

INMATEH -

**AGRICULTURAL
ENGINEERING**

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Editorial

The National Institute of Research-Development for Machines and Installations designed to Agriculture and Food Industry - INMA Bucharest has the oldest and most prestigious research activity in the field of agricultural machinery and mechanizing technologies in Romania.

Short History

- ✓ *In 1927, the first research Center for Agricultural Machinery in Agricultural Research Institute of Romania - ICAR (Establishing Law was published in O.D. no. 97/05.05.1927) was established;*
- ✓ *In 1930, was founded The Testing Department of Agricultural Machinery and Tools by transforming Agricultural Research Centre of ICAR- that founded the science of methodologies and experimental techniques in the field (Decision no. 2000/1930 of ICAR, Manager - GHEORGHE IONESCU ȘIȘEȘTI);*
- ✓ *In 1952, was established the Research Institute for Mechanization and Electrification of Agriculture - ICMA Băneasa, by transforming the Department of Agricultural Machines and Tools Testing;*
- ✓ *In 1979, the Research Institute of Scientific and Technological Engineering for Agricultural Machinery and Tools - ICSITMUA was founded - subordinated to Ministry of Machine Building Industry - MICM, by unifying ICMA subordinated to MAA with ICPMA subordinated to MICM;*
- ✓ *In 1996 the National Institute of Research-Development for Machines and Installations designed to Agriculture and Food Industry - INMA was founded - according to G.D. no.1308/25.11.1996, by reorganizing ICSITMUA, G.D no. 1308/1996 coordinated by the Ministry of Education and Research G.D. no. 823/2004;*
- ✓ *In 2008 INMA has been accredited to carry out research and developing activities financed from public funds under G.D. no. 551/2007, Decision of the National Authority for Scientific Research - ANCSno. 9634/2008.*

As a result of widening the spectrum of communication, dissemination and implementation of scientific research results, in 2000 was founded the institute magazine, issued under the name of SCIENTIFIC PAPERS (INMATEH), ISSN 1583 – 1019.

*Starting with volume 30, no. 1/2010, the magazine changed its name to INMATEH - *Agricultural Engineering*, appearing both in print format (ISSN 2068 - 4215), and online (ISSN online: 2068 - 2239). The magazine is bilingual, abstract being published in native language and English, with a rhythm of three issues / year: January-April, May-August, September-December and is recognized by CNCSIS – with B⁺ category. Published articles are from the field of AGRICULTURAL ENGINEERING: technologies and technical equipment for agriculture and food industry, renewable energy, machinery testing, environment, transport in agriculture etc. and are evaluated by specialists inside the country and abroad, in mentioned domains.*

*Technical level and performance processes, technology and machinery for agriculture and food industry increasing, according to national requirements and European and international regulations, as well as exploitation of renewable resources in terms of efficiency, life, health and environment protection represent referential elements for the magazine „INMATEH - *Agricultural Engineering*”.*

We are thankful to all readers, publishers and assessors.

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TECHNICAL AND ECONOMIC ASPECTS OF BIOGAS PRODUCTION AT A SMALL AGRICULTURAL ENTERPRISE WITH MODELING OF THE OPTIMAL DISTRIBUTION OF ENERGY RESOURCES FOR PROFITS MAXIMIZATION

ТЕХНІЧНІ ТА ЕКОНОМІЧНІ АСПЕКТИ ВИРОБНИЦТВА БІОГАЗУ НА МАЛОМУ СІЛЬСЬКОГОСПОДАРСЬКОМУ ПІДПРИЄМСТВІ З МОДЕЛЮВАННЯМ ОПТИМАЛЬНОГО РОЗПОДІЛУ ЕНЕРГЕТИЧНИХ РЕСУРСІВ ДЛЯ МАКСИМІЗАЦІЇ ПРИБУТКУ

Tokarchuk D.M., Pryshliak N.V., Tokarchuk O.A., Mazur K.V. ¹

Vinnitsa National Agrarian University / Ukraine
Tel: +380970447755; E-mail: pryshliak.vnau@gmail.com
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ABSTRACT

The use of biogas is one of the ways to supplement and partially replace traditional fuels in rural areas. The feasibility of farms' energy supply from their own energy source and the need to reduce harmful emissions into the environment make the biogas plant an indispensable element of modern livestock complexes. The article considers the possibility of using biogas for energy supply of an agricultural enterprise. The schemes and design capabilities of biogas plant for small and medium size farms are considered. The list and volume of products that can be obtained from the operation of the biogas plant have been determined. Economic indicators of the use of animal manure for biogas production have been determined. A comparison of the cost-effectiveness of using biogas energy products has been conducted.

РЕЗЮМЕ

Одним із шляхів доповнення і часткової заміни традиційних видів палива в сільській місцевості є використання біогазу. Доцільність автономного енергозабезпечення ферм з власного джерела енергії та необхідність зменшення шкідливих викидів у навколишнє середовище роблять блок з виробництва біогазу обов'язковим елементом сучасних тваринницьких комплексів. У статті розглянуто можливість використання біогазового палива для енергозабезпечення сільськогосподарського підприємства. Розглянуто схеми і конструктивні можливості фермерської біогазової установки для малих і середніх ферм. Обраховано перелік та обсяг продукції, яку даватиме біогазова установка підприємству. Визначено економічні показники використання гною тварин на виробництво біогазу. Проведено порівняння економічної ефективності використання енергетичних продуктів біогазового виробництва.

INTRODUCTION

The processing and disposal of organic waste by decomposing it under anaerobic conditions to produce combustible gas and its energy use has been utilised by people since ancient times. At the same time, the process of biological decomposition of organic substances with the formation of methane has not changed over the past millennia. The issue of waste accumulation and recycling combines environmental, resource and energy aspects, since waste is not only polluting the environment, but it is also a carrier of useful components (Berezyuk S. et al 2019). The increasing interest of utilizing biogas as substitute to natural gas or its exploitation as transport fuel opened new paths in the development of biogas upgrading techniques (Angelidaki I. et al, 2018).

¹ Tokarchuk D.M., Ph.D. Econ.; Pryshliak N.V., Ph.D. Econ.; Tokarchuk O.A., Ph.D. Eng.

Countries that lack energy reserves, as well as those that are concerned about the negative impacts of the production and use of fossil fuels, actively stimulate the development, production and consumption of alternative energy in general and bioenergy, in particular, at the state level (*Kaletnik H. et al, 2019*).

In Ukraine, one of the promising areas is the processing of livestock biomass by anaerobic digestion with the formation of biogas, which is then used to produce bioenergy. An important argument in favour of this energy source is the need to solve environmental problems arising from the disposal of agricultural waste.

The energy and climate policies in the EU and the introduction of various support schemes for promoting the utilization of renewable resources have encouraged the development of biogas plants for energy production. Anaerobic digestion provides opportunities for biogas to be used for generating energy, such as electricity, heat and fuel with additional economic, environmental and climate benefits. (*Scarlat N. et al, 2018*).

The environmental impacts and high long-term costs of poor waste disposal have pushed the industry to realize the potential of turning this problem into an economic and sustainable initiative. Anaerobic digestion and the production of biogas can provide an efficient means of meeting several objectives concerning energy, environmental, and waste management policy (*Adnan A. et al, 2019*).

Ukraine has identified development of its agriculture as a strategic goal (*Zulauf C. et al, 2018*). At the same time 115 million tons of agricultural plant waste and about 97 million tons of animal waste are generated annually in Ukraine (*Pryshliak N., Tokarchuk D., 2020*).

An important aspect in the introduction of sustainable crop production and livestock production is the development of integrated technologies using methane digestion processes in the utilization of biomass, which produces biogas. Fermentation from agricultural waste produces not only biogas, but also concentrated organic fertilizers, which are a valuable product for use in modern technologies for growing crops. At the same time, biogas production requires considerable financial investment to implement innovative projects, however, the expected benefit from using biogas products outweighs what has to become an influential factor in stimulating production (*Tokarchuk, D., 2016*).

A number of works by foreign and domestic scientists have been devoted to the study of the current state and prospects of development of biogas technologies. As noted by *Holm-Nielsen J. et al, (2009)*, anaerobic digestion of animal manure and slurries offers several benefits by improving their fertilizer qualities, reducing odours and pathogens and producing a renewable fuel – the biogas. *Rasi S. et al, (2007)*, studied biogas composition and variation in three different biogas production plants to provide information pertaining to its potential use as biofuel. *Achinas S. et al, (2017)*, noted that biogas economy is related to factors such as waste availability and logistics, process efficiency, and end-product properties.

Manure is a livestock residue that causes high environmental burdens in different categories. Its usage in biogas production is an environmentally beneficial way not only to reduce these impacts, but also to produce energy and biofertilizers (*Esteves E. et al, 2019*). The use of biomethane lowers water, soil and air pollution not only because it eliminates fossil fuel related pollution but the risk of potentially devastating accidents is also remarkably reduced (*Bharathiraja B. et al, 2018*).

Korznikova M. et al, (2008), explored the possibilities of using biotechnology to process livestock and poultry waste into biogas to produce clean energy and prevent environmental pollution. Taking into account microbiological and biochemical bases of conversion of organic matter waste, the authors determined the optimal technological parameters of the process.

Suslov D., (2014), considered the use of biogas for agricultural gas supply. The author has developed a gas supply system for a pig farm, which includes a gas supply source – a biogas plant. *Blades. L. et al, (2017)*, investigates the application of a circular economy in a rural agricultural setting in Northern Ireland, centred around a typical anaerobic digestion (AD) plant, showing its potential to provide renewable energy for the electricity and transport fuel needs of an average dairy farm and associated milk processing facilities.

Kurbatova T., (2018), analyses energy potential of agricultural biomass in Ukraine, economic tools, aimed at stimulating electricity generation from biogas based on animal waste, the results of their impact on biogas plants deployment.

Based on the EU experience and features of farm functioning, *Yevdokimov Y. et al, (2018)*, approved that the biogas installation has not only the economic effect (profit and additional profit) for company, but also ecological and social effects for rural area, where this farm was located.

Therefore, to ensure efficient utilization of agricultural waste while ensuring energy generation, it is expedient to study more deeply the technical and economic aspects of biogas production. The aim of this study is to investigate technical and economic aspects of biogas production at a small agricultural enterprise and to model the optimal distribution of energy resources for profits maximization.

MATERIALS AND METHODS

Livestock waste is considered to be the most appropriate substrates for biogas production (as a separate substrate or in combination with other substrates). Unlike other types of biomass, such as energy crops, manure is produced as by-products of animal husbandry, which require disposal in an environmentally sustainable manner. In addition, manure is a good substrate for biogas production, as it is easily mixed with other feedstock, such as corn silage, plant residues and others.

The biogas plant operates on the principle of anaerobic digestion (without oxygen access). Liquid biowaste is delivered via a self-alloyed manure removal system to a receiving tank or pumped by faecal pumps through a pipeline. The primary preparation of raw materials takes place in a receiving tank (homogenization tank), biowaste is brought to a certain moisture consistency by mixing. After this, the primary fermentation of excrement occurs and biofeedstock is loaded into the reactors (bioreactor, fermenter). The bioreactor is a completely sealed tank, treated with anti-acid and anti-corrosion coating from the outside. Also, bioreactors are insulated, for each biogas plant the layer of insulation is calculated individually. It depends on the climatic conditions of the region where the biogas plant will be built. In conditions of Ukraine, insulation is necessary as winter temperatures are low enough.

The bioreactor can be made of both monolithic reinforced concrete and steel tanks. The biogas reactor operates on a continuous cycle basis. The prepared substrate is loaded into bioreactors daily, and the fermented feed is discharged from the reactor. The operation of the entire biogas station is controlled by commands from the central software module in the program-time mode and by limit value sensors. In biogas plants, a modular principle is applied, which enables the installation to operate in a complex, involving all reactors. In the case if there is a need to replace or shut down individual reactors, it is possible to regulate the technological process. It allows in case of an emergency to repair the unit without completely stopping the entire technological module. The application of the modular principle with increasing power can easily increase the number of bioreactors in a modular complex.

Mixing is carried out mechanically by means of mixers installed in the reactor or hydraulically (by pumps or by the pressure of the produced gas).

After fermentation of biowaste, two products are obtained - biogas and mineralized nitrogen fertilizers. The biogas reactor can be used for more than 25-30 years.

There are many different designs of biogas plants. They are distinguished by:

- way of loading raw materials;
- appearance;
- constituent parts of the structure;
- the materials from which they are constructed (*Kaletnik, G. 2018*).

By the method of loading feedstock, the digestors are divided into batch and continuous loading. Such installations differ in the time of fermentation and the regularity of loading feedstock. The most efficient in terms of biogas production and fertilizer production are continuous loading installations.

By design, the plants vary depending on the method of accumulation and storage of biogas. Gas can be collected in the upper solid part of the reactor, under a flexible dome, or in a special gas tank, floating or standing separately from the reactor.

We consider the possibility of producing biogas at a small agricultural enterprise in our study. This enterprise has the following annual livestock population: cattle - 30 heads, pigs - 15 heads, dairy cows - 15 heads, sheep - 30 heads.

Since the number of animals is small, the enterprise needs a low-power biogas plant. Its advantages are a high level of equipment standardization.

For small and medium-sized farms we offer the biogas production plant (fig. 1) with the possibility of processing from 0.3 to 1.5 tons of feedstock per day. The volume of the reactor ranges from 5 to 25 m³.

Loading and mixing of raw materials are mechanized and carried out using a pneumatic system. With the help of mechanical mixers, the fermentation process in the reactor is distributed evenly throughout the volume.

Raw materials are heated in the biogas plant reactor using a heat exchanger with a biogas-fired boiler. The fermentation mixture remains in the reactor for as long as it is biologically necessary for the decomposition of biological substances by bacteria. The pipeline for unloading raw materials has branches for collecting biofertilizers in storage and for loading them into vehicles for transportation to the field.

The device of this biogas plant (see Fig. 1.) provides manual preparation and pneumatic loading of raw materials into the reactor, part of the produced biogas is used to heat the raw materials in the reactor. Mixing is done by biogas.

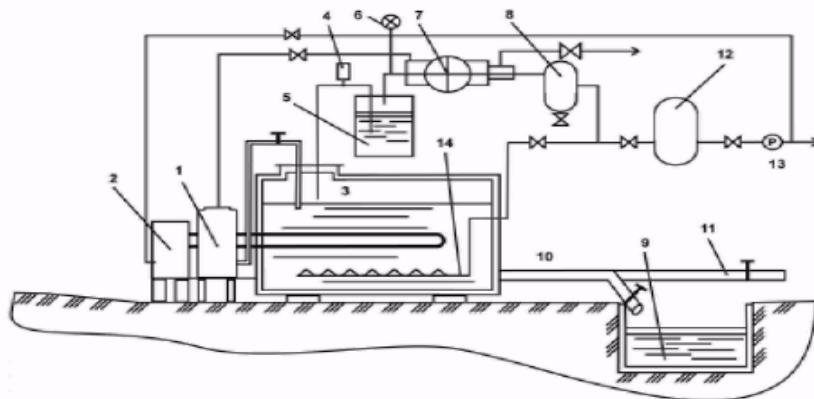


Fig. 1 - Scheme of a farm biogas plant with a gas tank, manual preparation and pneumatic loading and mixing of raw materials, with heating of the raw materials in the reactor

1 - feed hopper; 2 - water heating boiler, 3 - reactor; 4 - safety valve; 5 - a water lock; 6 - pressure gauge;
7 - compressor; 8 - receiver; 9 - biofertilizer storage; 10 - unloading of raw materials;
11 - pipe removal for loading into transport; 12 - gas tank; 13 - gas gear; 14 - mixing device.

Biogas plant for medium and large farms is proposed (Fig. 2). Its distinctive feature is the presence of a special tank for the preparation of raw materials, from which they are supplied with a compressor to the loading hopper, and then, using compressed biogas, to the installation reactor.

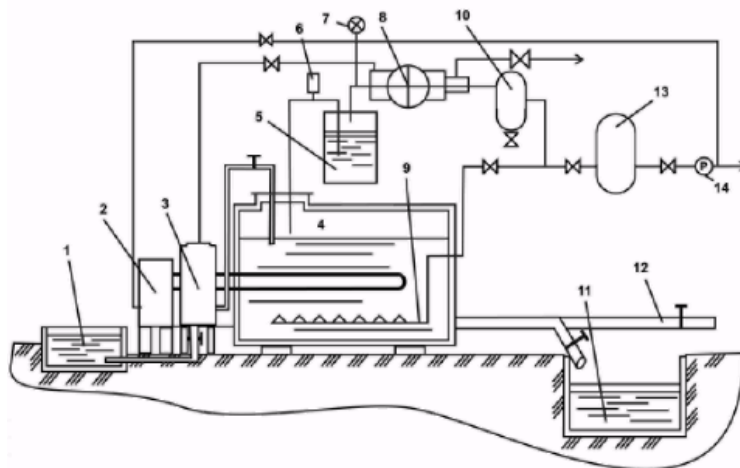


Fig. 2 - Scheme of a farm biogas plant with a gas tank, mechanical preparation and pneumatic loading and mixing of raw materials with heating of raw materials in the reactor

1 - manure receiver; 2 - water boiler; 3 - loading hopper; 4 - reactor; 5 - a water lock; 6 - safety valve;
7 - pressure gauge; 8 - compressor; 9 - gas mixer; 10 - receiver; 11 – biofertilizer storage;
12 - pipe removal for loading into vehicles; 13 - gas tank; 14 - gas gear.

Part of the biogas products is used for the operation of the heating system. The plant is equipped with automatic biogas extraction and a gas tank for its storage. The presence of a heating system allows you to operate a biogas plant in all modes of fermentation. Biogas is selected automatically and is stored in the gas tank. The installation can operate in any temperature regime of fermentation of raw materials.

To perform the task of improving the technical characteristics of a simple biogas plant that can be used in a conventional small enterprise, it is proposed to improve the design of the biogas reactor. The proposed design is based on the task of improving the biogas reactor by increasing the efficiency of maintaining the substrate heating temperature for biogas separation.

To solve the problem of optimal distribution of energy resources (based on biogas from waste) in order to maximize the profit of the enterprise mathematical methods were used. For this, the adapted technique of *Gavrisha V.I. and Perebinis I. (2014)* was used.

In the calculations, we take the indices for the use of biogas:

- 1 - for cogeneration unit.
- 2 - in a gas engine generator,
- 3 - in a gas boiler,
- 4 - for refuelling agricultural machinery.

Biogas consumption in the i^{th} direction will be denoted by x_i (m^3).

It is proposed to consider the annual economic effect of the use of biogas in a conditional enterprise as a criterion of an economic-mathematical model. It makes the difference between the cost of energy resources (motor fuel, electric and thermal energy) obtained with the help of biogas, and the costs of acquiring and operating the corresponding energy equipment (cogeneration unit, heat-generating equipment, automobile gas-filling compressor station).

RESULTS

The results achieved in the development of rural technical support for the use of biogas plants are only a small step in solving the general complex problem. Technologies for processing organics using biomass of plant origin in biogas plants are spreading due to the reduction in the number of cattle and the increase in the cost of traditional energy sources.

The cost of a biogas plant (Fig 1) that meets the needs of a notional enterprise in Ukraine is 12.7 thousand Euros. In addition to the biogas plant itself, the enterprise will need a cogeneration plant, which will turn biogas into electric and heat energy. Its cost in Ukraine is 3.8 thousand Euros. Thus, the total cost of the equipment will be 16.5 thousand Euros. It is relatively low, since the capacity of the installation is small and amounts to 40.5 thousand m^3 of biogas per year.

The amount of produced biogas depends on the physicochemical properties of the feed, loaded into a fermenter. The level of biogas production is calculated per kilogram of dry mass contained in raw materials.

The biogas output from animal waste is significantly affected by the animal feeding ration, their age, and other factors that appear during the experimental study of fermentation processes.

The amount of generated waste depends on the age and type of keeping animals, as well as on the time of year. The average amount of biogas that can be obtained from 1 m^3 of animal excretion is estimated at 20-25 m^3 , although the volume of 30-35 m^3 is considered to be a cost-effective amount in the technical and technological plan. It is also possible to add plant wastes having a high dry matter content to animal manure. According to the proposal of the equipment manufacturer (biogas plant Fig. 1), biogas is usually processed into heat and electric energy by a cogeneration unit. In addition, the biogas plant will give ready to use biofertilizer, which can be implemented on the market or used on the farm. The amount of biogas production products per day and per year is shown in Table 1.

Table 1

The list and quantity of products that the biogas plant will provide to the enterprise

List of products received	Quantity per day	Quantity per year
Biogas output		
Biogas output from cattle manure, (m^3)	63.8	23287.0
Biogas output from pig manure, (m^3)	3.2	1170.0
Biogas output from sheep manure, (m^3)	7.1	2592.0
Biogas output from dairy cow manure, (m^3)	37.1	13530.0
Total biogas output, (m^3)	111.2	40579.0
Biofertilizer output		
Biofertilizer output from cattle manure, (t)	5.6	2027.0
Biofertilizer output from pig manure, (t)	0.3	102.0
Biofertilizer output from sheep manure, (t)	0.6	226.0
Biofertilizer output from dairy cow manure, (t)	3.2	1178.0
Total biofertilizer output, (t)	9.7	3532.0
Electric and heat energy production		
Electric energy based on biogas, ($kW \cdot h$)	225.0	82132.0
Heat energy based on biogas, ($kW \cdot h$)	244.6	89274.0

The obtained heat and electric energy will be partially used to support the operation of the biogas plant, and the rest will be replaced by the purchase of similar products.

We analyse the economic efficiency of introducing biogas production based on the use of animal waste in a notional enterprise in Ukraine in the Table 2. To calculate the annual economic effect, we add the cost of electric and heat energy based on biogas and biofertilizers and subtract the reduced costs of a biogas plant. We calculate the payback period of investments as the quotient of dividing the investments by the annual economic effect (see Table 2).

Table 2

Economic indicators of the use of animal manure for biogas production	
Indicator	Value
The cost of electricity based on biogas, (thousand Euro)	4.51
The cost of heat energy based on biogas, (thousand Euro)	4.80
The cost of biofertilizers, (thousand Euro)	5.53
Capital investments, (thousand Euro)	19.77
Depreciation of equipment, (thousand Euro)	1.65
Costs of servicing a biogas plant (salaries, payroll, electricity, repairs and maintenance), (thousand Euro)	2.68
Presented costs for a biogas plant, (thousand Euro)	7.30
Annual economic effect, (thousand Euro)	7.55
Payback period, (years)	2.62

The calculations showed that the annual economic effect will be 7.55 thousand Euro, the payback period for a biogas and cogeneration plant is relatively small - 2.6 years.

So, we calculated the list and quantity of products that the biogas plant will provide to the enterprise and the economic efficiency of the biogas plant (Fig.1) according to the parameters proposed by the equipment manufacturer.

To improve the natural and economic indicators of biogas production and products based on it, it is necessary to technically improve the biogas plant. Low productivity is the disadvantage of most small biogas plants due to uneven heating of the substrate and the technical complexity of the design.

The problem is solved by equipping the heating element with a cleaning device, that periodically moves to different sides of the rotating screw, at the ends of which there are reversing switches, and cleans the surface of the elements from sticking particles of the biomass substrate (Liubin M.V., Tokarchuk O.A. et al, 2018). A scheme of an improved biogas reactor and A-A section are shown in Fig. 3, 4.

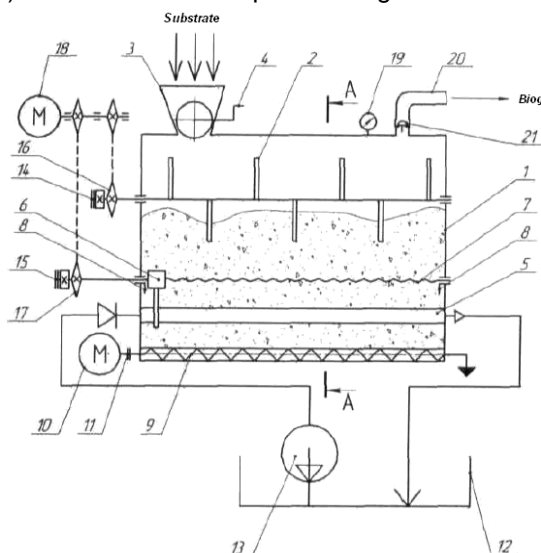


Fig. 3 - Scheme of biogas reactor

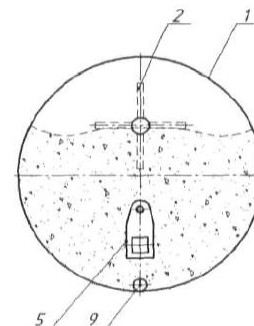


Fig. 4 - A-A section

Biogas reactor contains a tank 1 with a stirrer 2 located inside it, a loading hopper 3 with an integrated slide gate valve 4, a heating element 5, equipped with a cleaning device 6, that periodically moves along a rotary screw 7, at the ends of which there are reversing switches 8, an unloading screw 9, which transfers the torque from the gear motor 10 using the clutch 11 to the tank 12, the pump 13, the electromagnetic

clutches 14 and 15, located on the corresponding sprockets 16 and 17, the electric motor 18, electric contact pressure gauge 19 and a consumer pipe 20 equipped by mechanical valve 21.

Biogas reactor operates as follows. With the open gate valve 4 through the hopper 3, the substrate is fed into the tank 1, which is filled in 2/3 of the volume. For an effective fermentation process, an electric motor 18 is turned on, followed by an electromagnetic clutch 14 located on the sprocket 16, which drives the stirrer 2. To increase the efficiency of fermentation in biogas reactor, a thermophilic mode is used, in which the temperature inside the biogas reactor must be maintained within the range of 50...55°C, therefore, from the tank 12, the coolant (hot water) is supplied through the pump 13 to the heating element 5, which heats the substrate.

In the process of heating the substrate, its particles stick to the surface of the heating element 5 over a period of time, which leads to a decrease in heat transfer. Therefore, to ensure efficient heat transfer of the heating element 5 during operation of the motor 18 by activating the electromagnetic clutch 15 located on the sprocket 17, the cleaning device 6 is actuated, which moves along the heating element 5 by means of rotating screw 7, at the ends of which switches 8 are arranged, that provide a change in the direction of movement of the treatment device 6. Biogas resulting from the fermentation of the substrate, accumulates in the upper part of the tank 1. At that time electric contact pressure gauge 19 controls pressure. If the pressure increases, the mechanical valve 21 is opening and biogas is released from the tank 1 through the consumer pipe 20 and the pressure is reduced.

By reducing the intensity of biogas production, the biomass substrate is discharged from the tank 1. To do this, gear motor 10 is turned on, which transmits torque through the clutch 11 to the discharge screw 9. Particular attention should be paid to the homogeneity of the fermentation mixture. The bacteria must be constantly supplied with organic matter in the reactor. This requires a constant flow of homogeneous organic mixture into the reactor.

Biogas has a small amount of sulphur in its composition, which affects the durability of biogas plants. To extract sulphur from biogas, fresh air is blown onto the surface of the fermentation mixture in the reactor by a small compressor. This leads to the fact that special microorganisms convert gaseous sulphur into a solid state, which becomes a valuable component of organic fertilizers.

Thus, the application of proposed cleaning device for heating element of the biogas reactor 15 makes it possible to significantly improve the efficiency of heat transfer and to ensure the continuous release of biogas for a certain period of time.

It is expected that after the proposed improvement of the reactor, the economic indicators of biogas production will improve: the annual economic effect will be 7.87 thousand Euro, the return period - 2.58 years.

Not only the efficient process of biogas production, but also its rational use is important for agricultural enterprise. There are different ways of using the obtained biogas within the agrarian formation; it is necessary to choose the option that will be most effective in the enterprise. The electricity generated from biogas is partly used to support the operation of the plant, and most of it is used for the enterprise's own needs. Excess energy can be sold to the state at a "green tariff". In addition to electricity, it also generates thermal energy that is used for the needs of the enterprise. It is also possible to use biogas as a motor fuel. Our task is to develop an economic and mathematical model of optimal distribution of biogas for energy purposes.

The purpose of mathematical modelling is to determine which energy needs and in what volumes it is advisable to use the resulting biogas to replace traditional energy resources at the maximum possible cost.

Thus, the objective function, which represents the annual economic effect, has the following form:

$$W = Ee + Eh + Ef - \sum_{i=1}^n (E_{H_i} \cdot K_i + OC_i) - W \cdot Pe - Q \cdot Pe \rightarrow \max \quad (1)$$

where Ee , Eh , Ef – gross income from the production of electric energy, heat energy and diesel substitution, respectively, (Euro);

E_{H_i} – normative coefficient of economic efficiency of capital investments in the i^{th} direction of the use of biogas;

K_i – capital investments buried in the i^{th} direction of biogas use, (Euro);

n – number of directions of biogas use;

OC_i – operating costs for the maintenance of energy equipment for the i^{th} direction of biogas use, (Euro/year);

Pe – the price of electricity purchased by the enterprise, (Euro/(kWh));

W, Q – shortage, respectively, of the electrical and thermal energy required to ensure the operation of the biogas plant, (kWh).

The components of the gross income from the replacement of energy resources are the following.

1. Electricity:

$$Ee = \begin{cases} \left(\frac{x_1 + x_2}{be_e} - We_0 \right) \cdot Pe & \text{with } \frac{x_1 + x_2}{be_e} \leq We_0 + We_f \\ We_f \cdot Pe + \left[\frac{x_1 + x_2}{be_e} - We_0 - We_f \right] \cdot Pe_0 & \text{with } \frac{x_1 + x_2}{be_e} \geq We_0 + We_f \end{cases} \quad (2)$$

where be_e – specific biogas consumption for electric energy production, (m³/(kWh));

We_0, We_f – annual electricity demand for biogas plant and enterprise, (kWh);

Pe_0 - wholesale price for electricity, (Euro / (kWh)).

2. Gross income from the use of thermal energy:

$$Eh = \begin{cases} 0 & \text{with } \frac{x_1}{be_h} + \frac{x_3}{be_b} \leq Qe_0 \\ \left[\left(\frac{x_1}{be_h} - Qe_0 \right) \cdot \frac{T_0}{365} - \frac{x_3}{be_b} \right] \cdot P_f & \text{with } \frac{x_1}{be_h} + \frac{x_3}{be_b} < Qe_0 + Qe_f \end{cases} \quad (3)$$

where T_0 – annual duration of the enterprise's need for heat energy, (days); be_h, be_b – specific consumption of biogas for heat energy production in cogeneration and boiler plants, (m³/kWh);

Qe_0, Qe_f – annual heat demand for biogas plant and enterprise, (kWh);

P_f – the price of heat energy, (Euro/kWh).

3. Gross revenue from diesel replacement by biogas:

$$Ef = \frac{x_4 \cdot Q_b}{\rho \cdot Q_d} \cdot P_f \quad (4)$$

where: ρ – diesel density, $\rho = 0,83$ kg/l; Q_b, Q_d – lower calorific value of biogas and diesel fuel, respectively, (MJ/m³ (MJ/kg)); P_f – the price of diesel fuel, (Euro/l).

The deficit of electric and thermal energy to ensure the operation of a biogas plant is determined by the formulas:

$$W = \begin{cases} 0 & \text{with } \frac{x_1}{be} + \frac{x_2}{be} \geq Ne_0 \\ We_0 - \left(\frac{x_1}{be} + \frac{x_2}{be} \right) & \text{with } \frac{x_1}{be} + \frac{x_2}{be} < Ne_0 \end{cases} \quad (5)$$

and

$$Q = \begin{cases} 0 & \text{with } \frac{x_1}{be_h} + \frac{x_3}{be_b} \geq Qe_0 \\ Qe_0 - \left(\frac{x_1}{be_h} + \frac{x_3}{be_b} \right) & \text{with } \frac{x_1}{be_h} + \frac{x_3}{be_b} < Qe_0 \end{cases} \quad (6)$$

We consider the limitations of the parameters of the objective function. Limitations on annual biogas use will be as follows:

$$\sum_{i=1}^n x_i \leq V, \quad (7)$$

where V - annual production of biogas, m³.

The amount of thermal energy that can be produced is limited by two components. The first is the restrictions on its use for the needs of a biogas plant and the enterprise:

$$\left(\frac{x_1 \cdot T_0}{365 \cdot be_h} + \frac{x_2}{be_b} \right) < Qe_0 + Qe_f \quad (8)$$

The second limitation is due to the fact that the daily use of biogas by heat generating capacities should not exceed the productivity of a biogas plant. This condition has the following mathematical notation:

$$V \geq x_1 + x_2 + x_3 \cdot \frac{365}{T_0} \quad (9)$$

Here we do not take into account the simultaneous use of biogas to provide the enterprise with thermal energy and the replacement of biogas of diesel fuel, because they do not coincide in time.

Limitations on the replacement of diesel fuel, which uses agrarian formations, also has two components, the first one is the maximum need for gaseous fuel:

$$x_4 \leq (1 - \lambda) \cdot Md \cdot \frac{Q_0}{Q_0} \quad (10)$$

where: λ – the proportion of inflammatory dose of diesel fuel when the diesel engine is operating on the gas-diesel cycle; Md – annual requirement of the enterprise in diesel fuel, (kg).

The second one takes into account the duration and simultaneity of the work of agricultural machinery with other biogas consumers and is limited by the daily output of a biogas plant:

$$V \geq x_1 + x_2 + x_4 \cdot \frac{365}{T_{am}} \quad (11)$$

where: T_{am} - annual duration of use of agricultural machinery, (days).

Thus, the objective function (1) and the restrictions on the use of biogas in various directions are formulated. To solve this problem, a program was developed in the Excel environment using the built-in "Solution Search" function.

It is necessary to determine the optimal use of biogas from agricultural waste for a notional enterprise. The productivity of biogas plant is 40.5 thousand m^3 per year. The company buys natural gas in the amount of 4 thousand m^3 per year, as well as diesel fuel, part of which can be replaced by biogas.

The efficiency of using energy products of biogas production offered by the manufacturer of equipment for biogas plants, after the proposed improvement of the reactor and optimized variants for the conditions of the notional enterprise are shown in table 3.

Table 3

Comparison of the economic efficiency of the use of energy products of biogas production

Indicator	Option offered by equipment manufacturer	Optimized option 1	Option after the proposed improvement of the reactor	Optimized option 2
Biogas costs in different directions, (thousand m^3):				
• cogeneration plant	40.5	25.5	41.5	26.1
• gas boiler	0	6.9	0	7.1
• motor fuel	0	8.1	0	8.3
Power of cogeneration plant, (kW)				
• electric	10.0	6.5	10.2	6.6
• heat	12.0	7.7	12.3	7.9
Boiler plant power, (kW)	0	8.5	0	8.7
Annual production, (thousand kWh)				
• electric energy	82.1	55.5	84.1	56.9
• energy	89.3	45	91.5	46.1
Substituted diesel fuel, (m^3)	0.00	4.7	0	4.8
Additional investments, (thousand Euro)	19.80	24.5	20.3	25.1
Annual economic effect (value of the objective function), (thousand Euro)	7.55	9.78	7.87	10.19
Payback period, (years)	2.62	2.51	2.58	2.46

It is advisable for the enterprise to convert only part of the biogas into electric and heat energy. It is economically viable to use part of biogas as a substitute for natural gas.

It is necessary to take into account in the calculations that biogas is equal to natural gas at a coefficient of 0.6, therefore, 6.9 thousand m³ of biogas will meet 4.1 thousand m³ of natural gas, that is, the notional enterprise will be able to completely refuse to purchase natural gas. The cost of purchasing diesel fuel is growing annually, so it is advisable to partially replace it by biogas.

CONCLUSIONS

Biogas production is an important area of providing agricultural enterprises with energy resources. Simple biogas plants are recommended to be installed for small farms, which, on the one hand, are easy to operate, and on the other, have problems with the uniformity of substrate heating. In the proposed design of a biogas reactor, the problem is solved by the retrofitting of the heating element with a treatment device.

The economic indicators of using a simple biogas plant and a plant with an advanced reactor are calculated. Using economic and mathematical modelling, the optimal distribution of the energy resource based on biogas from waste was carried out. The calculations performed show that for a conditional enterprise with 30 head of cattle, 15 head of pigs, 15 head of dairy cows and 30 head of sheep, the best option is to use biogas to ensure the operation of the cogeneration plant, boiler and diesel fuel replacement, that differ from the option that the manufacturer of equipment for biogas plants offers.

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Edited by: INMA Bucharest

6, Ion Ionescu de la Brad Blvd., sect. 1, Bucharest, ROMANIA

Tel: +4021.269.32.60; Fax: +4021.269.32.73

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e-mail: inmatehjournal@gmail.com