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Analysis of reliability and fault resilience of a biogas plant with a cogeneration unit in the power supply system of an agro-industrial complex

Abstract: This paper analyzes the reliability and fault tolerance of a biogas plant with a cogeneration unit as a complex electrotechnological system. Fault tolerance is considered an integral aspect of reliability, reflecting the system's ability to localize failures, maintain partial operation, and restore functionality. The plant's stability depends on coordinated operation of substrate preparation, anaerobic digestion, and energy conversion subsystems. The system exhibits predominantly serial reliability, where failure of critical components can disrupt the entire process.

The study applies structural reliability analysis and exponential failure models, considering both serial and redundant configurations. Key indicators include MTBF, MTTR, expected failures, and availability. Major failure factors are aggressive biogas conditions, substrate variability, thermal

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instability, mechanical wear, and electrical system faults. The cogeneration unit is identified as the most critical element, contributing over 65% of downtime.

A case study shows a total failure rate of $\Sigma\lambda = 1.07$ failures/year, with reliability $R(1) \approx 0.40$–0.43 and about one failure per year. With preventive maintenance and partial redundancy, downtime is limited to 22 hours annually, and availability reaches $A \approx 0.9975$.

The results indicate that system performance is determined not by complete failure-free operation, but by fault tolerance and rapid recovery. Practical measures include redundancy of key components, automated monitoring, and optimized maintenance strategies.

Keywords: biogas plant, system reliability, fault tolerance, cogeneration unit, failure rate, availability factor, redundancy, agro-industrial complex

1. Statement of the problem

The development of renewable energy is one of the priority areas of Ukraine's energy policy, especially in the context of the growing cost of traditional energy sources and the need to increase the energy independence of the agro-industrial complex. Among modern renewable energy technologies, biogas plants occupy a special place, as they combine energy production with effective utilization of organic waste from livestock, crop production, and the food industry. Biogas formed in the process of anaerobic digestion can be used to generate electricity and heat, as well as to produce biomethane, which increases the economic attractiveness of such facilities (Kaletnik 2010; Honcharuk et al. 2024; Popp et al. 2021).

At the same time, biogas plants are complex multi-component technical systems, which include mechanical, thermal, and electrical units, united by a single technological process. Failure of any of the critical elements can lead not only to a stop in electricity generation, but also to disruption of biochemical processes in the bioreactor, the restoration of which requires a significant amount of time. This leads to increased requirements for the reliability and fault tolerance of biogas plants, especially in conditions of autonomous operation and limited backup power supply, typical of agro-industrial enterprises (Kaletnik et al. 2019; Koval et al. 2025).

The problem of reliability is complicated by the specific operating conditions of biogas plants. These include the aggressive environment of biogas with a high content of hydrogen sulfide and moisture, variability of the composition and properties of the substrate, uneven loads, as well as a significant proportion of equipment operating in continuous mode. In such conditions, the traditional approach, focused only on ensuring trouble-free operation, is insufficient. Instead, the fault tolerance of the system, the ability to quickly localize failures and restore operability with minimal loss of time and energy, becomes of paramount importance.

2. Analysis of recent research and publications

A current scientific and applied task is a comprehensive analysis of the reliability of biogas plants, taking into account the structure of the technological and energy paths, determining the most critical elements that affect downtime and generation losses, as well as substantiating technical and organizational measures aimed at increasing the availability factor and stability of biogas power plants (Alavian et al. 2019; Rozen et al. 2013).

The biogas plant includes subsystems for substrate preparation and supply, anaerobic digestion, and energy utilization of biogas. The main elements are a tank for collecting and homogenizing raw materials, a homogenizer, solid and liquid raw materials supply units, a bioreactor with mixing and heating systems, a cogeneration unit, as well as equipment for draining, squeezing, and recycling fermented mass.

A biogas plant is a complex, multi-component technical system in which the failure of individual elements can lead to a decrease in the intensity of the anaerobic digestion process, a violation of the thermal regime of the bioreactor, or a complete stop of the production of electrical and thermal energy. In this regard, it is advisable to assess the reliability of both the technological path of the plant, which includes the receipt and preparation of the substrate, the fermentation process and the utilization of biogas, and the energy path, which includes the conversion of biogas in the cogeneration unit and the power supply of its own and external consumers (Generowicz and Barbusinski 2023; Sher et al. 2024; Rasi et al. 2022).

This approach allows for a comprehensive consideration of the relationship between equipment reliability, the permissible level of biogas use, and the stability of projected electricity generation under the conditions of industrial operation of biogas plants in the agro-industrial complex.

3. Aim of scientific research

This work considers the issue of determining the permissible level of biogas use for the projected generation of electricity, taking into account the reliability of the functioning of the main technological and energy equipment of the biogas plant. Particular attention is paid to the impact of failures of individual nodes on the continuity of the process of generating electricity and heat.

4. Results and discussion

System reliability and its dependence on elements. The reliability of a power supply system is defined as the ability of the system to perform specified functions under specified operating conditions for a specified period of time (Stadnik 2018; Kaletnik et al. 2021). For complex technical systems, in particular power and biogas plants with cogeneration units, the reliability of the system is formed on the basis of the reliability of individual elements that make up its composition.

The probability of failure-free operation of an element is determined by the reliability function (1, 2):

$$R(t) = P\{T > t \tag{1}$$

where:

(T) – random variable of the element's uptime,
(t) – operating time.

For most elements of electrical installations during normal operation, the reliability function is described by an exponential distribution law (5):

$$R(t) = e^{-\lambda t} \tag{2}$$

where:

λ – failure rate, 1/hour or 1/year.

Causes of failure of elements of power supply systems. Failure of elements of electrical installations of biogas plants can be caused by the following main groups of reasons:

- structural – design flaws, equipment selection errors;
- production – material defects, manufacturing technology violations;
- operational – overload, violation of operating modes, personnel errors;
- aging and wear – insulation degradation, corrosion, material fatigue;
- environmental influences – high humidity, aggressive gases (H_2S, NH_3), temperature fluctuations typical of biogas plants.

Main indicators of reliability of system elements. The following indicators are used to quantitatively assess reliability (8):

Failure rate:

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{3}$$

where:

f(*t*) – density of the time-to-failure distribution.

During normal operation (9):

$$\lambda(t) = \lambda = const \quad (4)$$

Average uptime:

$$T_{MTBF} = \frac{1}{\lambda} \quad (5)$$

where:

MTBF – Mean Time Between Failures.

Probability of failure (1, 2):

$$Q(t) = 1 - R(t) \quad (6)$$

Reliability of the system as a set of elements. Sequential connection of elements.

For a system with a series connection of (*n*) elements:

$$R_{s(t)} = \prod_{i=1}^{n} R_{i(t)} \quad (7)$$

where:

$R_{s(t)}$ – reliability function of the entire system,

or with an exponential law:

$$R_s(t) = e^{-}\left(\sum_{i=1}^{n} \lambda i\right)t \quad (8)$$

This is typical for systems where the failure of any element leads to the shutdown of the entire installation (for example, generator – transformer – line).

Parallel (redundant) connection (1, 2):

$$R_s(t) = 1 - \prod_{i=1}^{n} \left[1 - R_i(t)\right] \quad (9)$$

Redundancy is widely used in the power supply of biogas plants to increase overall reliability.

Reliability indicators of electrical installations and systems. For electrical power systems, operational indicators are also used:

Readiness factor:

$$K = \frac{T_{op}}{T_{op} + T_{rep.}} \tag{10}$$

where:

T_{op} – mean operating time,

T_{rep} – mean time to repair (MTTR).

1. Average duration of power outages.
2. Failure rate (SAIFI).
3. Average duration of failures (SAIDI).

These indicators are critically important for autonomous power systems of the agricultural industry, where a power outage can lead to a halt in technological processes.

Methods for restoring system functionality. Restoration of the operability of electrical power systems is carried out by the following methods:

1. Operational redundancy (duplication of generators, transformers, power sources).
2. Scheduled preventive maintenance (regular inspections, replacement of worn components).
3. Automatic recovery (APV, ATS, automated control systems).
4. Modular principle of system construction (quick replacement of a faulty element without stopping the entire installation).

The use of these methods allows for a significant reduction of downtime, an increase in the availability factor, and ensures a stable energy supply to consumers.

Generalization for biogas energy systems. For autonomous biogas power plants of the agricultural and industrial complex, the reliability of electrical installations is a critical factor in efficiency. High reliability is achieved through optimal equipment selection, redundancy of key elements, failure rate control and implementation of modern diagnostic, and control systems.

Reliability and fault tolerance of the system (for a biogas plant according to Fig. 1). A biogas plant is a complex multi-component technical system, the stability of which is determined by the coordinated functioning of the substrate preparation units, the anaerobic digestion process, and the energy conversion of biogas. In conditions of industrial operation, typical for modern large-capacity biogas complexes (Fig. 1), the failure of individual elements can lead to a decrease in biogas yield, a violation of the thermal regime of the reactor, or a complete stop of the production of electrical and thermal energy. Therefore, assessing the reliability and fault tolerance of a biogas plant is a necessary stage of analyzing its efficiency, which allows justifying the feasibility of backing up critical units, choosing a maintenance strategy, and increasing the availability factor of the system as a whole.

Let’s consider the top 5 biogas complexes by capacity for 2025.

Currently, a number of powerful biogas complexes are known in Ukraine, including:

1. "Biogas Ladyzhyn" (MHP), Vinnytsia region. Capacity: 24 MW (first stage – 12 MW, design capacity of both stages – 24 MW).

2. Teofipol Energy Company, Khmelnytskyi region. Capacity: 15.6 MW. Feature: The complex operates on the basis of a sugar factory, using beet pulp and corn silage.

3. Bioenergy complex "Globyne" ("Astarta-Kyiv"), Poltava region. Capacity: 12 MW.

4. Biogas complex "Oril-Lider" (MHP), Dnipropetrovsk region. Capacity: 5.5 MW. Feature: The first large-scale biogas project of the MHP holding, launched for the utilization of poultry waste.

5. Biogas plant "Hals Agro", Chernihiv region. Capacity: ~6 MW (in cogeneration equivalent). Feature: One of the first plants that in 2024–2025 was modernized for the production of biomethane (with a capacity of up to 3 million m^3/year) for supply to gas distribution networks.

Development of biogas production plants is one of the promising areas of activity. With the help of a biogas plant, it is possible to process waste from livestock, agriculture, breweries, and sugar industry enterprises to obtain a valuable product – biogas. Biogas, in turn, is an energy carrier that can be converted using special generators into electricity, heat or steam. The use of biogas plants in the agricultural sector allows reducing the need for purchased energy carriers along with the ecological disposal of industrial waste.

A biogas plant (Fig. 1) is a multi-component technical system, where failure of individual components can lead to a decrease in fermentation productivity or a stoppage of electricity/heat production. Therefore, it is advisable to assess the reliability of the technological path (substrate acquisition and preparation → fermentation → gas utilization) and the reliability of the energy path (biogas → cogeneration → electricity supply to own/external consumers) (Stadnik 2018; Stadnik et al. 2025).

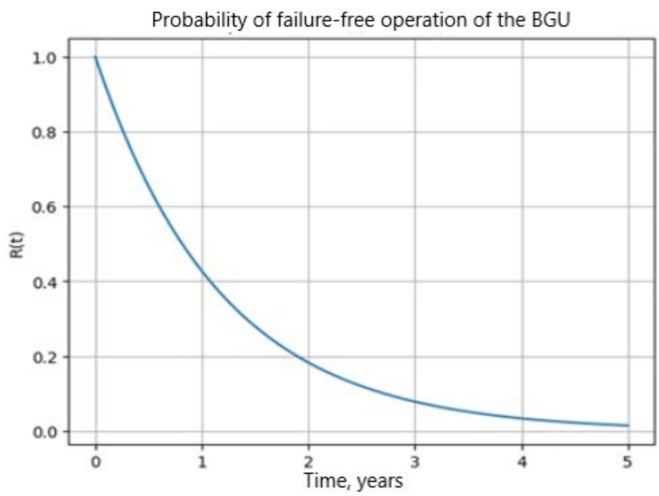


Fig. 1. Dependence of the probability of failure-free operation of a biogas plant on the operation time

Rys. 1. Zależność prawdopodobieństwa bezawaryjnej pracy biogazowni od czasu eksploatacji

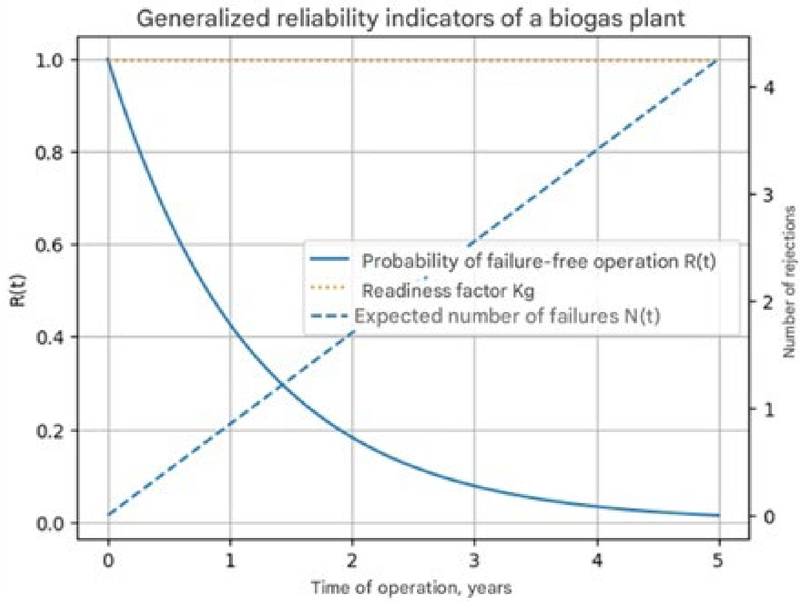


Fig. 2. Generalized reliability graph of a biogas plant

Rys. 2. Uogólniony wykres niezawodności biogazowni

Linking the elements of Figure 1 to the reliability model. To assess the continuity of electricity generation, the following "availability chain" (functional reliability diagram) is critical:

- substrate preparation: 1 (farm) → 2 (collection and homogenization tank) → 3 (homogenizer) → 4/5 (solid/liquid substrate supply),
- fermentation and process support: 6 (bioreactor) together with 8 (mixer) and 9 (heating circuit),
- energy conversion: 7 (cogeneration unit),
- digestate output/utilization (mainly technological continuity): 10–12 (output, squeezing, fertilizer application).

For electrical continuity (namely "the plant produces kWh"), it is most often believed that the shutdown/failure of any of nodes 2–9 or 7 stops generation (sequential structure), while nodes 10–12 affect long-term operation (digestate accumulation, sanitary/environmental restrictions), but do not always lead to an instant loss of generation.

Reliability equation for *BGU* elements and system

The element's fail-safe function:

$$R_i(t) = P\{Ti > t\} \tag{11}$$

For the period of normal operation (which is typical for most electromechanical elements subject to scheduled maintenance), an exponential model is used (1, 2):

$$R_i\left(t\right)=e^{-\lambda t} \tag{12}$$

where:

λ_i – failure rate of the *i*-th element.

Sequential system (generation is possible only when all critical elements are operational):

$$R_{BGP}(t)=\prod_{i=1}^{n}R_i(t) \tag{13}$$

where:

BGP – Biogas Plant,

and for the exponential case:

$$R_{BGP}(t)=e^{-}\left(\sum\nolimits_{i=1}^{n}\lambda i\right)t \tag{14}$$

Parallel redundancy (e.g., two feed pumps or duplication of a critical node):

$$R_{par}(t)=1-\prod_{i=1}^{n}(1-R_J(t)) \tag{15}$$

Causes of failure in the context of a biogas plant. The following typical causes of failure are characteristic of a biogas plant (linked to the nodes in Fig. 1):

1. Corrosion and aggressive impurities in biogas (H_2S, moisture) → increased risk of failures in the gas path and in 7 (engine/generator), ignition elements, and heat exchange.
2. Variability of substrate composition (moisture, solid inclusions) → feed failures 4/5, overloads 3 and 8, process unevenness in 6.
3. Thermal deviations → failures/decrease in efficiency 9, which causes a "cold failure" of the process and a drop in gas formation in 6.
4. Mechanical wear and overload of drives → 3, 8, pumps 4/5.
5. Electrical reasons (overvoltages, automation errors, switching failures) → control/protection unit and electrical part 7 (Voznyak et al. 2025).

Reliability indicators relevant to *BGU*. In addition to *R*(*t*) for the operation of a biogas power plant, it is advisable to provide:

Mean Time Between Failures (*MTBF*):

$$T_{MTBF,i}=\frac{1}{\lambda i} \tag{16}$$

Probability of failure:

$$Q(t) = 1 - R(t) \tag{17}$$

Availability factor (for a maintainable system):

$$Kg = \frac{T_{op}}{T_{op} + T_{rep}} \tag{18}$$

Typical values of failure rates and recovery times were adopted based on operational statistics and published studies (Alavian et al. 2019; Generowicz and Barbusinski 2023) (Table 1).

The expected number of failures per year is determined based on the total failure rate of critical elements of the biogas plant and, for typical industrial operation conditions, is about one emergency stop per year. The expected annual downtime and the plant availability factor are determined taking into account the average recovery time, with high values of the availability factor indicating the maintainability of the system and the stability of the projected electricity generation.

Expected number of failures per year (8):

$$N_{fr} = \sum \lambda_i = 0.85_{\text{FR}} \text{ /year} \tag{19}$$

On average, there is ≈ 1 emergency stop per year, which is quite typical for BSU.

Expected downtime per year

Annual downtime:

$$\begin{aligned} T_{down} &= \sum \lambda_i \cdot MTTR_i \\ T_{down} &= 0.20 \cdot 8 + 0.15 \cdot 24 + 0.10 \cdot 12 + 0.10 \cdot 10 + 0.30 \cdot 48 \\ T_{down} &= 1.6 + 3.6 + 1.2 + 1.0 + 14.4 = 21.8 \text{ hours/year} \end{aligned} \tag{20}$$

Plant availability factor

Working hours per year:

$$\begin{aligned} T_o &= 8{,}760 - 21.8 = 8{,}738.2 \text{ hours} \\ K_g &= \frac{T_o}{T_o + T_o} = \frac{8{,}738.2}{8{,}760} = 0.9975 \end{aligned} \tag{21}$$

where:

T_o – operating hours per year.

The probability of failure-free operation of a biogas plant during the year is relatively low, which is due to the complexity of the system and the presence of a significant number of critical

Table 1. Failure rates and mean time to repair for biogas plant components

Tabela 1. Intensywność awarii i średni czas odtworzenia elementów biogazowni

Node	λ [1/year]	MTTR [h]	Justification of λ	Sources
Substrate supply – pumps (4/5)	0.20	8	Centrifugal/screw pumps in abrasive slurry media; value consistent with pump failure statistics in agricultural applications	Alavian et al. 2019; Generowicz and Barbusinski 2023
Inlet homogenizer (3)	0.15	12	Mechanical agitator with gearbox; elevated wear due to solid inclusions in substrate	Generowicz and Barbusinski 2023; operational data
Bioreactor vessel (6)	0.02	72	Passive pressurised vessel; low intrinsic failure rate but long restoration due to process shutdown	Rasi et al. 2022
Reactor mixer (8)	0.15	24	Submerged agitator; difficult access for maintenance; corrosion from H_2S-saturated medium	Alavian et al. 2019; Sher et al. 2024
Reactor heating circuit (9)	0.10	12	Circulation pump and valve assembly; failure triggered by thermal cycling and scale formation	Generowicz and Barbusinski 2023
Gas path/ desulfurisation (6 → 7)	0.10	10	H_2S condensate corrosion of piping, fittings and pressure sensors	Rasi et al. 2022; Sher et al. 2024
Cogeneration unit – ICE/generator (7)	0.30	48	Internal combustion engine on raw biogas; dominant contributor to total downtime (>65%); scheduled overhaul every 8,000 h	Alavian et al. 2019; Generowicz and Barbusinski 2023; Rasi et al. 2022
Electrical switchgear/ control (8-el)	0.05	6	Low-voltage automation and protection relays; failures typically caused by voltage transients	Rozen et al. 2013
Digestate discharge (10)	0.05	4	Gravity-fed or pumped outlet; low failure probability; does not immediately stop generation	Operational data
Digestate press/ separator (11)	0.08	8	Screw-press mechanical wear; failure affects digestate handling but not immediate biogas output	Generowicz and Barbusinski 2023
Liquid fertiliser tanker/ spreader (12)	0.04	4	Mobile unit; failure causes digestate accumulation but does not stop fermentation or generation	Operational data
System total (serial critical path: 3–9)	Σ = 1.07	~22 h/ year	Calculated per equations (19)–(21); nodes 10–12 excluded from critical path	—

elements, the failure of which during a long period of operation is statistically probable. At the same time, a high value of the availability factor indicates the maintainability of the plant and its ability to quickly restore its performance; therefore, for biogas power plants, the determining indicator of efficiency is not failure-free operation, but failure tolerance and stability of energy generation.

Uptime per year ($R(1) \approx 0.4$–0.5. But availability is very high:

$$Kg \approx 0.977$$

The main contribution to the total downtime of a biogas plant is formed by the cogeneration unit, which accounts for more than 65% of the total time losses, which is due to the complexity of its maintenance and the duration of restoration. At the same time, the redundancy of the substrate supply nodes significantly reduces their impact on emergency shutdowns, practically eliminating these elements from the list of critical ones. For the considered biogas plant with partial redundancy of critical nodes, the expected number of emergency failures is about one per year, and the total annual downtime is about 22 hours, which ensures a high availability factor at the level of $Kg \approx 0.977$ and meets the requirements of industrial operation of biogas power plants.

Example of calculating the reliability of a *BGU* (illustrative). Below is an example for assessing the reliability of annual failure-free generation (without stops), using a simplified serial model of critical subsystems: substrate preparation/supply → reactor and process support → cogeneration.

Accepted elements (correspondence to Fig. 1)

1. E_1 : substrate supply (4/5)
2. E_2 : homogenization/mixing at the inlet (3)
3. E_3 : bioreactor (6)
4. E_4 : reactor mixer (8)
5. E_5 : heating circuit (9)
6. E_6 : gas part to the consumer (conditionally, between 6 and 7)
7. E_7 : cogeneration unit (7)
8. E_8 : electrical connection/switching (conditional)

Note: the failure rates presented below are illustrative and are used solely to demonstrate the calculation procedure. In the article, they are replaced with data from the passport/reference books/operation statistics of a specific *BGU*.

Applied failure rates (1/year) [1].

1. $\lambda 1 = 0.20$ (substrate supply 4/5)
2. $\lambda 2 = 0.15$ (homogenization 3)
3. $\lambda 3 = 0.02$ (reactor 6)
4. $\lambda 4 = 0.15$ (mixer 8)
5. $\lambda 5 = 0.10$ (heating 9)
6. $\lambda 6 = 0.10$ (gas part up to 7)
7. $\lambda 7 = 0.30$ (cogeneration 7)
8. $\lambda 8 = 0.05$ (electrical part)

Sum of intensities:

$$\sum \lambda i = 0.921 / \text{year} \tag{22}$$

Probability of failure-free operation in 1 year

$$R_{BGP}(1) = e^{-0.92 \cdot 1} = 0.399 \tag{23}$$

That is, the probability of operating for a year without any failure/stoppage under this model is ≈ 0.40. In practice, this is a normal situation: stations are usually not "fail-safe", but maintainable, so availability becomes the key, and not $R(t)$ "without any failure".

Redundancy effect (example for feed unit 4/5). If the substrate feed unit is implemented as two parallel pumps (1+1 reserve):

$$R_{par}(t) = 1 - (1 - e^{-\lambda 1 t})^2 \tag{24}$$

$$t = 1 \text{ year}:$$
$$R_1(1) = e^{-0.20} = 0.819$$
$$R_{1par}(1) = 1 - (1 - 0.819)^2 = 0.967$$

Then the reliability of the system with supply redundancy:

$$R_{par}(t) = 1 - (1 - e^{-\lambda 1 t})^2$$

$$R^*_{BGU.}(1) = R_{1par}(1) \cdot e^{-(\sum \lambda i - \lambda 1) \cdot 1} \approx 0.471 \tag{25}$$

Therefore, even partial redundancy significantly increases the probability of failure-free operation (Kaletnik et al. 2020; Kaletnik and Yaropud 2023; Stadnik et al. 2025).

Methods for restoring operation (fault tolerance) for *BGU*. For autonomous biogas plants of the agricultural complex, the following approaches are practically appropriate:

1. Redundancy of critical nodes:

- feed redundancy 4/5; backup drives/mixers 8 (or quick replacement); backup pump/valve in circuit 9.

2. Automated switching and protections:

- automatic restart of equipment (within safety limits);
- emergency modes for maintaining the temperature of the reactor 6 (priority 9).

3. Preventive maintenance and diagnostics:

- vibration/current control of drives 3, 8, 4/5;
- H_2S/moisture control to reduce the load by 7;
- thermal control of the reactor and heat exchange (6, 9).

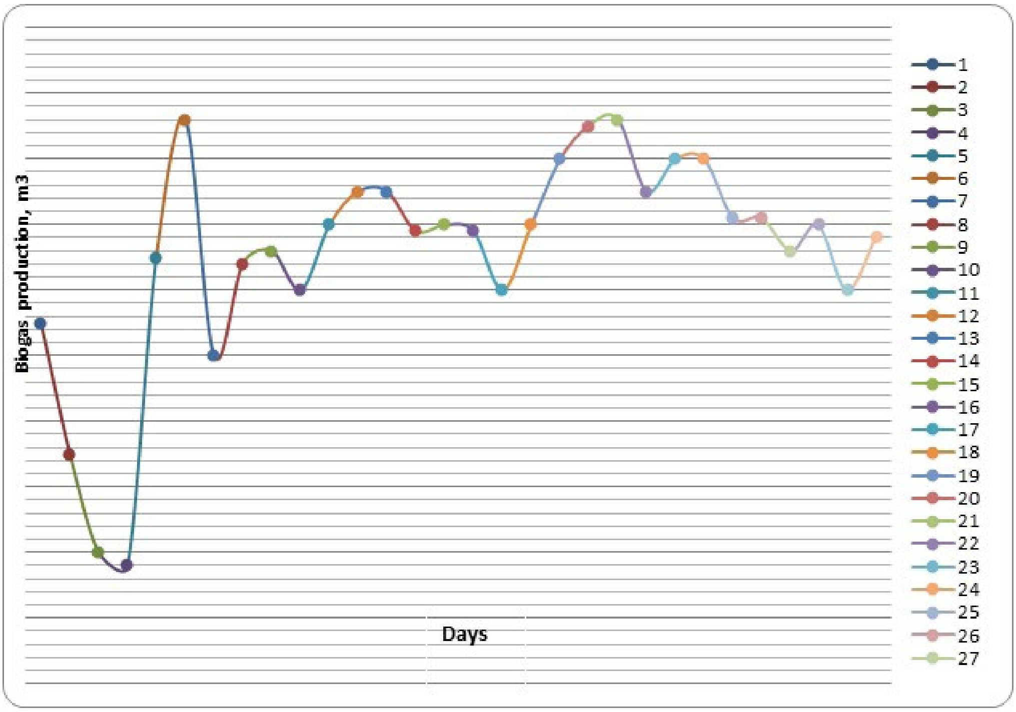


Fig. 3. Biogas production with gradual loading of raw materials

Rys. 3. Produkcja biogazu przy stopniowym załadunku surowców

4. Modularity and maintainability:

- quick-release assemblies of drives, pumps, sensors;
- spare parts composition for elements with the largest λ_i.

The reliability of a biogas plant (Fig. 1) is determined by the reliability of critical subsystems of substrate preparation (2–5), fermentation and process support (6, 8, 9), and cogeneration (7). For the normal period of operation, an exponential model was applied $R_i(t) = e^{-\lambda_i t}$. For a serial structure of critical elements $R_{BGU.}(t) = \exp[-(\Sigma\lambda_i)t]$. The illustrative calculation given for $t = 1$ year gave $R_{BGU}.(1) \approx 0.399$ which emphasizes the expediency of assessing not only reliability, but also readiness and maintainability. It is shown that the redundancy of the substrate supply unit (4/5) according to a parallel scheme increases the annual reliability of the system (in the example – up to ≈ 0.471). Increasing fault tolerance is achieved by redundancy, automation of switching, scheduled maintenance, control of aggressive impurities in biogas, and modularity of the design.

Generalized reliability of the biogas plant (elements 1–12). The biogas plant, the schematic diagram of which is shown in Figure 1, is a complex multi-component technical system that combines technological and energy paths. To assess its reliability, all elements 1–12 are considered as components of a single system, the failure of which affects the continuity of biogas, electric and thermal energy production to varying degrees.

1. Structural diagram of reliability. From the point of view of functioning, it is advisable to divide the system into three subsystems:

I. Subsystem of preparation and supply of substrate (1 – farm; 2 – collection and homogenization tank; 3 – homogenizer; 4 – loading of solid raw materials; 5 – loading of liquid manure).

II. Subsystem of anaerobic digestion (6 – bioreactor; 8 – mixer; 9 – reactor heating circuit).

III. Subsystem of energy and material utilization (7 – cogeneration unit; 10 – output of fermented mass; 11 – squeezing of fermented mass; 12 – application of liquid fertilizer).

To ensure full operability of the installation, all three subsystems must be in working condition, therefore the overall reliability structure is mainly consistent in nature.

2. Reliability functions of elements. The probability of failure-free operation of an individual element is defined as (10):

$$R_i(t) = P\{T_i > t\} \tag{26}$$

During normal operation, the exponential distribution law is used for the elements of the biogas plant:

$$R_i(t) = e^{-\lambda i t} \tag{27}$$

where:

λ_i – failure rate of the 3rd element.

3. Generalized equation of biogas plant reliability. The total probability of failure-free operation of a biogas plant, taking into account all elements (1–12), is determined by the product of the reliability functions of individual elements:

$$R_{BGU.}(t) = \prod_{i=1}^{12} R_i(t) \tag{28}$$

For the exponential model:

$$R_{BGU.}(t) = exp\left(\sum_{i=12}^{12} \lambda_i t\right) \tag{29}$$

where:

$\sum_{i=12}^{12} \lambda_i t$ – total failure rate of the entire installation.

4. Integral system reliability indicators

Installation failure rate:

$$\lambda_{BGU.} \sum_{i=12}^{12} \lambda_i t \quad (30)$$

Average uptime:

$$T \frac{1}{\lambda_{BGU}} \quad (31)$$

Probability of failure:

$$Q(t) = 1 - R_{BGU.}(t) \quad (32)$$

5. Plant availability factor

For a repairable biogas plant, the availability factor is defined as:

$$Kg = \frac{T_{op}}{T_{op} + T_{rep}} \quad (33)$$

The availability factor takes into account both the reliability of the elements and the efficiency of maintenance and repair.

6. The nature of the influence of individual elements on the reliability of the system:

- elements 1–5 determine the stability of substrate supply and the uniformity of bioreactor loading;
- elements 6, 8, 9 are critical for maintaining the anaerobic process; their failure can lead to long process shutdowns;
- element 7 is key to the production of electrical and thermal energy;
- elements 10–12 affect long-term continuity of operation and environmental safety, but are less likely to cause an instantaneous loss of generation.

What it shows: exponential decrease in the probability that the biogas plant will operate without any failure during time *t*.

The mathematical basis of the dependence is the exponential law of reliability: the probability of failure-free operation of the system decreases exponentially, and the rate of decrease is determined by the total failure intensity of critical elements. Therefore, even with relatively small values of failure intensities of individual nodes, but with their large number and predominantly sequential structure, the overall failure-free operation of the plant over a long time interval decreases quite quickly (Burlaka et al. 2024).

Practical interpretation of the result: after just one year of operation, the value $R(1) \approx 0.43$ means that "working a year without any failure" is unlikely, and this is normal for complex energy technology systems. In real conditions, biogas plants operate as maintainable objects: failures can occur, but the system quickly recovers and continues generation. That is why for biogas plants, the key indicator of operational efficiency is not absolute reliability, but the availability factor and fault tolerance, which reflect the ability of the plant to minimize downtime and ensure stable energy production.

Mathematical basis:

$$R(t) = e^{-\lambda t}, \lambda = 0.851 / \text{year} \tag{34}$$

- after 1 year $R(1) \approx 0.43$;
- this is normal for complex energy systems;
- therefore, for *BGU*, the key indicator is readiness, not absolute reliability.

The overall reliability of a biogas plant is formed on the basis of the total reliability of elements 1–12 and has a predominantly sequential structure. Therefore, increasing fault tolerance is achieved by backing up critical nodes, reducing recovery time, and implementing automated control systems. This approach ensures stable operation of biogas power plants and effective use of bioenergy potential in the agricultural and industrial complex.

To assess the effectiveness and practical feasibility of implementing biogas plants, it is not enough to consider only the reliability and fault tolerance indicators of equipment. It is also important to analyze the quantitative indicators of biogas production, which directly depend on the volumes and characteristics of raw materials, loading modes, and operating conditions of the plant. That is why, after analyzing the reliability of the system, it is advisable to proceed to studying the dynamics of biogas production and its potential, which allows for a comprehensive assessment of the operation of the biogas plant both from the standpoint of technical stability and from the standpoint of energy efficiency.

Based on the experimental data of daily biogas production for 30 days (Fig. 4) (5, 6, 8), a regression analysis was performed to obtain an analytical relationship between the operation time and the level of biogas generation (Hontaruk et al. 2024; Smith et al. 2025).

Taking into account the nature of the anaerobic digestion process (initial fluctuations, growth, and reaching a quasi-stationary mode), a second-order polynomial regression was chosen to approximate the data, which provides sufficient accuracy and physical interpretability of the results.

Based on the experimental data of daily biogas production for 30 days (Fig. 4), a regression analysis was performed to establish an analytical relationship between operation time and the level of biogas generation. Taking into account the nature of the anaerobic digestion process – initial fluctuations, gradual growth, and transition to a quasi-stationary mode – a second-order polynomial regression was selected as the approximation model.

Data processing in MS Excel yielded the following regression equation:

$$G(t) = -0.31t^2 + 14.8t + 231.5 \tag{35}$$

where:

$G(t)$ – daily biogas production [m^3/day],

t – operating time [days].

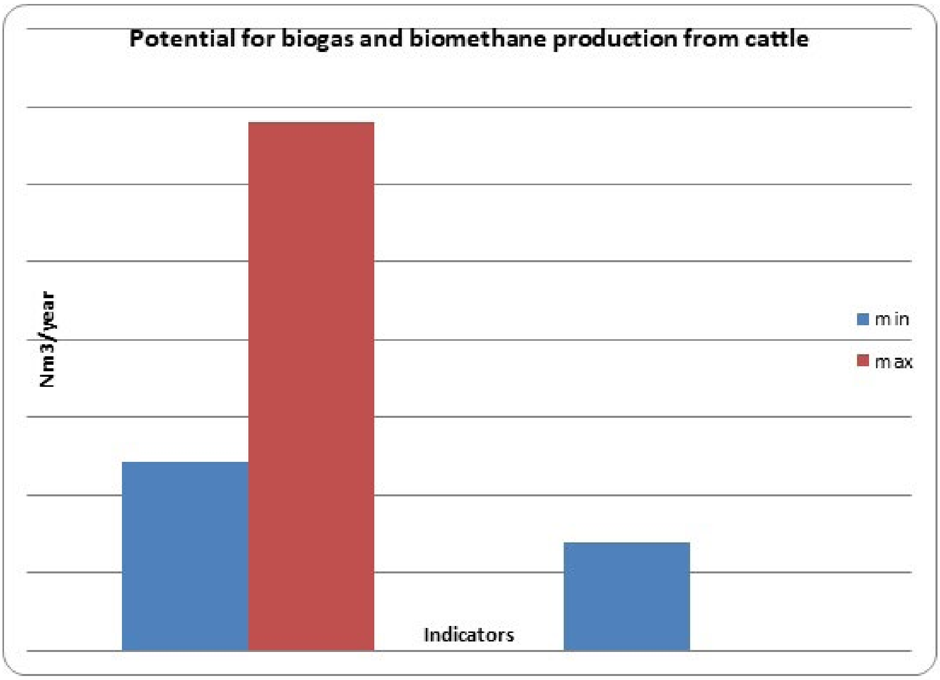


Fig. 4. Potential for biogas and biomethane production from cattle

Rys. 4. Potencjał produkcji biogazu i biometanu z bydła

The negative coefficient at t^2 ($a = -0.31$) reflects the deceleration of gas formation after the bioreactor reaches a quasi-stationary regime, indicating substrate stabilization and microbiological adaptation. The linear coefficient ($b = 14.8$) characterizes the general upward trend in daily productivity during the loading phase, while the constant term ($c = 231.5$ m^3/day) represents the initial level of biogas output at $t = 0$.

The coefficient of determination:

$$R^2 \approx 0.87 \tag{36}$$

which indicates sufficient adequacy of the model for further engineering assessments.

To estimate the potential (theoretical) volume of biogas generation for the calculation period, integration of the regression equation was used.

General formula:

$$V_{Biogas} = \int_{t_1}^{t_2} G(t)dt \tag{37}$$

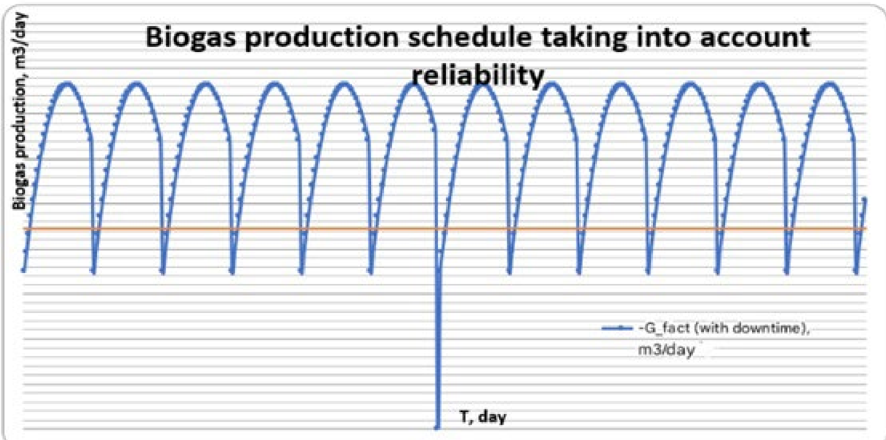


Fig. 5. Biogas production schedule taking into account reliability

Rys. 5. Harmonogram produkcji biogazu z uwzględnieniem niezawodności

Integrating the regression equation over time allows us to determine the total volume of biogas produced by the biogas plant over a given period of operation by summing the instantaneous intensity of gas formation. The resulting volume of biogas is an integral indicator of the efficiency of the anaerobic digestion process and is used to predict the possible production of electrical and thermal energy, taking into account the reliability of the equipment:

$$\int(-0.19t^2 + 9.6t + 230)dt = -0.063t^3 + 4.8t^2 + 230t \tag{38}$$

Calculation for the period 1–30 days:

$$\begin{aligned} V_{Biogas} &= [-0.063t^3 + 4.8t^2 + 230t]_1^{30} \\ V_{Biogas} &\approx 10,600\,\mathrm{m}^3 \end{aligned} \tag{39}$$

The obtained value characterizes the maximum possible volume of biogas under the condition of continuous operation of the installation without taking into account failures and downtime.

Analysis of the results obtained (Fig. 6)

Analysis of the regression curve and the integral generation volume allows us to draw the following conclusions:

- in the first days, significant production fluctuations are observed, associated with the adaptation of the microbiological system;
- starting from approximately 10–12 days, the process enters a stabilized mode;
- a negative coefficient at (t^2) indicates limited growth and reaching a plateau;

✦ the integral generation volume reflects the energy potential of the installation with gradual loading of raw materials.

Transition to reduced generation levels taking into account system reliability.

However, the resulting integral volume of biogas is theoretical, since in real operating conditions the operation of a biogas plant is affected by equipment failures, downtime, and routine shutdowns.

To take these factors into account, the system availability factor (K_g) is used.

$$V_r = K_g \cdot V_{Biogas} \qquad K_g = 0.9975 \tag{40}$$

K_g	–	biogas plant readiness coefficient;
$V_r \approx 10{,}574\ m^3$	–	this is the actual volume of biogas used during the calculation period, taking into account the reliability of the equipment.

The physical meaning of the value is as follows: of the total theoretically possible volume of biogas, only about 10.6 thousand m^3 can actually be used to generate electricity and heat, since part of the time the installation is idle due to failures and repairs. This value is obtained taking into account the availability factor K_g and characterizes the real energy potential of a biogas plant under industrial operation conditions.

$$V_r \approx 10{,}574\ m^3 \tag{41}$$

Physically, this means that due to equipment downtime associated with failures and restoration of operability, about 26 m^3 of biogas cannot be used for energy utilization. The small value of losses confirms the high availability factor of the system and the effectiveness of the applied backup and maintenance measures.

Biogas losses due to unreliability:

$$\Delta V = (1 - Kg) \cdot V_{Biogas} \approx 26\ m^3 \tag{42}$$

This is the amount of biogas losses due to the unreliability of the biogas plant.

Thus, even with a high level of plant reliability, there is a measurable decrease in the actual generation level, which must be taken into account in feasibility calculations.

The results obtained are consistent with estimates of the annual potential for biogas and biomethane production from cattle waste (Fig. 6), where the range of values is determined by both raw material factors and the operational reliability of the system (Honcharuk et al. 2024; Koval et al. 2025).

Regression analysis and integration of the biogas generation equation allow us to determine the theoretical potential for energy production with gradual loading of raw materials. Taking into

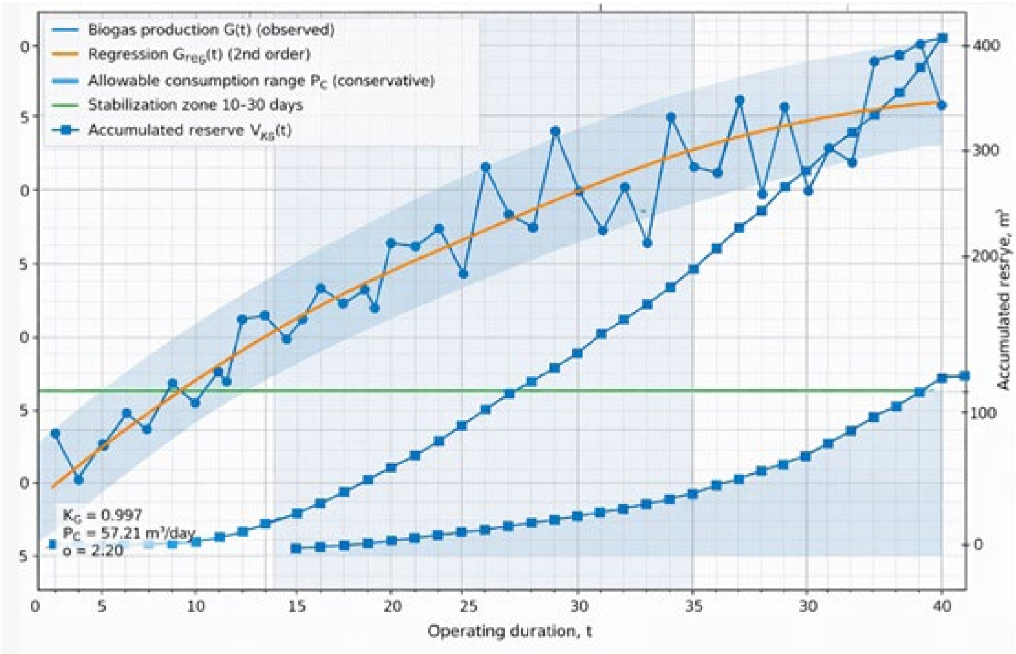


Fig. 6. Consumption and storage schedule of a biogas plant

Rys. 6. Harmonogram zużycia i magazynowania biogazowni

account the availability factor shows a decrease in the actual generation level due to the reliability of the technological system, which provides a comprehensive assessment of the efficiency of the biogas plant.

Reliability indicators:

$$Kg = 0.9975, N_{fail} = 0.85 \text{ year}^{-1}, \ T_{down} = 21.8 \text{ h/year}. \tag{43}$$

Regression equation, regression with reliability in mind.

In the upper part of Figure 6, the coefficients and indicators are written:

This quadratic regression equation describes the change in daily biogas production productivity depending on the operating time. Regression (2nd order) (Fig. 5):

$$G_{reg}(t) = at^2 + bt + c \, [\text{m}^3/\text{day}] \tag{44}$$

where:

- G_{reg} – predicted daily amount of biogas at time t [m^3/day],
- t – time (day, week, or other accepted interval),

a – curvature coefficient, reflecting the acceleration or deceleration of the gas formation process (the influence of bioreactor stabilization, substrate depletion, temperature changes),

b – linear component that characterizes the general trend of growth or decline in productivity,

c – initial value of daily biogas output at $t = 0$.

The essence of the model: 2nd order regression allows more adequately than linear regression to describe real processes in a bioreactor, where productivity is not constant, but varies nonlinearly over time. Such a model is convenient for further integration to determine the total volume of biogas and to predict energy production taking into account the reliability of the system.

Considering reliability:

$$G_{rel}(t) = Kg \cdot G_{reg}(t) \tag{45}$$

Actual generation taking into account downtime:

$$G_{act}(t) = A(t) \cdot G_{rel}(t), A(t) \in \{0,1\} \tag{46}$$

where:

$A(t) = 0$ during downtime, $A(t) = 1$ during operation.

$$\begin{aligned} V_{30,t} &= \int_{1}^{30} G_{reg}(t)dt \\ V_{30,} &= K_g \cdot V_{30,t} \\ \Delta V_{Kg} &= (1 - K_g) \cdot V_{30,t} \end{aligned} \tag{47}$$

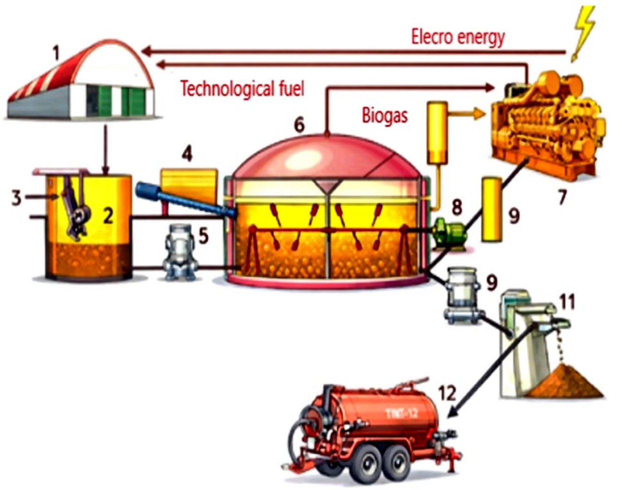
Let's determine the acceptable level of consumption P_c, is determined conservatively – as the lower limit of consumption in the stable zone (10–30 days), a reserve is formed here, which is used in case of failures. with a margin:

$$P_c = \frac{\min}{t \in [10;30]} (K_g \cdot (G_{reg}(t) - 1,645\sigma)) \tag{48}$$

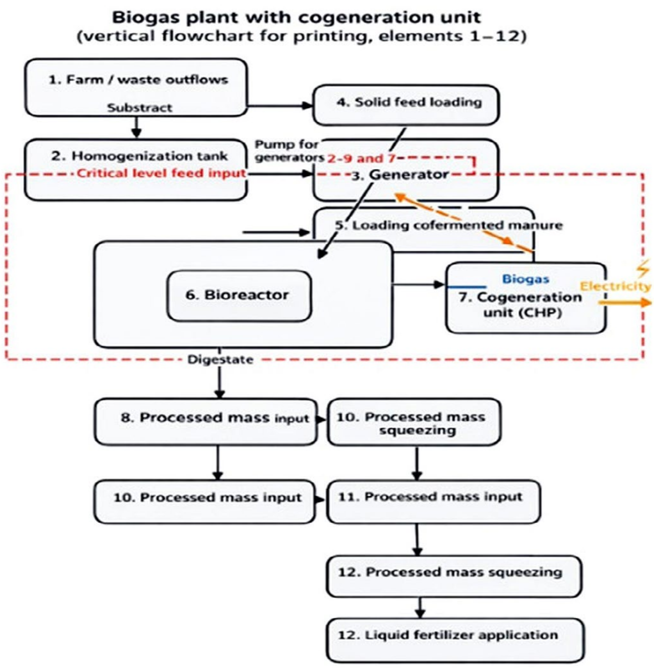
where:

σ – SCR of regression residuals.

P_c – level that is highly unlikely to be exceeded by consumption, even taking into account statistical variation.



A



B

Fig. 7. Technological scheme (A) and structural diagram (B) of the biogas plant: 1 – farm; 2 – collection and homogenization tank; 3 – homogenizer; 4 – solid raw material loading; 5 – liquid manure loading; 6 – Bioreactor; 7 – cogeneration unit; 8 – mixer; 9 – reactor heating circuit; 10 – fermented mass output; 11 – fermented mass squeezing; 12 – liquid fertilizer application

Rys. 7. Schemat technologiczny (A) i schemat strukturalny (B) biogazowni

The graph shows the change in daily biogas production, its predicted value according to the regression model, and the allowable consumption level. The actual production values have fluctuations due to the peculiarities of the technological process, while the regression curve reflects the average trend of biogas generation over time.

The allowable consumption level is determined conservatively in the stable operation zone, taking into account the availability factor and statistical reserve. This approach ensures that consumption does not exceed reliably available production even in the presence of random deviations and short-term failures.

The reserve accumulation curve shows the volume of biogas that is formed during periods of excess production over consumption and is used to cover the deficit during downtime. The graph clearly demonstrates that the combination of conservative consumption and reserve ensures stable autonomous operation of the biogas plant.

This approach allows us to visually and analytically demonstrate the cause-and-effect relationship: equipment redundancy leads to reduced downtime, which, in turn, ensures an increase in the permissible level of energy consumption and stable autonomous operation of the biogas plant.

Autonomous energy consumption and redundancy of the biogas plant. For autonomous biogas power plants of the agro-industrial complex, the issue of energy consumption should be considered in close connection with the reliability and fault tolerance of the equipment. Unlike network power plants, autonomous facilities do not have the ability to compensate for the generation deficit at the expense of external power supply, therefore, any failure or downtime directly affects the stability of technological and production processes (Dubik et al. 2024; Veselovska et al. 2025).

The permissible level of autonomous consumption is determined not by the maximum or average level of biogas production, but by guaranteed generation taking into account the reliability of the system. That is why when analyzing the autonomous mode, it is advisable to focus on a conservative level of consumption, which can be stably ensured even in the presence of emergency shutdowns and scheduled repairs.

Comparison of scenarios of operation of a biogas plant with and without redundancy shows that in the absence of redundancy elements, the permissible level of autonomous consumption is significantly reduced. The increase in the duration of downtime leads to the need to either limit the load of consumers or introduce additional energy sources to compensate for the deficit. In turn, redundancy of critical nodes allows you to reduce the duration and frequency of downtime, which directly increases the level of available energy for autonomous consumption.

The role of redundancy in autonomous mode. The greatest impact on the autonomous operation of a biogas plant is the failure of elements that directly stop the generation process. These include the substrate supply, mixing and heating units of the bioreactor, as well as the cogeneration unit. Redundancy of these elements provides the ability to localize the failure without completely stopping the plant or with a significant reduction in downtime.

In the context of autonomous energy supply, redundancy performs a dual function. First, it increases the availability factor of the biogas plant, which allows you to increase the permissible load of consumers without the risk of an emergency energy shortage. Second, redundancy reduces the power requirements of external or auxiliary power sources, as the need for extended downtime coverage is reduced.

Generalized recommendations. To ensure stable autonomous operation of biogas plants in the agro-industrial complex, it is advisable to:

- determine the permissible level of consumption taking into account the actual availability of the system, not only the nominal capacity;
- reserve nodes, the failure of which leads to an immediate stop of generation;
- combine equipment redundancy with the optimal choice of a backup energy source;
- consider an autonomous biogas plant as a single system where reliability, consumption and redundancy are interrelated elements.

This approach allows ensuring the continuity of energy supply, reducing the risks of technological failures, and increasing the overall efficiency of using bioenergy potential in autonomous conditions.

Conclusion

This study performed a comprehensive reliability and fault tolerance analysis of a biogas plant with a cogeneration unit as a multi-component electrotechnological system operating in the agro-industrial sector. The following specific results were obtained.

The total failure rate of the critical serial path (nodes 3–9) was determined as $\Sigma\lambda = 1.07$ failures/year, which corresponds to a probability of failure-free operation over a one-year period of $R(1) \approx 0.40$–0.43. This value confirms that absolute failure-free operation over extended periods is statistically improbable for systems of this complexity, and therefore fault tolerance rather than zero-failure performance must be adopted as the primary operational criterion.

The expected number of emergency stops per year is approximately one event ($N \approx 1.07$), with a total annual downtime of approximately 22 hours. Under these conditions, the plant availability factor reaches $A \approx 0.9975$, which satisfies the requirements of industrial operation of biogas power plants in the agro-industrial complex.

The cogeneration unit (node 7) was identified as the dominant contributor to total downtime, accounting for more than 65% of annual time losses, owing to its failure rate of $\lambda_7 = 0.30$ failures/year and a mean time to repair of MTTR = 48 hours. Introduction of parallel redundancy for the substrate supply unit (nodes 4/5) was shown to increase the annual system reliability from $R(1) \approx 0.40$ to $R(1) \approx 0.47$, demonstrating the measurable benefit of even partial redundancy.

Regression analysis of 30-day biogas production data yielded the equation $G(t) = -0.31\, t^2 + 14.8\, t + 231.5$ ($R^2 = 0.87$), from which the theoretical generation volume over the calculation period was estimated at approximately 10,600 m^3. Accounting for the availability factor, the actual utilizable volume is approximately 10,574 m^3, with biogas losses due to equipment downtime amounting to approximately 26 m^3 – confirming the high practical efficiency of the proposed maintenance and redundancy strategy.

The principal engineering measures for improving system reliability are: redundancy of substrate supply and reactor mixing units; automated switching and emergency temperature maintenance in the bioreactor; scheduled preventive maintenance with vibration and H_2S/moisture monitoring; and modular design enabling rapid component replacement without full system shutdown.

Directions for further research. Future studies should address the following aspects that remain beyond the scope of the present work. First, a probabilistic sensitivity analysis is needed to quantify the relative contribution of each node to overall system unavailability under varying substrate compositions and seasonal loading conditions. Second, the applicability of non-exponential failure distribution models – in particular Weibull distributions accounting for aging and wear-out phases – should be evaluated for critical components such as the cogeneration unit and submerged mixers. Third, an economic optimization model linking redundancy investment costs with availability gain and avoided generation losses would provide a practical decision-support tool for biogas plant operators. Finally, validation of the proposed reliability model against long-term operational data from multiple industrial biogas facilities in Ukraine is recommended to confirm the generalizability of the obtained numerical estimates.

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The Authors have no conflicts of interest to declare.

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Mykola Stadnik, Andrii Shtuts, Vitalii Yaropud, Ihor Kupchuk

Analiza niezawodności i odporności na awarie biogazowni z układem kogeneracyjnym w systemie zasilania sektora rolno--przemysłowego

Streszczenie

W artykule przedstawiono kompleksowe badanie niezawodności i odporności na awarie biogazowni z układem kogeneracyjnym, rozpatrywanej jako złożony wielokomponentowy system elektrotechnologiczny. Odporność na awarie jest traktowana jako integralne kryterium niezawodności systemu, charakteryzujące zdolność instalacji do lokalizowania uszkodzeń, utrzymania częściowej sprawności operacyjnej oraz szybkiego przywracania pełnej funkcjonalności, a nie jako odrębna właściwość niezależna od niezawodności. Stabilność operacyjna instalacji jest determinowana skoordynowanym funkcjonowaniem podsystemów przygotowania i podawania substratu, procesu fermentacji beztlenowej oraz jednostki konwersji energii biogazu. Wykazano, że ogólna niezawodność systemu dla przemysłowych biogazowni w sektorze rolno-przemysłowym ma charakter głównie szeregowy, ponieważ awaria dowolnego elementu krytycznego może prowadzić do zakłócenia procesu technologicznego lub całkowitego wyłączenia produkcji energii elektrycznej i cieplnej.

Podstawę metodologiczną badań stanowi strukturalna analiza niezawodności oraz zastosowanie wykładniczych modeli rozkładu uszkodzeń dla elementów systemu. Rozważono zarówno konfiguracje szeregowe, jak i równoległe (redundantne), w celu oceny wpływu awarii elementów oraz redundancji na funkcjonowanie systemu. Ocena niezawodności została przeprowadzona z wykorzystaniem kluczowych wskaźników, w tym średniego czasu między awariami (MTBF), średniego czasu naprawy (MTTR), oczekiwanej liczby awarii oraz współczynnika gotowości odzwierciedlającego udział czasu, w którym system pozostaje sprawny operacyjnie.

Zidentyfikowano główne czynniki awaryjności, w tym agresywne środowisko biogazu, zmienność składu substratu, niestabilność termiczną w bioreaktorze, mechaniczne zużycie pomp i napędów oraz awarie elektrycznych układów sterowania i zabezpieczeń. Analiza wykazała, że układ kogeneracyjny ma największy wpływ na całkowity czas przestojów, przy intensywności uszkodzeń λ_7 = 0,30 awarii/rok i średnim czasie naprawy wynoszącym 48 godzin, co stanowi ponad 65% łącznego rocznego czasu przestojów, natomiast awarie podsystemów pomocniczych mogą być skutecznie ograniczane poprzez redundancję.

Studium przypadku biogazowni o średniej mocy wykazało, że całkowita intensywność uszkodzeń krytycznej ścieżki szeregowej wynosi $\Sigma\lambda$ = 1,07 awarii/rok, co daje prawdopodobieństwo bezawaryjnej pracy w ciągu roku $R(1) \approx 0{,}40$–$0{,}43$, przy oczekiwanej częstości awarii wynoszącej około jednego zdarzenia rocznie. W warunkach planowej konserwacji zapobiegawczej i częściowej redundancji elementów krytycznych roczny czas przestojów nie przekracza 22 godzin, a współczynnik gotowości osiąga $A \approx 0{,}9975$, zapewniając niezawodną eksploatację przemysłową.

Wyniki potwierdzają, że dla biogazowych systemów energetycznych kluczowym kryterium efektywności nie jest absolutna bezawaryjność, lecz odporność na awarie i zdolność do szybkiego przywracania funkcjonalności. Praktyczne znaczenie badań polega na uzasadnieniu środków inżynieryjnych i organizacyjnych – takich jak redundancja węzłów krytycznych, wdrożenie zautomatyzowanych systemów monitorowania i zabezpieczeń oraz optymalizacja strategii utrzymania ruchu – które zwiększają niezawodność systemu i zapewniają efektywne wykorzystanie energii biogazu w sektorze rolno-przemysłowym.

Słowa kluczowe: biogazownia, niezawodność systemu, odporność na awarie, układ kogeneracyjny, wskaźnik awaryjności, współczynnik dostępności, redundancja, sektor rolno-przemysłowy