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Mykola Stadnik[1], Andrii Shtuts[2], Vitalii Yaropud[3], Ihor Kupchuk[4]

Development of an algorithm for power supply to a livestock farm using biogas

Abstract: The article examines the enhancement of energy autonomy for livestock farms through the implementation of power supply systems based on renewable energy sources – specifically, biogas plants and solar generation. A comprehensive methodology is proposed for assessing the energy potential of agricultural organic waste, including manure, manure effluents, and feed residues. The assessment takes into account the chemical composition, moisture content, and total volume of raw materials, enabling accurate estimation of biogas output through anaerobic digestion. Analytical models are presented to calculate the potential electrical and thermal energy output per cubic meter of biogas, considering the efficiency and technical characteristics of the generator set. The farm's energy consumption profile was developed, including a detailed daily load schedule, peak demand, and average daily usage.

✉ Corresponding Author: Ihor Kupchuk; e-mail: kupchuk.igor@i.ua

[1] Engineering and Technology Faculty, Vinnytsia National Agrarian University, Ukraine; ORCID iD: 0000-0003-2109-6219; e-mail: stadnik_mykola@vsau.vin.ua

[2] Engineering and Technology Faculty, Vinnytsia National Agrarian University, Ukraine; ORCID iD: 0000-0002-4242-2100; e-mail: shtuts1989@gmail.com

[3] Engineering and Technology Faculty, Vinnytsia National Agrarian University, Ukraine; ORCID iD: 0000-0003-0502-1356; e-mail: yaropud77@gmail.com

[4] Engineering and Technology Faculty, Vinnytsia National Agrarian University, Ukraine; ORCID iD: 0000-0002-2973-6914; e-mail: kupchuk.igor@i.ua

Based on this analysis, the optimal capacity of the biogas plant and the required area of photovoltaic panels were calculated to ensure full coverage of the farm's energy needs. Scenarios for seasonal generation adjustment are discussed, as well as the possibility of connecting to the external power grid in case of electricity surplus.
The scientific result of the study is the development of a scalable and adaptable algorithm for designing autonomous energy supply systems for livestock farms, based on balancing biogas production with electricity consumption.
The proposed solution enhances the energy resilience and sustainability of the agricultural sector.

Keywords: cogeneration plants, load schedule, generator, thermal energy, energy efficiency

1. Statement of the problem

Modern technological processes in farms, in particular in the livestock industry, place increased demands on the stability, reliability, and cost-effectiveness of power supply systems. Uninterrupted power supply is necessary both for maintaining the vital activity of animals (lighting, ventilation, heating), and for the operation of automation systems, pumps, cooling equipment, milking machines, and other technological equipment (Kaletnik and Yaropud 2023). In this regard, the relevance of implementing autonomous energy solutions based on renewable energy sources is increasing.

One of the most promising areas for ensuring energy independence of livestock farms is the implementation of power supply systems based on the use of biogas. Biogas is a fuel that is formed as a result of anaerobic fermentation of organic materials, in particular manure, feed residues, and agricultural waste. These resources are produced in large volumes in livestock complexes, and instead of creating an ecological burden on the environment, they can be effectively converted into electrical and thermal energy (Kaletnik et al. 2017).

Biogas power plants are of particular practical value in agriculture, as they allow combining the utilization of organic waste with the production of energy for domestic consumption. This not only contributes to reducing energy costs and increasing the economic efficiency of production, but also significantly improves the ecological balance of the farm. In the context of the global transition to "green" energy and reducing greenhouse gas emissions, this model of farm operation meets the principles of sustainable development.

When designing or modernizing livestock farms, it is necessary to consider the possibility of integrating renewable energy sources. In particular, combining biogas plants with solar generation systems allows you to cover the farm's electricity needs throughout the year to the maximum. This is especially important in remote regions with limited access to centralized networks or with unstable power supply quality.

One of the key elements of a bioenergy system is a properly selected cogeneration unit – a device that allows for the simultaneous production of electrical and thermal energy by burning biogas. This approach increases the overall efficiency of the energy system to 80–90%, since it uses both electrical and thermal energy, which is usually dissipated in traditional generators (Kaletnik et al. 2020; Kupchuk et al. 2022).

The thermal energy obtained in the cogeneration process can be used to heat livestock buildings, heat water, maintain temperature in bioreactors, or even for technological processing processes. Thanks to this, the farm not only covers its own energy needs but also creates the opportunity for energy-independent farming even during periods of increased loads.

An additional efficiency factor is the use of battery energy storage systems or gas tanks to store excess biogas, which allows for balancing the energy load and avoiding energy losses. Such solutions ensure stability of supply even in cases of reduced system performance due to weather conditions or a temporary reduction in waste volumes.

Thus, the introduction of biogas energy technologies in livestock farms allows for significantly increasing the level of energy autonomy, reducing energy costs, reducing emissions of harmful substances, and improving the ecological situation in the region. At the same time, it opens up wide opportunities for the implementation of the concept of an "energy independent farm", which is extremely relevant in the context of energy crises, rising fuel prices, and global climate change.

2. Analysis of recent research and publications

The issue of ensuring energy autonomy of the agricultural sector through the implementation of biogas plants is attracting increasing attention from researchers in the context of increasing energy efficiency and reducing dependence on traditional energy sources. The works (Stadnik 2018; Stadnik et al. 2021; Koval et al. 2025) cover a wide range of issues related to technological, environmental, and economic aspects of the implementation of biogas technologies in agriculture.

In scientific research, the technological process of anaerobic digestion of organic waste is characterized, and the biogas yield is estimated depending on the type of raw material (Koval et al. 2025). The research focuses on the optimization of fermentation parameters, the influence of temperature on the activity of microorganisms, as well as on the design features of bioreactors. It is important to analyze the composition of biogas, methane content, and impurities that can affect the combustion efficiency and resource of cogeneration plants.

In the publication (Stadnik et al. 2021), an attempt is made to assess the economic feasibility of building biogas complexes based on the scale of livestock production. The relationship between capital investments and project payback periods is considered, depending on the size of the livestock, the type of animals, and the volume of waste received. Considerable attention is paid to savings on traditional energy sources and the possibility of selling excess electricity to the general network at a "green" tariff.

The paper (Stadnik 2018) presents examples of biogas plants operating in farms in the European Union countries, in particular Germany, Denmark, and Austria. It analyzes state support in the field of bioenergy, stimulation of decentralized energy production, and regulatory aspects of grid connection.

At the same time, it should be noted that the main attention in the indicated sources is focused on the general characteristics of biogas plants, their technological parameters, and the impact on the economy of agricultural production. There are no in-depth studies devoted to modeling the autonomous energy supply of livestock farms, taking into account load schedules typical for the region. In particular, daily and seasonal fluctuations in electricity consumption, which are of crucial importance in the design of cogeneration systems capable of ensuring continuous power supply to facilities, are not taken into account (Yang et al. 2025).

Also ignored are aspects of dynamic regulation of biogas energy production according to load changes, the possibility of biogas storage, or the use of buffer tanks to accumulate excess gas for further use during peak demand hours. Most studies do not consider the complex combination of biogas plants with solar power plants, which, in conditions of variable insolation and different daily electricity consumption profiles, is key to achieving true autonomy.

Special attention is paid to the problem of synchronizing electricity generation with the consumption schedule. This requires calculations and modeling of typical farm loads, which take into account the features of feeding, milking, ventilation, heating, and other processes characteristic of a specific type of livestock production (pig farms, poultry farms, dairy farms, etc.).

However, the article lacks a comprehensive overview of the current international experience in the use of biogas cogeneration systems on livestock farms. To broaden the scientific context and strengthen the argumentation, it is appropriate to include an analysis of such implementations in countries like Germany, Denmark, the Netherlands, and others, where integrated bioenergy systems have been widely deployed. In these countries, significant progress has been made in developing and scaling farm-based biogas units with combined heat and power (CHP) generation. Their experience demonstrates the efficiency of grid-connected and off-grid systems, the use of smart energy management technologies, and policy instruments such as feed-in tariffs and subsidies for decentralized renewable energy. Including these practices provides valuable benchmarks for evaluating and modeling energy-autonomous solutions in agriculture under different climatic, economic, and infrastructural conditions.

Thus, despite the significant contribution of previous scientific works to the development of the theory and practice of biogas energy, there remains a pressing need for research that would combine:

- quantitative assessment of the production of electrical and thermal energy based on the specific composition of organic raw materials;
- adaptation of the power supply system to the specific conditions of the farm;
- application of energy flow control algorithms under variable load conditions;
- analysis of the operating modes of the cogeneration plant, taking into account seasonal and daily changes.

The research proposed in this paper is aimed precisely at filling these scientific and technical gaps through a comprehensive analysis of the energy supply of a livestock farm using a biogas plant in combination with other energy sources, as well as the development of a model of autonomous power supply focused on practical application in Ukrainian conditions.

3. Aim of scientific research

The aim of this research is to increase the energy efficiency and reliability of power supply systems of livestock farms by implementing a cogeneration plant, which allows for the simultaneous production of electrical and thermal energy from biogas produced as a result of anaerobic digestion of organic waste.

4. Results and Discussion

Unlike other renewable energy sources, such as solar or wind energy, which are characterized by unstable production, biogas energy is more predictable and adapted to the needs of the agricultural sector. Biogas plants allow the utilization of significant volumes of organic residues, including manure, litter, and feed residues, and transform them into energy-valuable products: biogas (mainly methane), electricity, heat, and fertilizers after fermentation.

Particular attention is paid to the assessment of the energy potential of biogas cogeneration plants in view of their ability to provide the base load of a livestock enterprise. It has been studied that the fuel energy utilization ratio in cogeneration plants reaches 80–90%, which significantly exceeds the similar indicators of traditional power supply systems. At the same time, it is noted that for the effective implementation of biogas complexes, a preliminary technical and energy justification is necessary based on the specific characteristics of the farm, taking into account the volume of livestock waste, load structure, seasonal fluctuations in energy consumption, and the possibilities of biogas storage or accumulation.

One of the key parameters in assessing the energy efficiency of a biogas plant is the average daily biogas yield per unit of raw material, which depends on the type of animal, housing conditions, feeding ration, humidity, and type of fermentation process. According to studies (Power Link cogeneration plants, 2025), the average values of the excrement yield from different animal species, provided that the waste moisture content is 79%, can be used to quantify the biogas production potential (Table 1).

Table 1. Specific methane yield [m^3 CH_4 per head per day] depending on the type of farm animal

Tabela 1. Jednostkowa wydajność metanu [m^3 CH_4 na osobnika na dzień] w zależności od rodzaju zwierząt gospodarskich

Animal species	Specific methane yield [m^3/heads/day]
Cattle (cattle)	1.2
Pigs	0.3
Sheep	0.1
Goats	0.09
Chickens	0.065
Turkeys	0.08

Given the above data, it can be concluded that the most energy-efficient for biogas production are cattle farms, pig farms, and large poultry farms. With proper design and operation of a biogas plant with a built-in cogeneration system (based on a gas piston or gas turbine unit), it is possible to ensure not only full coverage of the farm's own needs for electricity and heat, but also excess energy production, which can be directed for sale to an external network or storage.

In addition, the study emphasizes the need to take into account changes in daily and seasonal load schedules, which requires the development of appropriate algorithms for managing energy supply and energy storage. The modeling results show that, by ensuring hourly coordination between generation and consumption, biogas cogeneration plants can serve as the basis for a stable autonomous energy supply for medium and large-scale farms.

Thus, the conducted research confirms the practical feasibility and energy efficiency of biogas plants for creating an autonomous power supply system for livestock farming. Further work should focus on mathematical modeling of processes, optimization of the technological chain "raw material – biogas – energy", as well as on assessing economic efficiency, taking into account real tariffs, equipment costs, and resource potential of the farm.

Table 2 presents summarized data on the average daily output of excrement from different types of farm animals and poultry, as well as the specific biogas output per unit of dry matter. A correction factor (×10) was taken into account for poultry, since the mass of their waste is much smaller and the structure is different from the waste of large mammals. In particular, the amount of excrement (in terms of feces and urine), dry matter content, minimum and maximum biogas output are indicated (m^3/kg dry matter), average methane content (%), and calculated specific methane volume (m^3) per animal per day.

These indicators allow us to quantitatively assess the potential of biogas production in the conditions of a specific farm. Having determined the average amount of waste from one animal and knowing the number of livestock on the farm, it is possible to calculate the total daily volume of organic waste generated, which can later be used as raw material for the biogas plant.

The data obtained are the basis for the next stage – calculating the total volume of biogas generated on the farm and assessing its energy potential. In this case, it is important to take into account not only theoretical indicators, but also real operating conditions, in particular, the

Table 2. Biogas yield from animal excrement

Tabela 2. Wydajność biogazu z odchodów zwierzęcych

Average daily output of excrement from one animal (for birds x10) [kg]					Gas outlet [m^3/kg (dry)]		Methane [%]	Methane [m^3 specific]
Animal species	total excrement	dung	urine	dry matter	min.	max.		
Bulls	40.0	30.0	10.0	6.3	0.25	0.35	65	1.433
Cows	55.0	35.0	20.0	7.35	0.25	0.35	65	1.194
Young cattle up to 4 months old	7.5	5.0	2.5	1.05	0.25	0.35	65	0.171
Young cattle up to 4–6 months old	14.0	10.0	4.0	2.1	0.25	0.35	65	0.341
Young cattle up to 6–12 months old	26.0	14.0	12.0	2.94	0.25	0.35	65	0.478
Young cattle over 12 months old	27.0	20.0	7.0	4.2	0.25	0.35	65	0.683
Horses	23.0	17.5	5.5	3.675	0.2	0.3	57	0.419
Sheep and goats	2.8	2.0	0.8	0.42	0.3	0.62	70	0.088
Sows with piglets	22.0	12.0	10.0	2.52	0.34	0.58	67	0.574
Sows, without piglets	17.0	9.0	8.0	1.89	0.34	0.58	67	0.431
Boar	15.0	9.0	6.0	1.89	0.34	0.58	67	0.431
Pigs being fed	12.0	7.0	5.0	1.47	0.34	0.58	67	0.335
Chickens	2.5	–	–	0.525	0.31	0.62	60	0.098
Broilers	3.0	–	–	0.63	0.31	0.62	60	0.117
Turkeys	4.3	–	–	0.903	0.31	0.62	60	0.168
Ducks	5.5	–	–	1.155	0.31	0.62	60	0.215
Geese	6.0	–	–	1.26	0.31	0.62	60	0.234

reliability and efficiency of the equipment for anaerobic digestion (methane plant). The reliability of the functioning of the methane plant determines what actual volume of biogas can be stably obtained and fed to the cogeneration plant.

A cogeneration plant, which simultaneously produces electrical and thermal energy from biogas, is a central element of the energy supply system. At the same time, part of the generated electricity is consumed by the farm itself, including the needs of the methane tank equipment, pumps, automation, and ventilation system. According to available estimates, the electricity consumption of internal technological needs can be up to 25% of the total amount of generated electricity, so this factor must be taken into account when determining the net energy effect.

Thus, the data in Table 2 are the starting point for further calculations – first, the total volume of biogas produced is determined, then, taking into account the efficiency coefficients of the cogeneration plant and consumption for own needs, the possible volume of electricity production is determined. This, in turn, allows you to form the energy balance of the farm and assess the effectiveness of the implementation of bioenergy technologies in livestock farming.

For the functioning of the biogas power plant (maintaining the mesophilic mode and the operation of electrical equipment), the cogenerator consumes up to 25% of the produced biogas (Stadnik et al. 2021).

Having analyzed gas generators of different types and manufacturers, we will determine how much electricity can be produced from gas, depending on the amount of gas:

$$E_0 = (V/P) \tag{1}$$

Let's determine how much electricity the methane tank uses for its own needs:

$$E_M = E_0 \cdot 0.25 \tag{2}$$

So, let's determine the amount of electricity that remains for the farm's own needs:

$$E = E_0 - E_M \tag{3}$$

PowerLink cogeneration plants have a total efficiency of 78.8%, of which 32.7% is electrical efficiency and 46.1% is thermal efficiency (Stadnik et al. 2021). Let us find the ratio of these efficiencies:

$$k = \eta_{heat}/\eta_{electric} = 46.1/32.7 = 1.4 \tag{4}$$

where:

η_{heat} – thermal efficiency,
$\eta_{electric}$ – electrical efficiency.

Let's determine how much thermal energy can be produced using these cogeneration plants:

$$Q_{product} = E \cdot k \tag{5}$$

where:

k – ratio of thermal and eclectic efficiency,
E – the amount of electricity that can be produced by the PowerLink cogeneration unit.

The study of the level of biogas consumption will be carried out, taking into account the reliability of the biogas unit to ensure stable operation of the power supply system through the use of biogas units in livestock farms.

The study of generation is devoted to the issue of research (Stadnik et al. 2021). Based on research (Stadnik et al. 2025), a graph was constructed (Fig. 1), from which it can be seen that fermentation is accompanied by two periods of maximum biogas output.

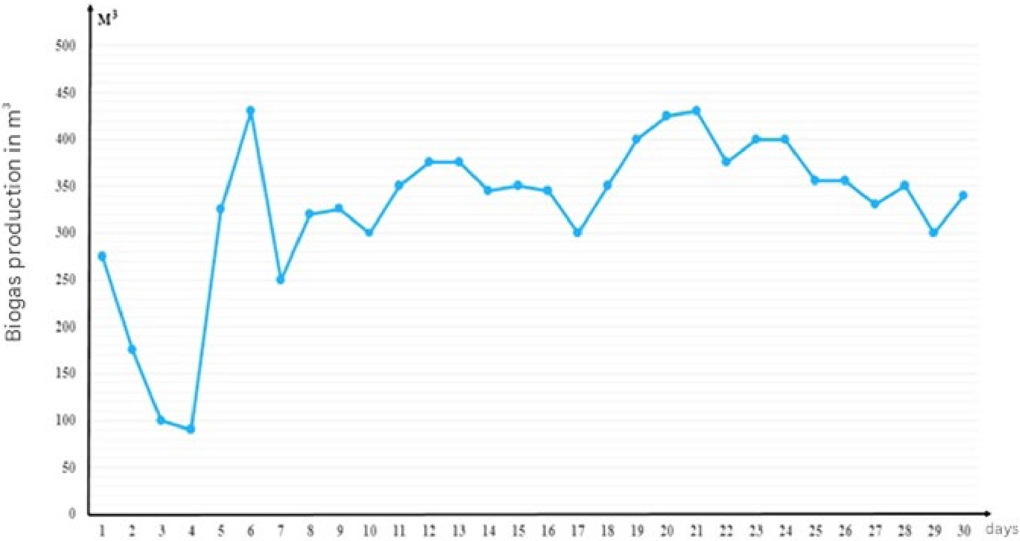

Fig. 1. Biogas production schedule with gradual loading of raw materials

Rys. 1. Harmonogram produkcji biogazu ze stopniowym załadunkiem surowców

Initially, the generation is high, but then it drops sharply because there is a gradual loading of manure, but starting from the fifth day of fermentation, a sharp increase in biogas generation is observed. On the eighth day of generation, the biogas output stabilizes, and in the following days, a relatively uniform biogas generation is observed, but on the 21st day, the maximum biogas output is observed again.

For uniform distribution of biogas output over time, continuous manure feeding is used in the methane tank. It involves feeding a large amount of manure in small portions, with simultaneous removal of spent biosludge.

It follows that if new portions of manure are loaded as often as possible, then biogas production will be more uniform. Manure is loaded into the methane tank every 1 hour (Kaletnik et al. 2017; Stadnik et al. 2025).

The reliability of the electricity supply depends on the reliability of the gas supply and the reliability of the biogas plant equipment. Using the data in (Fig. 1), we will supplement them with indicators of equipment reliability and show them in (Fig. 2). This graph shows that biogas production took place in the period ($t_1 - t_2$), then we observe that biogas production stopped in the area ($t_2 - t_3$). This is due to equipment failure, which forced the work to be stopped. At the site ($t_3 - t_4$) biogas production was resumed, etc.

The level of gas consumption is determined by the stability of its operation, namely: the moments of maximum production, while part of the gas is sent to the reserve, and the other to the production of electricity. At the time of non-operational state, electricity production occurs at the expense of reserves.

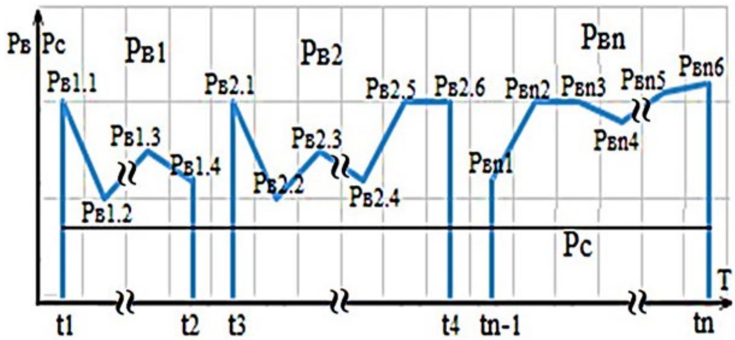

Fig. 2. Biogas production schedule taking into account the reliability of the installation

Rys. 2. Harmonogram produkcji biogazu z uwzględnieniem niezawodności instalacji

The downtime areas are determined by the reliability of the equipment included in the biogas plant.

The condition (6) (Lut et al. 2008) general formula for the reliability of series-connected equipment was formulated for operation.

For systems where the elements are connected in series (failure of one element leads to failure of the entire system), the overall reliability is defined as the product of the reliabilities of the individual elements:

$$R = R_1 \cdot R_2 \cdot \ldots \cdot R_n \tag{6}$$

where:

R – overall system reliability,

R_i – reliability of the i-th element.

This formula allows you to estimate the probability of failure-free operation of the entire system for a certain time.

Application in biogas plants. In biogas plants, the main components are:

- methane tank (anaerobic digestion reactor),
- raw material supply system,
- gas collection system,
- cogeneration plant (for the production of electricity and heat).

If the reliability of each of these components is known, the overall reliability of the entire installation can be calculated using the formula above.

Calculation example. Let's assume that the reliability of the main components of a biogas plant is as follows:

- methane tank: $R_1 = 0.98$,
- raw material supply system: $R_2 = 0.97$,

- gas collection system: $R_3 = 0.96$,
- cogeneration plant: $R_4 = 0.95$.

Then the overall reliability of the system is:

$$R = 0.98 \cdot 0.97 \cdot 0.96 \cdot 0.95 \approx 0.867$$

This means that the probability of failure-free operation of the entire installation within a given time is approximately 86.7%.

To assess the reliability of complex equipment, such as a biogas plant, it is advisable to use a general formula for series-connected elements. This allows you to take into account the impact of each component on the overall reliability of the system and make informed decisions about increasing the efficiency and reliability of the plant.

The level of gas consumption is determined by the stability of its operation, namely: the moments of maximum production, while part of the gas is sent to reserve, and the rest to produce electricity. At the time of non-operation, electricity production occurs at the expense of reserves.

For the work, condition (7) was formulated for the stable operation of the biogas plant, in terms of gas supply:

$$P_C \leq P_B \tag{7}$$

where:

P_C – biogas consumption level [m^3],
P_B – average biogas production level [m^3].

In order to find the permissible level of consumption, it is proposed to use formula (8) to determine P_C it is possible to use static data if available.

The formula for calculating the consumption level:

$$P_C = \frac{P_{B1}(t_2 - t_1) + P_{B2}(t_4 - t_3) + \ldots + P_{Bn}(t_n - t_{n-1})}{(t_2 - t_1) + (t_4 - t_3) + \ldots + (t_n - t_{n-1})} \tag{8}$$

where:

P_C – the acceptable level of consumption,
P_{B1},P_{Bn} – the average level of biogas production in the corresponding period of time is determined by formulas (9), (10), (11),
$(t_2 - t_1)$; $(t_4 - t_3)$; $(t_n - t_{n-1})$ – normal working hours,
$(t_2 - t_3)$; $(t_4 - t_{n-1})$ – recovery time,
t_n – time to restore the operation of the biogas plant.

$$P_{B1} = \frac{P_{B1.1} + P_{B1.2} + P_{B1.3} + P_{B1.4}}{4} \tag{9}$$

$$P_{B2} = \frac{P_{B2.1} + P_{B2.2} + P_{B2.3} + P_{B2.4} + P_{B2.5} + P_{B2.6}}{6} \tag{10}$$

$$P_{Bn} = \frac{P_{Bn.1} + P_{Bn.2} + P_{Bn.3} + P_{Bn.4} + P_{Bn.5} + P_{Bn.6}}{6} \tag{11}$$

Based on formula (8), it is possible to determine the level of biogas consumption by a diesel generator set for stable electricity generation.

For the stable operation of a diesel generator for the production of electricity using biogas, it is necessary to observe the condition that the consumption level is lower than the biogas production level. The difference in production and consumption is used to accumulate gas, which is used to produce electricity during the biogas plant's downtime. The paper proposes an approach to determining the level of biogas consumption and production, taking into account the reliability of the biogas plant equipment (Kaletnik 2010). Compliance with the proposed approaches will ensure the predicted level of electricity supply to the livestock farm.

For calculations, we assume the minimum gas yield and take into account only the methane content. The corresponding graphical dependence of the biogas yield from excrement for different species of animals and birds is shown in Figure 3.

To calculate the required amount of electricity, an experimental determination of the load schedule was carried out based on the analysis of electricity consumption on a small cattle farm (cattle). The farm's livestock consists of 60 dairy cows, 11 dry cows, and 29 young cattle, i.e., heifers and calves. Keeping in the winter-stall period (Kaletnik et al. 2020; Koval et al. 2025).

For energy calculations within the framework of this study, the use of biogas yield from animal excrement was adopted, which allows for ensuring increased reliability of the obtained

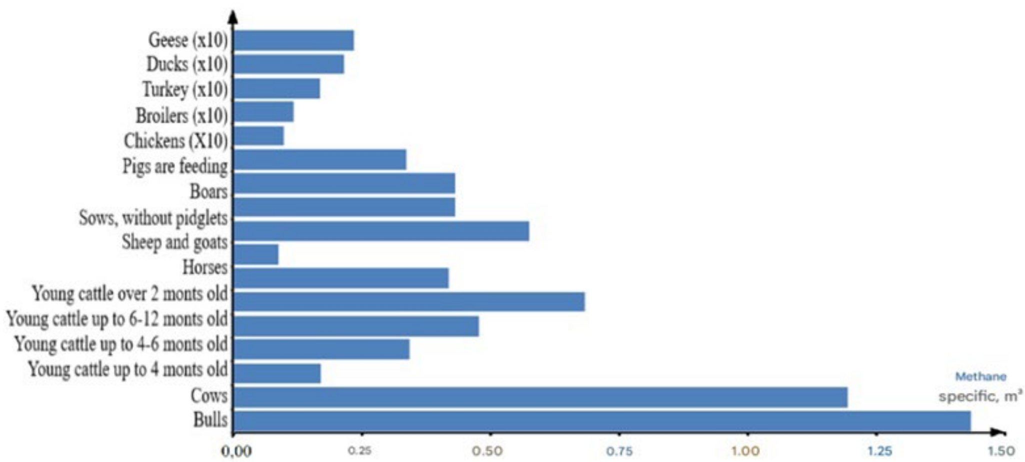

Fig. 3. Specific yield of methane obtained from biogas for different species of animals and birds

Rys. 3. Wydajność jednostkowa metanu uzyskanego z biogazu dla różnych gatunków zwierząt i ptaków results in a conservative version. In addition, the calculations took into account only the methane content in biogas as the main combustible component, since methane is the main source of energy during its combustion in cogeneration plants. This ensures the adequacy of calculations of the amount of electricity produced, taking into account the real operating conditions of the equipment.

The corresponding graphical dependence of the specific yield of methane obtained from biogas for different types of farm animals and birds is shown in Figure 2. This figure illustrates the average volume of methane that can be obtained from one kilogram of dry matter of excrement for each category of animals. The highest rates are characteristic of cattle (especially bulls and dairy cows), as well as sows, while birds, despite the higher amount of dry matter per unit mass, are characterized by a lower methane yield. This information is key to determining the potential for energy production on a farm of a certain profile.

To further calculate the amount of electricity that can be produced from biogas, a study was conducted. To this end, a daily load schedule was formed based on an analysis of the actual electricity consumption of a small livestock farm specializing in cattle (Table 3).

Table 3 shows diagrams of the operation of the equipment of the specified livestock farm using Excel, and a calculation of the load schedule was made by summing the capacities for the corresponding time ranges (Kaletnik et al. 2020; Stadnik et al. 2021; Koval et al. 2025).

The load schedule of the livestock farm, compiled on the basis of the calculations, is shown in Figure 4. From the analysis of this schedule, it is clearly seen that during the day, there are two distinct periods of peak load. The first peak period falls on the morning hours – from 6:30 to 7:00. During this time, electricity consumption on the farm increases sharply and exceeds the mark of 50 kilowatts. The second peak period falls on the lunch hour – from 14:00, when there is also a significant increase in electricity consumption, exceeding 50 kilowatts. These two zones of increased energy consumption are due to the simultaneous launch and operation of several energy-intensive installations and equipment that provide technological processes on the farm.

Understanding these peak loads is essential for optimizing power supply patterns and developing effective load balancing measures, including the use of alternative energy sources such as biogas. This will ensure a stable and uninterrupted power supply to the farm, reduce electricity costs, and increase overall energy efficiency.

The maximum consumption level is 58 kW.

$$W^{day} = \frac{\sum_{i=1}^{k} \left(P_i \cdot t_i \right)}{T} \tag{12}$$

where:

- k – total number of load change ranges corresponding to the switching on or off operations of consumers,
- P_i – installed power at the i-th interval of the load diagram,
- t_i – time of switching on of the consumer group at the i-th interval of the load diagram,
- T – duration of the daily cycle of switching on consumers:

TABLE 3. Diagrams of the operation of technological equipment of a livestock farm and calculation of the load schedule

TABELA 3. Schematy pracy urządzeń technologicznych gospodarstwa hodowlanego i obliczenia harmonogramu obciążeń

Operation	power	5:00	5:30	6:00	6:30	7:00	7:30	8:00	8:30	9:00	9:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30	16:00	16:30	17:00	17:30	18:00	18:30	19:00	19:30	20:00
Feeding of finished feed	3,2			1																1												
Serving root vegetables	3				1	1	1														1	1	1									
Grinding root vegetables	14				1	1	1														1	1	1									
Preparing hay flour	22		1	1															1	1												
	6	1	1					1	1					1	1					1	1					1	1					
Flour feeding	2,7				1		1														1		1									
Silage grinding	22				1	1															1	1										
Loading feed	1,5			1	1	1	1													1	1	1	1									
Preparation of mixtures	2,2			1	1	1	1													1	1	1	1									
	2,2				1	1	1	1													1	1	1	1								
Dispensing feed	12						1	1															1	1								
Milking cows	7			1	1	1	1	1	1																	1	1	1	1	1	1	1
Milk cooling	5							1	1	1	1	1	1	1	1													1	1	1	1	1
Manure cleaning	2,5	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Lighting	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Load, kW		9,5	32	39	58	56	49	36	22	8,5	8,5	8,5	8,5	15	15	3,5	3,5	3,5	26	38	57	49	42	18	3,5	17	17	16	16	16	16	16

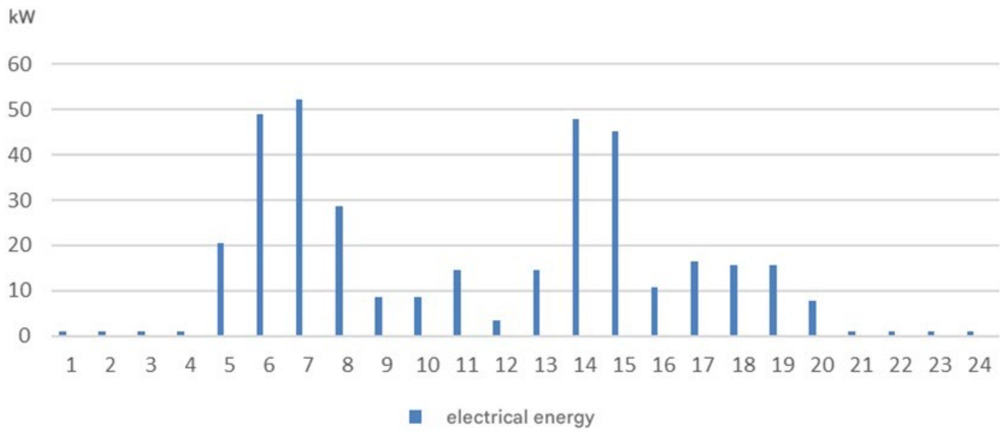

Fig. 4. Load schedule of a livestock farm

Rys. 4. Schemat obciążenia gospodarstwa hodowlanego

$$Q = \frac{P_1 \cdot t_1 + P_2 \cdot t_2 + P_3 \cdot t_3 + P_4 \cdot t_4 + P_5 \cdot t_5 + P_6 \cdot t_6 + P_7 \cdot t_7 + P_8 \cdot t_8}{T} \tag{13}$$

Let's determine the generator power:

$$Q = \frac{1 \cdot 4 + 30 \cdot 2 + 52 \cdot 1 + 28 \cdot 1 + 9 \cdot 5 + 46 \cdot 2 + 15 \cdot 5 + 1 \cdot 4}{4 + 2 + 1 + 1 + 5 + 2 + 5 + 4} = \frac{360}{24} = 15 \tag{14}$$

From this, it is given that the daily demand is 360 kW. Taking into account the farm's livestock (71 cows and 29 young animals over 12 months old), the daily biogas output according to the presented methodology will be 105 m^3. For calculations, reduce the amount of gas taking into account reliability. Namely, the recovery time, as shown in the literature data on permissible downtime of technological lines.

Taking into account the reliability of the biogas energy system. In the practice of operating technological equipment, in particular in biogas plants, an important factor is the reliability indicator, which characterizes the stability of equipment operation without failure. In accordance with regulatory requirements, the permissible level of downtime of biogas cogeneration plants is determined on the basis of technical documentation of manufacturers or industry standards.

According to methodological recommendations for calculation (Lut et al. 2008), the permissible downtime of technological lines for agricultural enterprises using biogas plants is on average:

- for the main technological equipment – up to 2 hours per day (i.e. ≈ 8.3% of daily time),
- for auxiliary equipment – up to 4 hours per day (≈ 16.7% of daily time).

In practice, taking into account emergency downtime, maintenance, fluctuations in raw material quality, and other unpredictable factors, it is recommended to introduce a reliability coefficient of 0.75–0.80, i.e., to take into account a decrease in the effective daily biogas yield by 20–25%. Thus, for further calculations, we assume a 25% reduction in the volume of biogas produced.

So, instead of 105 m³/day day, the actual volume of effective gas for energy production will be:

$$V_{effect} = 105 \cdot 0.75 = 78.75 \text{ m}^3\text{/day} \tag{15}$$

This value provides a realistic assessment of the potential of a cogeneration plant, taking into account reliability, which is important when selecting equipment and designing a power system (Table 4).

Table 4. Characteristics of cogeneration plants of different capacities

Tabela 4. Charakterystyka instalacji kogeneracyjnych o różnych mocach

No	Installation power [kW]	Daily biogas consumption [m^3]	Electrical efficiency [%]	Estimated biomass requirement [kg/day]
1	1	0.7–1.0	28–30	35–45
2	5	4–5	30–33	180–220
3	10	8–11	32–35	350–400
4	50	38–50	35–37	1,700–2,000
5	100	75–95	36–38	3,500–4,000
6	250	180–230	38–40	8,500–10,000
7	500	360–450	40–42	17,000–20,000
8	1,000	720–900	42–44	34,000–40,000

The data in the table are summarized based on typical technical characteristics of cogeneration plants, such as Jenbacher, 2G, MWM, which operate on biogas. The average heat of combustion of biogas is ≈ 21–23 MJ/m³.

For a farm with a daily biogas output after taking into account reliability at the level of ≈ 79 m^3/day, the most appropriate is to use a cogeneration plant with a capacity of up to 15–20 kW, which provides 78% of the farm's electricity needs.

When developing and implementing biogas cogeneration systems in the agricultural industry, an important factor is the permissible downtime of technological equipment (Fig 5). The reliability of energy supply directly affects the quality and volume of the main products of the farm. In (Kaletnik 2010; Kaletnik et al. 2021), the maximum permissible downtime durations of various technological processes and specific product losses are given, which allows taking into account the technical and economic risks in case of emergency or unstable energy supply.

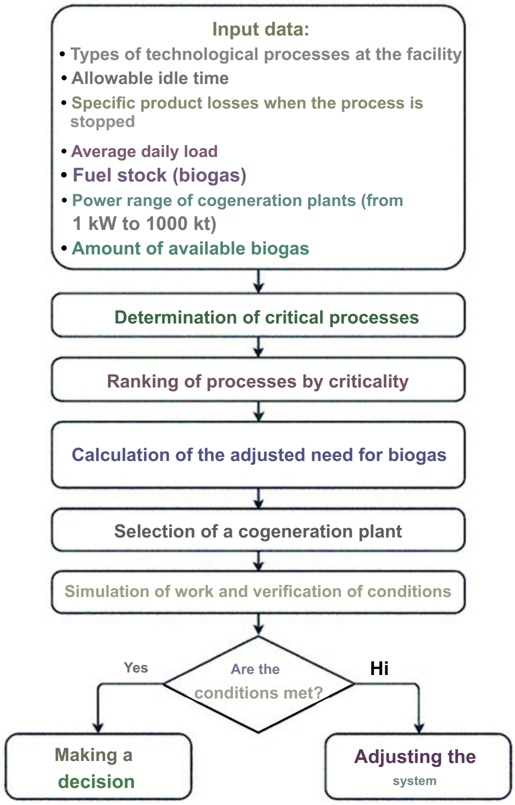

Fig. 5. Algorithm for taking into account the permissible downtime of technological lines for the selection of a cogeneration unit

Rys. 5. Algorytm uwzględniania dopuszczalnych czasów przestoju ciągów technologicznych przy doborze agregatu kogeneracyjnego

The main conclusions from the analysis (Kaletnik 2010; Kaletnik et al. 2021). On dairy farms: the milking process is the most sensitive to downtime – only 1.5 hours of downtime per day is allowed; the processes of watering, feeding and microclimate allow downtime of up to 3.0–3.5 hours, with a specific underproduction of up to 0.04 cu.u; primary milk processing – up to 3 hours, underproduction of 0.035 cu.u.

On cattle fattening farms: up to 3.5 hours of downtime per day is allowed, which is relatively acceptable for stable operation, taking into account the reserve.

On pig fattening complexes: the influence of external temperature significantly changes the permissible downtime: at 0…+12°C – no more than 6 hours, at +13…+20°C – up to 3 hours; at temperatures below –20°C – downtime is unacceptable, which requires uninterrupted operation of the system.

For greenhouses: the lowest level of permissible downtime is from 4 to 12 hours, depending on the temperature; specific product losses can reach 0.05 cu.u., which is economically significant.

Therefore, when choosing a cogeneration unit, it is necessary to take into account: minimum guaranteed time between failures (not less than 8000 hours/year), emergency backup system or integration with the network, automation of restart, and emergency power restoration. To ensure safe power supply to critical facilities (milking parlors, greenhouses, ventilation equipment), it is advisable to reduce the planned load by 20–25%, as already taken into account in the preliminary calculation of the biogas volume (105 m^3/day → 78,75 m^3/day).

Thus, the analysis allows us to reasonably take into account the reliability factor in the biogas energy supply system, which is critically important for farms with a continuous technological cycle. In the future, this should be taken into account when selecting the type of cogeneration plant, forming a maintenance schedule, and calculating the economic efficiency of the system. The amount of gas for further calculations should be reduced by 20–25%. This will take into account reliability.

Consider a series of cogeneration plants from 10 kW to 1000 kW, in Table 5.

To quantify the efficiency of biogas conversion into electrical energy, empirical formulas are used that take into account the main parameters of biogas and equipment. One of these is the formula for calculating the electrical energy obtained from 1 m^3 of biogas.

Electrical energy from 1 m^3 of biogas:

$$\eta_{el} = -0.000021 \cdot P + 0.00048 \cdot G + 0.19 \tag{16}$$

where:

- η_{el} – electrical energy obtained from 1 m^3 of biogas [kWh/m^3],
- P – gas generator power [W or kW] (to be specified according to context),
- G – methane content in biogas [%] (in volume fractions),
- 0.19 – the free term of the equation, which reflects the baseline level of electricity production in the absence of the influence of factors.

Estimating the amount of heat that can be obtained from one cubic meter of biogas is important for calculating the energy efficiency of the installation and designing the overall heating system of the farm. For this, an empirical formula is used.

Thermal energy from 1 m^3 of biogas:

$$\eta_{th} = -0.000014 \cdot P + 0.00041 \cdot G + 0.14 \tag{17}$$

- η_{th} – thermal energy obtained from 1 m^3 of biogas [kWh/m^3],
- P – installation power [W or kW],
- G – methane content in biogas [%],
- 0,14 – base level of heat transfer, which is taken into account even at minimum values of variables.

TABLE 5. Cogeneration series

TABELA 5. Szereg kogeneracyjny

Cogeneration plant	Electrical power [Watt (W)]	Thermal power [W]	Biogas consumption [m^3]	Electrical efficiency [%]	Thermal efficiency [%]	Electricity generation from 1 m^3 of biogas	Thermal energy production from 1 m^3 of biogas
PowerLink ACG10S-NG	10	22	3.6	30	64	2,8	6,1
PowerLink ACG20S-NG	20	46	7.2	30	66.3	2,8	6,4
PowerLink ACG30S-NG	30	65	9	36	57.6	3,3	7,2
PowerLink CG50-NG	50	73	14	32.7	46.1	3,6	5,2
PowerLink CG66-NG	66	91	17	38.8	52.7	3,9	5,3
PowerLink CG75-NG	75	106	20	37.2	53	3,7	5,3
PowerLink CG100-NG	100	138	28	35.8	52.6	3,5	5,0
PowerLink CG200-NG	200	263	54	35.2	49.3	3,8	4,9
PowerLink CG220-NG	220	237	51	43.8	47.2	4,3	4,7
PowerLink CG270-NG	270	368	68	40	54.3	4,0	5,4
PowerLink CG300-NG	300	365	76.7	37.4	49.8	4,0	4,8
PowerLink CG350-NG	350	439	84	42.3	52.9	4,2	5,2
PowerLink TCG600-NG	600	654	143	43.6	45.9	4,2	4,6
PowerLink TCG800-NG	800	855	189	43.8	45.8	4,2	4,6
PowerLink CG875-NG	875	1,026	229	39.3	43.2	3,9	4,5
PowerLink TCG1000-NG	1,000	1,028	233	39.3	40.4	4,2	4,4

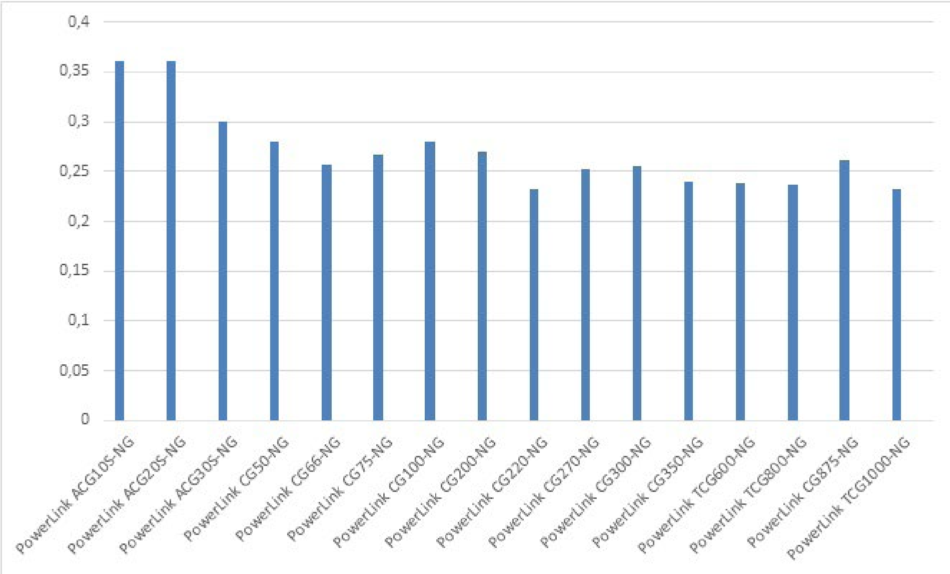

Fig. 6. Biogas consumption m^3 per 1 kW of electrical energy

Rys. 6. Zużycie biogazu m^3 na 1 kW energii elektrycznej

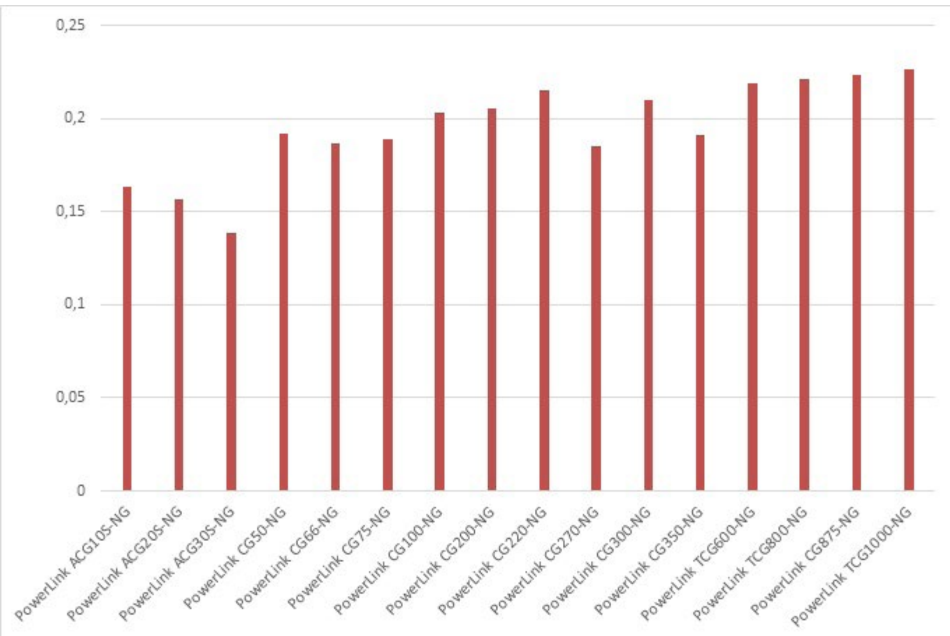

Fig. 7. Biogas consumption m^3 for 1 kW of thermal energy

Rys. 7. Zużycie biogazu m^3 na 1 kW energii cieplnej

Let's consider the PowerLink ACG20S-NG cogeneration unit, which covers 60% as can be seen from the regression equation. It is clear that with a decrease in power, specific costs increase for electricity.

Let's determine the minimum power of the cogeneration unit to cover the daily consumption of electricity, taking into account specific costs (Table 2)

$$\text{By expression } P_{\sum}^{\text{day}} = \sum_{i=1}^{k}(P_i \cdot t_i) \tag{18}$$

Let's determine the power of the cogeneration plant that provides coverage

$$Q \geq \frac{P}{\lambda} \tag{19}$$

where:

Q – production of electricity from 1 m^3 of biogas,

λ – fuel consumption.

Calculations and energy balance of the system. Calculations performed according to formulas (18) and (19) show that to ensure the electricity supply of a livestock farm in an autonomous mode, it is advisable to use a PowerLink CG50-NG cogeneration unit. This unit is capable of covering 78% of the facility's electrical needs while maintaining a high efficiency (EC), which meets the energy efficiency criteria (Kupchuk et al. 2022; Hontaruk et al. 2024).

After these calculations, we will obtain a coverage level of less than 100%, for full coverage of the daily consumption schedule, it is proposed to use solar energy, which in combination will provide the necessary level of coverage of the load schedule, taking into account reliability, consumption of the farm and biogas plant (Kaletnik et al. 2019; Honcharuk et al. 2024).

The maximum electrical load of the farm is 58 kW, while the PowerLink CG50-NG cogeneration unit has a nominal capacity of 50 kW. In this regard, there is a need to use an energy storage system (batteries) to cover the power deficit of 8 kW during peak loads (Kaletnik et al. 2022).

A basic algorithm for the functioning of the energy supply system has been developed, which takes into account the conditions of consumption, generation, and storage of electrical energy. According to the algorithm, in cases of high load or insufficient battery charge, the cogeneration plant is automatically turned on. According to the simulation results, the duration of the daily operation of the plant is on average 7.5 hours per day. At other times, the facility is powered using the stored energy (Galushchak et al. 2023).

The farm's heat consumption at different times of the year was analyzed separately. In the summer, the average daily heat consumption is 418.5 kWh, while in the winter this figure increases to 707.7 kWh. Thus, in the summer, there is a surplus of heat energy of 123 kWh, and in the winter, on the contrary, there is a deficit of 159.2 kWh.

Thus, the difference between the summer surplus and the winter deficit of heat energy is approximately 6.5 MWh, which requires optimization of heat storage or additional sources of heat supply in the winter.

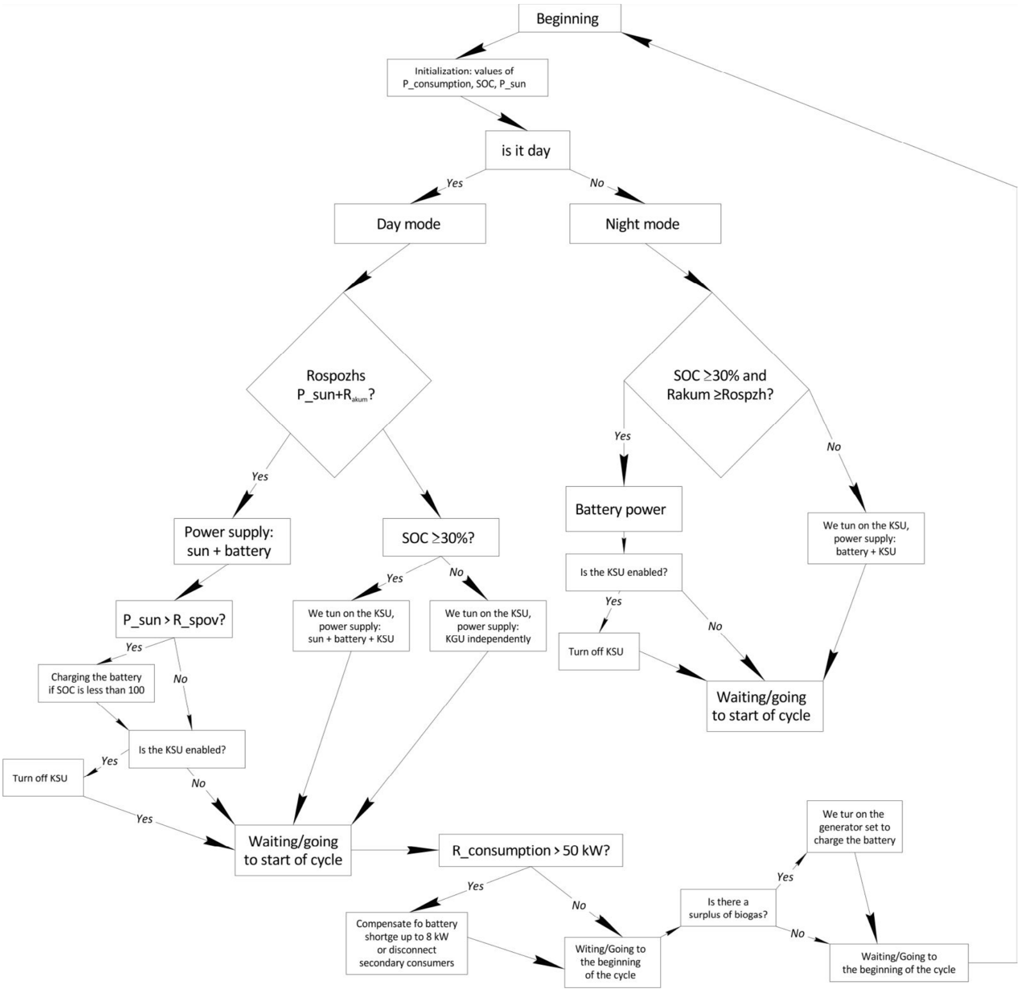

Fig. 8. Algorithm for the use and accumulation of energy in the energy supply of a livestock farm

Rys. 8. Algorytm wykorzystania i akumulacji energii w energetyce gospodarstwa hodowlanego

It was also established that during the year, a surplus of electricity of 5,475 kWh is formed, which can be used for the internal needs of the farm, charging batteries, or selling to the grid under the condition of two-way metering.

As a result, based on the calculations performed, it can be stated that the power supply system with the PowerLink CG50-NG cogeneration unit provides an energy supply level of 78%, and the annual heat balance can be balanced if additional measures are implemented to store or redistribute heat energy.

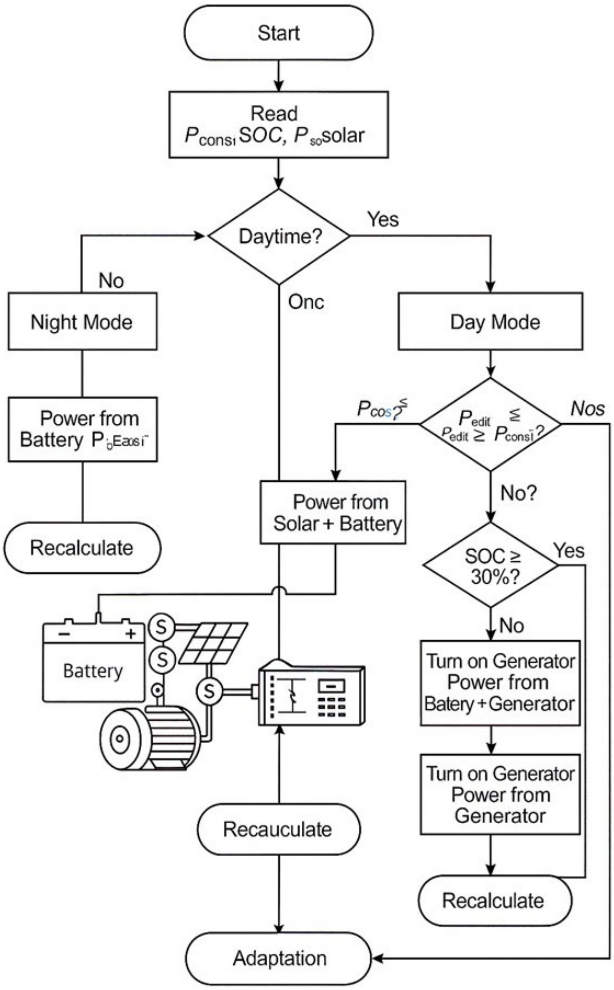

Fig. 9. Algorithm for the use and accumulation of energy in the energy supply of a livestock farm

Rys. 9. Algorytm wykorzystania i akumulacji energii w energetyce gospodarstwa hodowlanego

Conclusion

The study confirmed the high efficiency of implementing biogas plants on livestock farms. According to calculations, from 1 m^3 of biogas can be obtained on average from 2.7 to 4.3 kWh of electrical energy and from 4.4 to 7.2 kWh of thermal energy. This allows for the effective use of organic waste from livestock as a source of renewable energy with a high level of energy efficiency.

For a farm with a livestock population of up to 100 cattle (cattle), the daily biogas production volume is about 105 m^3. This is enough to generate 290–450 kWh of electricity and 410–750 kWh per day, which covers most of the needs of technological processes: lighting, ventilation, milking, water heating, etc.

The efficiency of a cogeneration system that simultaneously produces electricity and heat reaches 80–90%. This figure is significantly higher compared to traditional centralized power supply systems, where the efficiency does not exceed 35–40%. High efficiency is achieved by fully using thermal energy for heating livestock premises, drying feed, and heating water.

The combination of biogas plants with solar power generation allows balancing daily energy production. Solar panels cover an average of 20–25% of the farm's daily energy consumption, while the biogas plant provides an uninterrupted electricity supply in the evening and at night. This approach significantly increases the reliability and autonomy of energy supply.

The use of lithium-ion batteries for short-term energy backup is advisable within the range of 30–50 kWh, which allows for compensating for short-term peak loads. Additionally, the installation of biogas storage tanks with a volume of 500–1000 m^3 allows to ensure uninterrupted operation of the power system for 1–3 days even in adverse weather conditions or disruptions in the operation of individual elements of the system.

Summarizing the results, it can be concluded that the use of biogas as the main energy source in combination with solar generation and storage systems is an effective and sustainable solution for power supply and heat supply of livestock farms. This approach contributes to reducing energy dependence, ecological cleaning of production, and increasing the overall energy efficiency of the agricultural sector.

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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

Opracowanie algorytmu zasilania fermy hodowlanej przy użyciu biogazu

Streszczenie

W artykule rozważana jest kwestia zwiększenia autonomii energetycznej gospodarstw hodowlanych poprzez wdrożenie systemów zasilania opartych na odnawialnych źródłach energii, w szczególności biogazowniach i elektrowniach słonecznych. Zaproponowano kompleksowe podejście do oceny potencjału wytwarzania energii elektrycznej i ciepła, oparte na ilościowej analizie organicznych odpadów rolniczych, które mogą być przetwarzane na biogaz poprzez fermentację beztlenową. Pod uwagę brane są: całkowita objętość obornika, ścieków obornikowych, odpadów paszowych, a także skład chemiczny i wilgotność surowca. W artykule przedstawiono zależności analityczne, w szczególności równania do określania energii elektrycznej i cieplnej, jaką można uzyskać z jednego metra sześciennego biogazu, biorąc pod uwagę parametry technologiczne zespołu prądotwórczego. Ponadto w pracy przeanalizowano zapotrzebowanie energetyczne gospodarstwa, zbudowano dzienny harmonogram obciążeń, określono ilość zużywanej energii elektrycznej, jej wartości szczytowe i średnie dzienne zużycie. Na podstawie tych danych obliczono optymalną wydajność biogazowni i powierzchnię paneli słonecznych niezbędną do pełnego pokrycia potrzeb energetycznych. Rozważono warianty sezonowej regulacji wytwarzania, a także możliwość podłączenia do sieci zewnętrznej w przypadku nadwyżki produkcji energii elektrycznej. Proponowany system zasilania może być skalowany i dostosowywany do warunków konkretnego gospodarstwa, co czyni go uniwersalnym rozwiązaniem dla zwiększenia bezpieczeństwa energetycznego w sektorze rolnym.

Słowa kluczowe: elektrownie kogeneracyjne, harmonogram obciążenia, generator, energia cieplna, efektywność energetyczna