively harnessing renewable resources for distributed.

2. Gas turbine cogeneration module (module 2). Module 2, depicted in Fig. 3 [3], is responsible for the simultaneous production of electrical and thermal energy using a gas turbine generator. In operation, the gas turbine engine (GTE) converts the supplied gas fuel into electrical power. The engine's hot exhaust gases are then directed through a water-based heat exchanger, thereby generating thermal energy stored in the water accumulator. Finally, the generated electrical energy is delivered through a controller to the distributed generation bus.

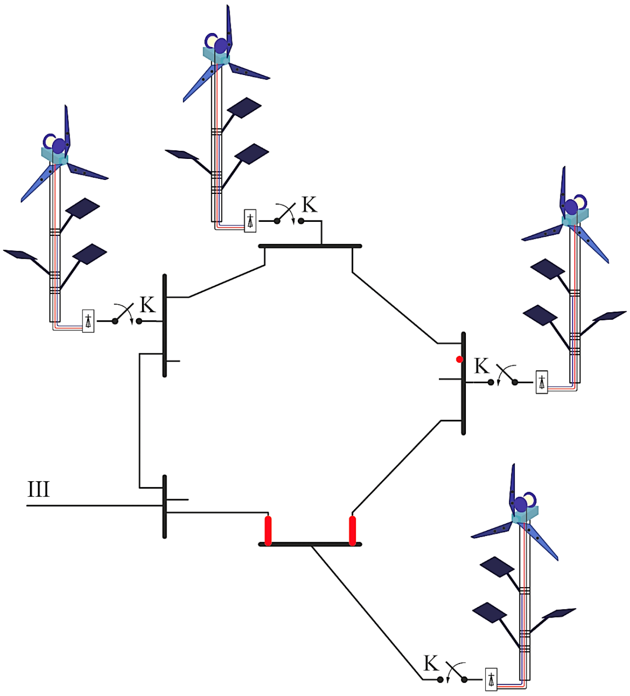


Fig. 2. Micro network of hybrid wind turbines (III – Common distributed generation bus line, *K* – Switches/circuit breakers used to connect or disconnect individual hybrid wind turbines from the micro-network

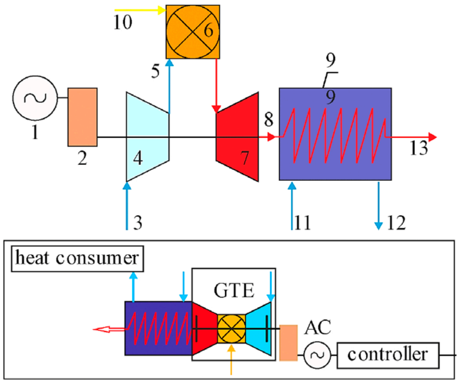


Fig. 3. Module generating thermal and electrical energy (Patent of the Republic of Kazakhstan for utility model No. 6070)

Schematic diagram of the gas turbine engine (GTE) module integrated into the cogenerative distributed generation (DG) system. The numbers indicate: (1) Electric generator; (2) Shaft coupling; (3) Ambient air intake; (4) Compressor; (5) Compressed air conduit; (6) Combustion chamber; (7) Turbine stage; (8) Turbine exhaust gas channel; (9) Water battery (heat exchanger); (10) Fuel (gas) inlet line; (11) Cold water inlet to heat exchanger; (12) Heated water outlet from heat exchanger; (13) Exhaust gas outlet to atmosphere. The AC power produced by the generator (1) is regulated by the controller and supplied to the common DG bus or distribution network as needed, while thermal energy is extracted via the water battery (9) for heating applications.

3. Biogas production module (module 3). Module 3, responsible for biogas production to fuel both the gas turbine engine and the consumer's demand, is illustrated in Fig. 4 [15, 17]. Its operation proceeds as follows: biological waste is introduced into a bioreactor, where it is processed to yield both biogas and nutrient-rich soil suitable for greenhouse use. A portion of the resulting biogas is routed to the gas turbine engine, while the remainder is directed to the consumer as a fuel source.

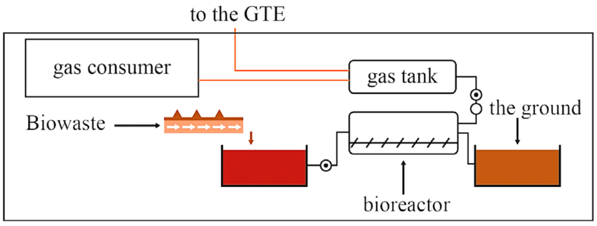


Fig. 4. The module producing biogas and soil for the greenhouse

4. Control and distribution module (module 4).

Module 4, responsible for overseeing system operations and distributing the generated electrical energy of the cogenerative DG, is illustrated in Fig. 5 [15–18]. Its function is as follows: all produced electrical energy is directed to a common DG bus. Using universal inverters, this energy can then be delivered either to a nearby distribution network – if available – or directly to the consumer. Notably, no surplus electrical energy is stored in the underground Energy Storage Unit (ESU) [3]. Instead, the Automatic Control Systems (ACS) manage and regulate the flow of this electrical output.

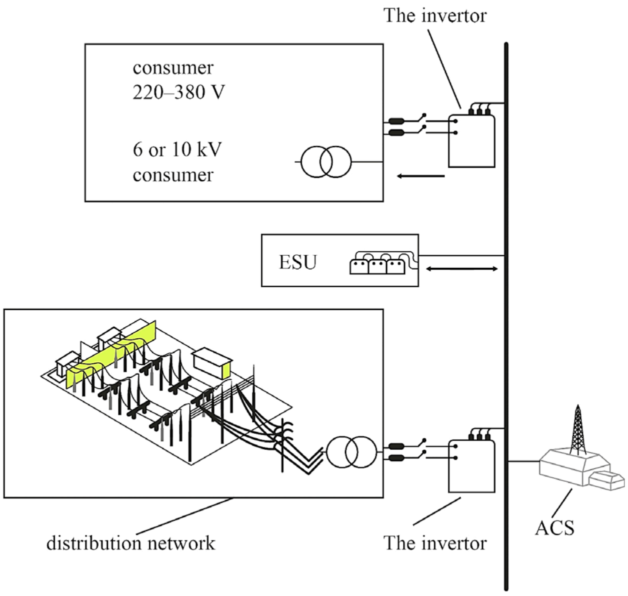


Fig. 5. Control module for the distribution of generated electrical energy

Based on these modules, it is possible to create a cogenerative power plant powered by renewable energy sources and generating electric, thermal and fuel in the form of gas for consumers.

The Fig. 6 shows the proposed cogenerative energy system of the DG. This system works as follows [19, 20]. Module 1 generates three types of electric current (Fig. 1). By converting these currents to direct current, it is transmitted to the common bus III. The automated control system controls the work of hybrid wind turbines.

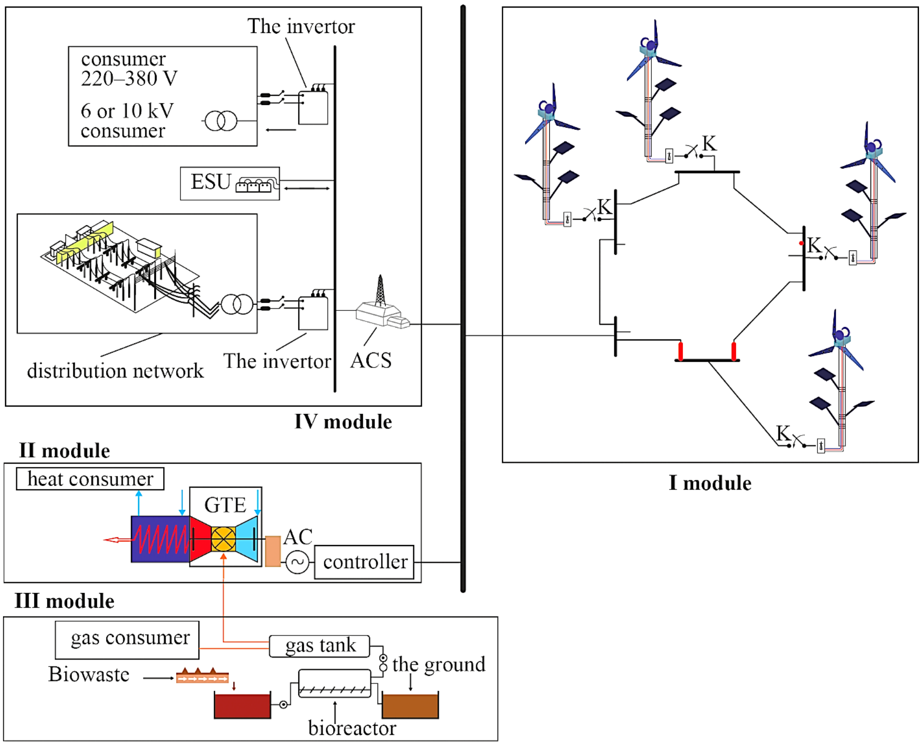


Fig. 6. Distributed generation operating in cogeneration mode (utility model patent No. 7970)

In principle, module 2 is designed to provide continuous generation of electrical energy in the absence of solar and wind energy. Depending on the demand for thermal energy and gas, the automatic control system starts the operation of this module. Module 3 by producing biogas from agricultural and livestock waste, biogas is produced at the bioreactor, which is transferred to module 2. Part is transferred to the consumer in the form of fuel energy. The electric energy contained in the common bus of the cogenerative DG, using module 4, is distributed to consumers [21–23].

5. 2. Results of experimental dependences of electricity generation by a wind-solar installation on wind speed

Tests conducted on the hybrid wind-solar module demonstrated a clear dependence of electrical output on wind speed, as detailed in Table 1.

The key observations include:

– at a wind speed of 4 m/s, the system generated 1.32 W of combined power, which increased steadily with wind speed, reaching 4.57 W at 13 m/s;

– solar panels contributed consistently to the power output, mitigating fluctuations caused by variable wind speeds, as shown in Fig. 7.

The experiments showed that as the wind speed increased, the total electrical power of the wind-solar system also increased. At lower wind speeds (around 4 m/s), the system produced around 1.32 W, and this power increased to around 4.57 W at 13 m/s. While the solar panels provided a relatively stable contribution (ranging from around 0.59 W to 0.96 W) regardless of the wind speed, the wind components produced much more power as the wind speed increased. To better understand the data, each measurement was plotted with error bars to show the uncertainty. A mathematical approximation using a linear fit gave a good representation of the relationship between wind speed and total power output. The high coefficient of determination ($R^2>0.97$) showed that this curve closely matched the measured data.

Table 1

Results of the operation of one wind-solar power plant in one hour at different wind speeds

V power	(m/s)	4	6	7,5	10	13
P coils	(Wt)	0.18	0.29	0.53	0.62	0.92
P photo panels	(Wt)	0.59	0.69	0.77	0.94	0.96
P generator	(Wt)	0.55	1.27	1.81	2.27	2.69
P general	(Wt)	1.32	2.25	3.11	3.83	4.57

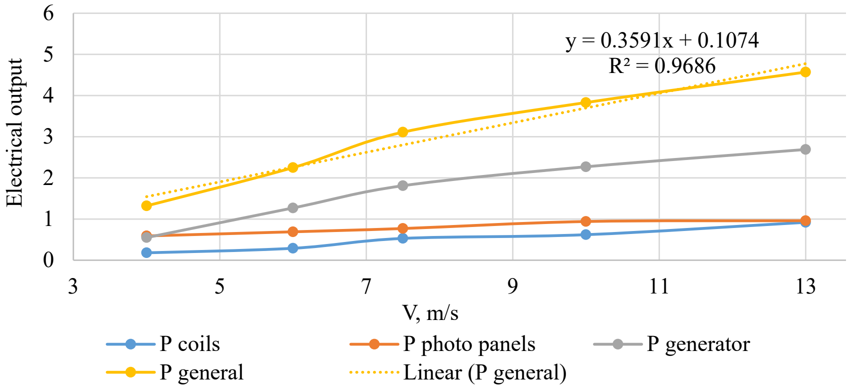


Fig. 7. Graph of the dependence of electric energy generation by a wind generator-solar installation on wind speed

These results confirm that higher wind speeds significantly increase the electrical power of the system. The stable contribution of the solar component helps reduce the overall variability, making the overall power supply more reliable.

5. 3. Identifying the experimental studies of electricity and useful heat from the volume of biogas

The relationship between biogas volume and energy production was evaluated, demonstrating the high efficiency of the cogenerative system:

– using 1 liter of biogas, the GTE produced 3.3 kW of electricity and 3500 kcal of heat per hour. When scaling up to a 30-liter household cylinder, the system can deliver 95 kW of electricity over 30–35 hours and generate 330,000 kcal of heat;

– experimental results are presented in Table 2, showing the power output (P) and heat (*Q*) generated at varying time intervals. Fig. 8 highlights these dependencies, confirming the system's cogenerative efficiency.

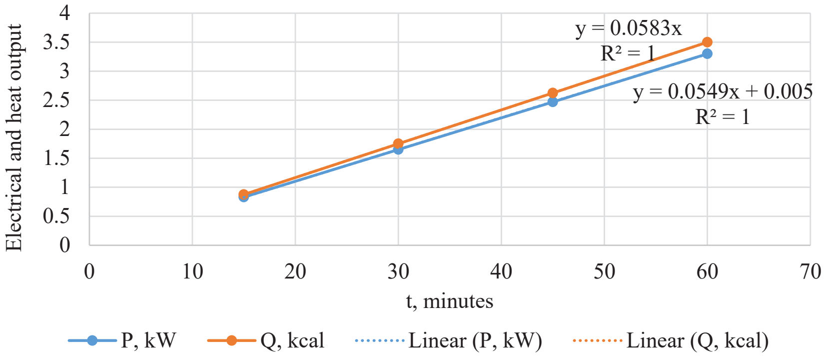


Fig. 8. Dependence of electric energy and useful heat on the volume of biogas

Table 2

Graph of time versus power source and heat

t, minutes	*P*, kW	*Q*, kcal
15	0.83	0.875
30	1.65	1.750
45	2.47	2.625
60	3.3	3.500

At the same time, the heat accumulator had a dimension of 2×2×3 m (Fig. 3). If the exhaust gas temperature is, say, 7000 C, then the thermal energy on the thermal accumulator is calculated by the formula:

$$Q = cm\Delta T. \tag{1}$$

If to take into account that for water it is equal to 4200 J/kg·deg, then it is not difficult to calculate the mass of water in the thermal accumulator.

The volume of the heat accumulator is 12 m^3. And the mass of water in it is 14.4 kg.

Below are the results obtained from the mathematical model.

Experience has shown that approximately 25 MJ of heat can be obtained from 1 m^3 of biogas (equivalent to 330×10^3 kcal).

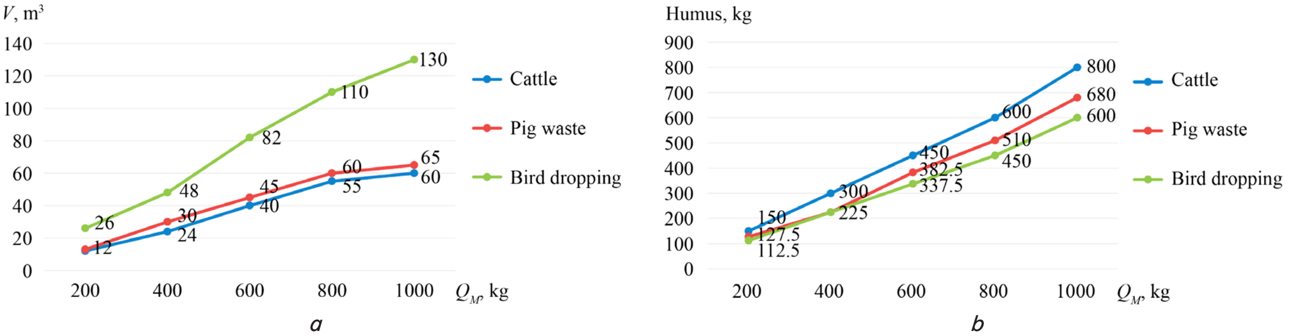
In Table 3 experimental data used to estimate the production of Q_m – useful thermal energy from the exhaust gas on a model gas turbine engine are presented (Fig. 9). Here the output of humus depends on the coefficient K determining the type of initial waste Q_M.

Experiments have further confirmed that about 25 MJ of heat can be obtained from 1 m^3 of biogas (equivalent to approximately 330,000 kcal), underscoring the substantial energy potential of this renewable fuel source. Table 3 presents the experimental data linking the type and amount of organic waste input (cattle, pig, and bird droppings) to biogas volume, humus production, and useful thermal energy (Q_m). These results show that different waste inputs yield varying amounts of biogas and humus, allowing for optimization of feedstock selection based on availability and desired energy outputs.

Table 3

The results obtained from the experiment

No.	Cattle, kg $K_1=1$					Pig waste, kg $K_2=0.85$					Bird droppings, kg $K_3=0.76$				
Q_M, kg	200	400	600	800	1000	200	400	600	800	1000	200	400	600	800	1000
Q_m, J	300	600	900	1200	1500	300	600	900	1200	1625	1500	1800	2250	2750	3250
$P(I,U)$, W	80	160	240	300	414	112	224	300	400	448.5	150	300	450	650	897
Humus, kg	150	300	450	600	800	127.5	255	382.5	510	680	112.5	225	337.5	450	600
V_c, m^3/kg	12	24	40	55	60	13	30	45	60	65	26	48	82	110	130



a *b*

Fig. 9. Dependence of the output of biogas (*a*) and humus (*b*) on the type of initial waste

6. Discussion of the results of a cogenerative distributed generation system to produce thermal and electric energy

The design results show that the cogenerative distributed generation (DG) system can provide a reliable, year-round supply of electric, thermal, and gas-based energy to remote consumers. By integrating wind turbines, solar panels, biogas production, and gas turbine engines into a single, flexible network, the system can deliver consistent power despite changes in weather or demand. A key feature of the design is a common DG bus, where all energy types – electrical, thermal, and fuel –come together. This approach transforms various, often unpredictable, inputs into a stable output. It also helps manage seasonal differences in sunlight and wind. Additionally, using biogas as a controlled fuel source ensures a backup supply when renewables are not available, making the entire system more resilient.

The results of this study demonstrate that the proposed cogenerative distributed generation (DG) system is capable of reliably supplying both electrical and thermal energy to consumers in remote regions. This success can be attributed to the integration of renewable energy sources, such as wind turbines and solar panels, with energy storage systems (batteries), as shown in Fig. 6. The combination of these elements ensures a stable energy output despite variations in wind speed or sunlight availability, as depicted in Fig. 7 and Table 1. However, the system's reliance on specific renewable resources, such as biogas from agricultural waste and consistent wind or solar input, highlights a limitation in its applicability to regions with constrained resource availability as in Fig. 8 and Table 2. A potential development to address this limitation would involve exploring alternative or supplementary renewable sources, such as hydrogen or geothermal energy, to enhance flexibility and reliability. Moreover, the estimation of useful thermal energy (Q_m) from the exhaust gas of a model gas turbine engine (Fig. 9) further demonstrates the importance of understanding and optimizing resource utilization. In Table 3, experimental data for Q_m are presented, showing how humus output depends on the coefficient K, which is influenced by the type of initial waste QM, thereby underscoring the need to carefully match resource inputs to desired energy outputs.

The proposed system's capability to provide uninterrupted power supply distinguishes it from traditional renewable energy systems that are highly dependent on weather conditions. Compared to earlier studies, such as [1], which highlight the challenges of integrating renewable energy systems, this study demonstrates that the cogenerative DG system can mitigate these limitations by dynamically balancing the energy flow between multiple sources and consumers. Similarly, the modular design and control strategy presented here build upon the work [2], who introduced thermal storage and demand response as key elements for managing variability, but this study extends the application to include cogeneration of thermal and fuel energy. Unlike other studies, such as those focusing on standalone wind-solar systems [3], the proposed system incorporates biogas production, ensuring energy availability even during prolonged periods of unfavorable weather.

Building on the optimal planning frameworks proposed by works [3, 4], our cogenerative *DG* system optimizes the integration of solar, wind, and biogas resources to enhance energy autonomy and operational flexibility. The advanced energy flow management and dynamic control algorithms employed in our system ensure stable energy provision irrespective of load fluctuations or renewable energy intermittency. This comprehensive optimization aligns with the multi-objective optimization approaches discussed in work [22], further reinforcing the system's ability to handle complex energy flow scenarios. In [5] emphasized the critical role of energy storage systems in mitigating renewable energy variability. Our study underscores this by integrating robust energy storage solutions, such as batteries, to ensure continuous energy supply. Additionally, our approach explores hybrid storage systems that cater to both thermal and electrical needs, overcoming the limitations of traditional storage configurations. This aligns with the findings of work [6], highlighted the importance of optimizing distributed generation resources and storage within a virtual power plant framework to handle load uncertainty effectively.

The work [21] highlighted the synergy between agriculture, energy, and environment in rural energy planning, which aligns with our focus on remote regions where such integrations can enhance sustainability. By incorporating biogas production from agricultural waste, our system not only provides a renewable energy source but also promotes waste-to-energy practices, contributing to a circular economy. [23] discussed the role of community-based virtual power plants and circular economy models, which resonates with our system's potential to support circular energy flows and community-level energy independence.

However, while the proposed cogenerative DG system shows promising results, several limitations exist. First, the system's performance depends on the availability of specific renewable resources, such as agricultural waste for biogas production and consistent wind or solar input, which may limit scalability in resource-constrained regions. Second, the accuracy of the results, particularly the optimization of energy flows, relies on the precision of the control algorithms and models validated under idealized conditions. Real-world implementation could introduce uncertainties due to equipment degradation and unexpected load variations. Furthermore, the energy management strategy assumes access to advanced electronics and control devices, which may not be feasible or cost-effective in some remote areas.

One notable disadvantage of this study is the lack of experimental validation for the control algorithm under real-world conditions. While computational simulations have validated the system's behavior, practical scenarios may present additional challenges such as maintenance issues and unforeseen environmental factors. Future work should focus on conducting field trials to evaluate the system's reliability, stability, and scalability in practice. Additionally, the economic feasibility of deploying such systems at scale remains underexplored and warrants further investigation.

Future development of the cogenerative *DG* system could involve refining the control algorithms to handle more complex and dynamic energy flow scenarios, such as incorporating additional renewable energy sources or advanced energy storage technologies. Expanding the range of environmental conditions tested in simulations, particularly for extreme scenarios, would further enhance the system's robustness. However, challenges such as ensuring the reproducibility of results across different geographic locations, managing the higher computational demands of more sophisticated control algorithms, and addressing the cost implications of deploying modular components might arise. Experimental studies involving pilot installations in diverse remote regions could help overcome these challenges and pave the way for wider adoption of the proposed system.

7. Conclusions

1. As a result of designing the cogenerative distributed generation system, which integrates wind turbines, solar panels, biogas-powered gas turbines, and energy storage solutions (batteries), a system capable of providing reliable and uninterrupted energy supply to remote areas was created. The system demonstrated high efficiency in providing both electrical and thermal energy, making it suitable for use in areas where connection to centralized power grids is not possible.

2. In conclusion, the approximation analysis demonstrates that the total generated power (P general) from the wind-solar installation can be effectively modeled as a function of wind speed using a simple linear relationship. The fitted equation, derived through least-squares regression, provides a strong correlation ($R^2 \approx 0.97$) between wind speed and total power output. This high degree of fit indicates that within the tested range of wind speeds, a linear model sufficiently captures the trend of increasing power generation. Although more complex models could be considered if greater precision or a wider range of conditions are examined, the current approximation successfully quantifies the relationship observed in the experimental data.

3. The linear trends observed and high correlation coefficients (R^2 values near unity) in both biogas and humus production, as seen in Fig. 9, validate the predictability and scalability of this approach. Overall, these findings confirm the system's capacity for stable, scalable energy production from biogas, effectively integrating electrical and thermal generation. The demonstrated efficiency, adaptability to different inputs, and effective energy storage solutions address the need for robust and reliable remote energy supply systems. Thus, the combination of multiple renewable-based modules in a hybrid DG arrangement proves both technically feasible and economically appealing, providing a foundation for deploying such systems in challenging environments where conventional energy infrastructure is unavailable or impractical.

Conflicts of Interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research, and its results presented in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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