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INCREASING OF PROCESS ENERGY EFFICIENCY OF BIOGAS PLANTS PRODUCTION PROCESSING

М.М. Максимов, В.О. Давидов, Г.В. Крусір, О.Б. Максимова. **Підвищення енергетичної ефективності процесу переробки продукції біогазових установок.** В результаті розкладання рослинної біомаси в біогазових установках виходить значна кількість такого ресурсу як зброджений залишок. Формально це цінне біодобриво, але на практиці існує безліч факторів, які можуть обмежувати його використання: сезонність в потреби, необхідність складування, істотні витрати на транспортування, необхідність попередньої обробки і т.п. Крім того, в завданню вирощування біомаси для подальшого її перетворення в електроенергію, екологічно чисті біодобрива також втрачають свою актуальність. З іншого боку, зброджений залишок має істотний енергетичний потенціал, використання якого може істотно підвищити глибину переробки вихідної біомаси в електроенергію. Проведена оцінка енергетичного потенціалу вихідної кукурудзяної біомаси та аналіз ефективності термічної обробки зброджених залишку в піролізної печі. Показано, що утилізація всіх продуктів піролізу дозволить підвищити вихід корисної енергії на 62% в порівнянні з енергетичним потенціалом виробу біогазу. Утилізація тільки пірогазу підвищує ефективність всього процесу на 38%.
Ключові слова: біогазова установка, зброджений залишок, піролізна піч

M.M. Maksimov, V.O. Davydov, G.V. Krusir, O.B. Maksimova. **Increasing of process energy efficiency of biogas plants production processing**. As a result of the decomposition of plant biomass in biogas digesters, a significant amount of such a resource as digestate is obtained. Formally, this is valuable biofertilizer, but in practice, there are many factors can limit its use. For example, seasonality in need, the need for storage, significant transportation costs, the need for pre-processing, etc. In addition, in the task of growing biomass for its subsequent transformation into electricity, environmentally friendly biofertilizers also lose their relevance. On the other hand, digestate has a significant energy potential. The use of this potential can substantially increase the depth of processing of the initial biomass into electricity. The work evaluates the energy potential of the initial corn biomass and analyzes the efficiency of the thermal treatment of digestate in a pyrolysis furnace. It is shown that utilization of all pyrolysis products will increase the yield of useful energy by 62% in comparison with the energy potential of biogas produced. Utilization of pyrogas only increases the efficiency of the entire process by 38%.
Keywords: biogas digesters, digestate, pyrolysis furnace

Introduction. In 2014 within the framework of the EU directive, the government of Ukraine decided to adopt a national plan of the action for renewable energy until 2020. Implementation of this plan on attracting institutional as well as Ukrainian investors in 2020 will increase the use of renewable energy sources in the total balance up to 11 % [1].

Bioenergy is one of the directions of renewable energy development. It examines various aspects of biomass into energy conversion - burning and pyrolysis, as well as production of biogas due to digestion. First of all, these areas are designed for the agrarian sector and industry, since the most sustainable and rapidly recoverable projects are created precisely on the basis of enterprises having own raw materials, where the fuel is waste from the main activity.

Although bioenergy technologies were originally conceived as an effective tool for waste disposal, recently there have been examples of purposeful technological growing of biomass with its subsequent transformation into biogas and production of heat and electric energy.

One of the problems of biogas production using anaerobic digestion technology is utilization of digestate. The depth of processing of the initial substrate does not exceed 80 %, and, for example, for silage corn is 50 %.

Theoretically, the digestate is an effective organic fertilizer. It balances the acid-base balance of the soil, contributing to its less exhaustion. Unlike mineral fertilizers, which are absorbed by only 35…50 %, biofertilizers are absorbed almost completely. Biofertilizers do not increase the nitrate con-

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tent in products and soil, while maintaining a high yield. As practice of foreign countries shows, when using liquid or solid biofertilizers, the yields increase by 40…50 %. The consumption is from one to five tons instead of 60 tons of fresh manure for 1 hectare of land.

In practice, all the positive characteristics of biofertilizers, as part of the production of BM energy, lose their attractiveness. If the task is to burn BM for the production of organized energy flows (electricity, gas), then the problem of accumulating nitrates in it loses its relevance. In addition, in order to take the fertilizer to the fields it is necessary to spend fuel and to apply special equipment. Recall that if the rate of manure application is 50…60 t/ha, biofertilizers – 1…5 t/ha, then mineral fertilizers are introduced in an amount of 150 kg/ha. All this leads to the fact that even if the owner has biofertilizer as a by–product of biogas production, exporting it to the fields economically has the maximum distance of expediency, which depends on many factors. In addition, there are few interested in buying biofertilizers of enterprises oriented to the production of agricultural crops, since the positive effect of transportation of biofertilizers and their export to fields disappears at the 10…20km line.

Analysis of the Ukrainian fertilizer market shows that the compound NPK fertilizer can be purchased on average for 10000 UAH/ton. Liquid biofertilizer will cost 35000 UAH per 1000 liters, and a solid biofertilizer will cost 5400 UAH per 1000 liters. Although liquid biofertilizer is usually a concentrate, which before dilution into the soil is diluted with water in a proportion of 1:50, the cost of mineral fertilizers will be lower. So the treatment of one hectare by mineral fertilizer on average will cost the owner 1500 UAH. Liquid fertilizer – 3500 UAH. Solid fertilizer – 13500 UAH.

Another important aspect of the production of biofertilizer is its apparent seasonal nature of consumption. It means that in off-season fertilizer has to be collected and stored and it leads to additional costs.

Thus, when converting biomass into energy by anaerobic digestion, the task of finding technology for economically feasible utilization of digestate arises.

Analysis of literary data and formulation of the problem. Today, the leading producers of biogas digesters, as the main method of CO disposal, use it as a fertilizer [2]. This approach has a number of shortcomings:

– CO cannot be used directly as a fertilizer, it requires preparatory processing (dewatering, separation into liquid and solid fractions, dilution with water);

– any fertilizer is claimed seasonally and requires storage rest of the time;

– for applying biofertilizers to fields, both for liquid fraction and for solid, special equipment is required;

– the cost of transporting biofertilizer over a distance of more than 10 km may in some cases exceed the economic effect of its use.

Therefore, recently there has been an increase in research in the field of alternative methods of CO utilizing. The results of a study of CO use as a raw material for compost are presented in [3]. It is shown that the storage of CO as a fertilizer is associated with the loss of nitrogen. Mixing bio fertilizer with phosphate fertilizer will protect the nitrogen component.

During work [4], there is a great potential for using a solid fraction as a food additive for livestock.

It is proposed in [5] to use pyrolysis technology for pyrocarbon production. This approach seems to be the most promising, as it allows to increase the output of fuel from a biogas digesters, and thus potentially increase the yield of thermal and electrical energy.

If we consider a biogas digesters as a source of fuel for a gas power plant, then it would be more logical to direct efforts to increase the yield of the gas component. This would improve the efficiency of the process on existing equipment. Taking into account that the technology of pyrolysis of organic nature substances (basic products in CO) has been sufficiently worked [6] and allows to control the yield of gas, liquid and solid components, the most promising is the use of pyrolysis for maximum extraction of CO from the gas component.

Purpose and objectives of the study. The purpose of this paper is to analyze the efficiency of the digestate combustion process from biogas digesters in a pyrolysis furnace. This approach should lead to the appearance of an additional gas component, as well as a certain amount of charbon and resin, which potentially will provide additional heat and electricity.

To achieve the purpose, the following tasks were identified:

– assess the energy potential of the initial substrate and efficiency of its transformation using methane digestion technology;

– evaluate chemical composition of digestate;

– estimate the energy potential when digestate is burned in a pyrolysis furnace with the maximum output of the gas component;

– analyze the energy efficiency of the whole process.

Table 1

Data on the sowing and harvesting of corn by years in the Odesa region

Year	Sowing, April	Harvesting, September	Period, days
1985	19	20	154
1986	27	22	148
1987	21	22	154
1988	19	8	142
1989	17	11	147
1990	19	11	145
1991	19	18	152
1992	21	15	147
1993	22	15	146
1994	18	14	151
1995	24	7	136
1996	23	19	149
1997	21	8	140

Materials and methods for studying the control system of the technological section of steam generation.

1. Energy potential of the initial substrate.

One of the main sources of biomass for biogas production is silage corn.

On average, the corn vegetation period is 147 days.

We estimate the amount of insolation of the photosynthesis bound by the reaction and accumulated in corn during this period. For an example, we consider the statistical value of the mean solar insolation for Odesa [7].

Table 2

Data of the mean solar insolation for Odessa, mJ m^2/day

month	January	Feb.	March	April	May	June	July	August	Sept.	October	Nov.	Dec.	year
Odesa	4.50	7.60	11.09	15.77	20.34	21.06	21.74	19.19	14.15	9.07	4.90	3.74	12.78

We will take into account that the average efficiency of the process of photosynthesis for agricultural crops is 3 %. Then, using the data of Table 3, we find that there are 2885.36×10000×0.03=865 GJ per 1 hectare of cultivated area.

On average, from one hectare, 15 tons of dry corn are obtained [13]. From one ton of corn BM, a maximum of 451.3 m^3 of biogas can be obtained with a methane content of 52 % [8]. The calorific value of such gas according to Mendeleyev's formula is 18.7 MJ/m^3. With 1 hectare we get 15×451.3=6769.5 m^3 of biogas. When it is disposed of, a total of 6769.5×18700000=127 GJ will be produced. Taking into account that the maximum efficiency of gas power plants (combined-cycle plants) reaches 60 %, more than 21.000 kWh of electricity can potentially be produced from the produced gas.

Thus, the process of obtaining biogas from corn BM by means of anaerobic digestion allows us to extract and use up to 9 % of the energy contained in it.

In fact, this figure can be much smaller. Despite the active introduction and use of biogas digesters, the mathematical apparatus for describing the output of biogas is poorly developed. It is impossible to accurately calculate in advance the depth of the decomposition of BM, the specific output of biogas and its composition, depending on the chemical composition of the raw materials, the composition of the microbiological consortium for methane digestion, etc. The number of control actions af-

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Table 3

Calculation of the total specific insolation

Month	Amount of days	Specific insolation, $mJ \cdot m^2$/day	Total insolation, $mJ \cdot m^2$/day
April	9	15.77	141.91
May	31	20.34	630.54
June	30	21.06	631.80
July	31	21.74	674.06
August	31	19.19	594.83
September	15	14.15	212.22
Total			2885.36

fecting the process technology is very limited. Typically, this is temperature, pH of the medium, temperature gradient and rate of change in the temperature inside the reactor, degree of hermeticity of the reactor, feed rate to the reactor and fresh portion of raw materials size, cut-off frequency, frequency and duration of the substrate mixing cycles inside the reactor. The natural factors are described by the set of possible parameters. The only species of bacteria involved in the process can be more than a thousand, and there is still a chemical composition and physical condition of the raw material.

It's almost impossible to calculate everything. For a long time, a stoichiometric approach was used to calculate the theoretically possible yield of biogas as a result of complete decomposition under ideal conditions [9]. In fact, the output of biogas is much smaller. Therefore, in the design of biogas digesters, experimental results are obtained using laboratory facilities simulating the required technical process in miniature. The statistics of large biogas digesters are also collected. Statistics are processed, grouped, and as a result, tables of recommended process parameters and approximate output parameters are obtained when different types of raw materials are used. But the spread in these tables is up to 50 %. Therefore, it is possible to predict, for example, the daily yield and biogas composition for the biogas digester being designed with exactly this accuracy. For example, according to various data, the output of biogas from a ton of corn substrates varies from 187 m^3/t to 550 m^3/t [8].

Nevertheless, the simplest calculations will allow us at least estimate the boundaries of the output of biogas, especially the upper one. We carry out a similar calculation and estimate the chemical composition of the digestate.

2. Evaluation of the digestate chemical composition.

Calculated as a dry weight, the original corn BM has the following composition:

–74.43 % starch ($C_6H_{10}O_5$);

–14.5 % protein ($NH_2 - CH_2 - COOH$);

–9.4 % fat ($C_{15}H_{31}COOH$);

–1.67 % mineral salts.

We determine the molar masses of the constituents.

$$M(C_6H_{10}O_5) = 72M(C) + 10M(H) + 80M(O) = 162 \text{ g/mol.}$$

$$M(NH_2 - CH_2 - COOH) = 24M(C) + 5M(H) + 32M(O) + 14M(N) = 75 \text{ g/mol.}$$

$$M(C_{15}H_{31}COOH) = 192M(C) + 32M(H) + 32M(O) = 254 \text{ g/mol.}$$

The molar masses of water, carbon dioxide, ammonia and methane are respectively equal to: 18, 44, 17 and 16 g / mol.

Calculated as 1 ton of raw material, we get:
starch – 744 kg;
protein – 145 kg;
fat – 94 kg.

The content of mineral salts is neglected due to their low concentration.

Let's calculate the number of moles of each component.

Starch: 744.3×1000/162 = 4594.4 mol.
Protein: 145×1000/75 = 1933.3 mol.
Fat: 94×1000/254 = 370.08 mol.

Total 1 ton of corn BM is:

$$4594.4\, C_6H_{10}O_5 + 1933.3\, NH_2 - CH_2 - COOH + 370.08\, C_{15}H_{31}COOH = C_{37354.59}H_{67454}O_{27579}N_{1933.3}.$$

To determine the stoichiometric yield of biogas, we use the formula [10]:

$$C_nH_aO_bN_d + \left(n - \frac{a}{4} - \frac{b}{2} + \frac{3d}{4}\right)H_2O \xrightarrow{\text{bacteria}} \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3d}{8}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4} + \frac{3d}{8}\right)CO_2 + dNH_3, \quad (1)$$

We put the data in (1) and obtain the theoretical yield of biogas at full decomposition under ideal conditions:

$$C_{37354.59}H_{67454}O_{27579}N_{1933.3} + 8151.7\ H_2O = 19489.2CH_4 + 17865.4CO_2 + 1933NH_3.$$

Calculated as kg, we get: 984.040 kg of corn BM+146.730 kg of water=311.828 kg of methane+786.076 kg of carbon dioxide+32,867 kg of ammonia.

In practice, the yield of biogas is much smaller. According to [8], from an average of 1 ton of corn substrate, 451.3 m^3 of biogas comes out at 52 % methane, which corresponds to 237.384 kg of methane and 213.916 kg of carbon dioxide, i.e. depth of processing is 54 %. Therefore, we assume that the actual yield will be described by a generalized chemical formula: $C_{20245.5}H_{45671.2}O_{19221}N_{1044}$.

We assume that 54 % of the initial nitrogen contained in the substrate went to the construction of protein compounds of the bacteria themselves and will be deduced from the digestate in the form of a liquid fraction. Then the solid residue can be described by expression:

$$C_{17109.1}H_{21782.5}O_{8358}N_{889.3}.$$

For convenience, in Table 4 there are given data on the change in the elemental composition of the feedstock and products obtained during the methane digestion process of 1 ton of corn substratum.

Table 4

Elemental composition of raw materials and products in the process of methane fermentation calculated as 1 ton of raw materials

Elements	Number of elements, mole				Weight, kg
	C	H	O	N	
Corn	37354.6	67453.6	27579	1933.3	984
Water	–	16303.3	8152	–	146.7
Initial substrate	37354.6	83757	35731	1933.3	1130.8
Main products including	20245.5	45671.2	19221	1044	610.8
– methane	10634.8	42539.2	–	–	170.2
– carbon dioxide	9610.67	–	19221	–	422.9
– ammonia	–	3132	–	1044	17.7
Digestate	17109.1	38085.8	16509	889.3	520
Digestate after drying	17109.1	21782.5	8358	889.3	373.3

We analyze the energy potential of this mixture from the point of view of its further processing in a pyrolysis furnace.

3. Energy potential of digestate when it is burned in a pyrolysis furnace.

Along with direct burning and gasification, pyrolysis is an effective method of thermochemical processing of biomass, industrial and household waste, and at the same time one of the least developed technologies for biomass energy use [11]. Pyrolysis is a process of thermal decomposition of organic compounds without access to oxygen and occurs at relatively low temperatures (500…800 °C) in comparison with the processes of gasification (800…1300 °C) and combustion (900…2000 °C).

The biomass pyrolysis reaction can be represented as follows: biomass + heat = C (carbonaceous matter) + resins + CO + CO_2 + H_2 + H_2O + CH_4 + C_nH_m. Primary products can be liquid, solid carbonaceous matter and gases, depending on the type and parameters of the pyrolysis process, secondary ones – energy, fuel and chemical products.

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Liquid pyrolysis products (“oils”, “pyrofuel”, “biofuels” or “resins”) in irreversible form represent a dense black resinous liquid, the yield of which can reach up to 80% of the mass of dry raw materials (with rapid low–temperature pyrolysis). Pyrofuel can be used as a substitute for boiler fuel (in gas turbines and diesel units).

The pyrolysis solid product is a carbonaceous substance ($Q^{р}_{н}$ = 30 MJ/kg), whose yield can reach 30…35 % of the mass of dry raw material during carbonization and slow pyrolysis, which can be used as fuel for household fireplaces, as well as for technological needs of the industry metallurgical, electric, pharmacological, water purification and gases).

Gaseous pyrolysis products are a medium-calorie gas ($Q^{р}_{н}$ = 15–22 MJ/kg), or low-calorie gas ($Q^{р}_{н}$ = 4–8 MJ/kg), in case of partial gasification. The yield of gaseous fuel reaches up to 70 % of the dry raw material mass during high–temperature rapid pyrolysis. The composition of the gas depends on the raw materials and process parameters. Such gas is usually used in the pyrolysis process itself to maintain the process temperature and to dry the row materials.

Chemical products of pyrolysis are several hundred chemical constituents. The possibility of extracting individual chemical products opens up wide opportunities in obtaining additional combustion components.

Modern technologies of BM pyrolysis are divided according to the following characteristics (Table 5): rate, heating (fast, slow pyrolysis), medium in which pyrolysis takes place (vacuum, hydropyrolysis, methanopyrolysis).

Table 5

Characteristics of the main pyrolysis technologies

Characteristics	Fast pyrolysis, low temperatures	Fast pyrolysis, high temperatures	Slow Pyrolysis
Process time	1 s	1 s	5…30 min
Size of raw material	small	small	average
Humidity of raw materials	very low	very low	low
Temperature, °C	450…600	650…900	500…700
Pressure, kPa	100	10-100	100
Gas:			
yield, % mass of dry raw material	Up to 30	Up to 70	Up to 40
heat of combustion, MJ/Nm3	10…20	10…20	5…10
Liquid:			
yield, % mass of dry raw material*	Up to 80	Up to 20	Up to 30
calorific value, MJ/kg	23	23	23
Solid:			
yield, % mass of dry raw material	Up to 15	Up to 20	20…30
calorific value, MJ/kg	30	30	30

We assume that using the technology of fast pyrolysis, the percentage composition of pyrolysis products (gas, tar, coal) will be 70, 15 and 15 %.

Then:

gas composes 0.7×373.3=261.31 kg or 261.31/1.2=217.7 nm^3;

resin 0.15×373.3=56 kg;

coal 0.15×373.3=56 kg.

Let's take the average heat of combustion of the resulting biogas equal to 15 MJ/Nm^3. Then the energy potential of pyrolysis products will be:

gas 217.7×15000000=3.27 GJ;

resin 56×23000000=1.29 GJ;

coal 56×30000000=1.68 GJ.

In total we receive 6.2 GJ.

We will take into account that 15 tons of initial material are collected from one hectare. Then the total yield of energy obtained in the pyrolysis furnace is 6.2×15=93.5 GJ. Of these, 49 GJ are accounted for by the gas component.

Thus, by exposing the digestate to a pyrolysis furnace, it is possible to increase the energy yield by 93.5/127=73 %. Utilization of only the gas component on the existing equipment will increase the energy output by 49/127=38 %.

In reality, the estimates obtained will be lower, since the amount of useful energy is determined by the efficiency of the installation at which the conversion of fuel energy to electrical energy occurs. So gas generators have an efficiency of up to 60 %, and thermal ones up to 40 %.

It should be specially noted that, despite the increased attention to the technologies of thermal conversion of biomass in recent decades, there are no mathematical models and results of their use for describing the processes of slow or rapid pyrolysis of biomass, even in small ranges of changes in basic technological parameters. Such a state of the theory of the processes under consideration is most likely due to the lack of experimental data sufficient for constructing mathematical models of pyrolysis and their subsequent use for predictive modeling of the results of thermal conversion technological cycles of wood biomass (primarily in bioenergy).

Based on the analysis and generalization of the results obtained earlier on the regularities of the regulated thermal decomposition of digester biomass, the following conclusions can be drawn.

1. It is established that for the group of specific materials studied the composition of pyrolysis products depends on the heating conditions (temperature and rate of its growth) in an inert atmosphere
2. Fast heating leads to an increase in the fraction of solid residue in pyrolysis products.
3. The main experimental data on the dependence of the share of solid, liquid and gaseous products of pyrolysis on the temperature and the heating rate are obtained for agricultural waste (barley, rice, wheat, straw, corn stalk, pomegranate seeds, cotton waste, sugar cane squeezes, etc.).
4. The results of generalizations of experimental data that would allow making an informed conclusion about the similarity (or similarity) of the mechanisms of thermal decomposition of different types of digester biomass and, accordingly, the dependences of the composition of pyrolysis products on temperature and the rate of its change, are not published.
5. Relationship between the yield of pyrolysis products and the structure or parameters of digester biomass, characterizing its composition or structure, has not been established.
6. There are no results of theoretical studies of the processes of both slow and fast pyrolysis of digester biomass under conditions of an inert atmosphere.
7. Optimal technological parameters for the implementation of specific technologies (thickness of the layer of ground vegetative biomass, temperature, heating rate, holding time, heat fluxes to the pyrolysis zone, conditions for diversion of products, etc. have not been established.

Results of the energy efficiency analysis of the whole process. In Fig. 1 there is presented the generalized structural scheme of cogeneration complex of electricity-oriented deep digestate processing.

As a rule, such complexes have a modular structure. The specific composition of the complexes depends on the individual needs of the customer.

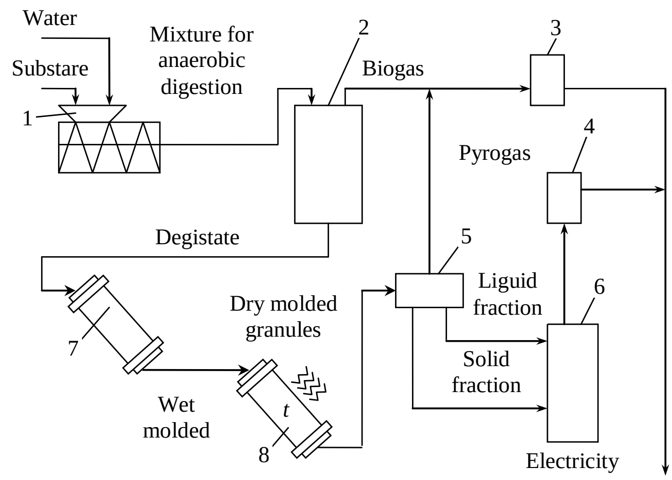

Fig. 1. General structural scheme of cogeneration complex of deep digestate processing: screw mixer (1); reactor-methanthenic (2); gas generator (3); electric generator on black oil (4); pyrolysis furnace (5); module for the production of heating oil (a s.ubstitute for fuel oil) (6); drum granulator (7); drum dryer(8)

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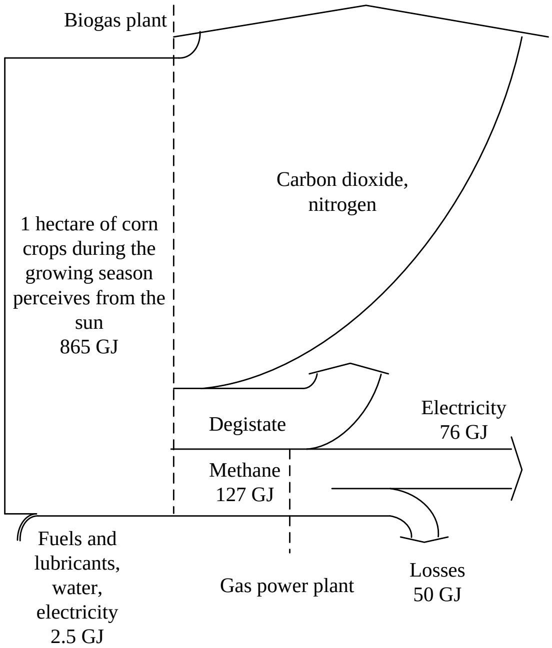

Fig. 2. Diagram of energy flows in a biogas digester

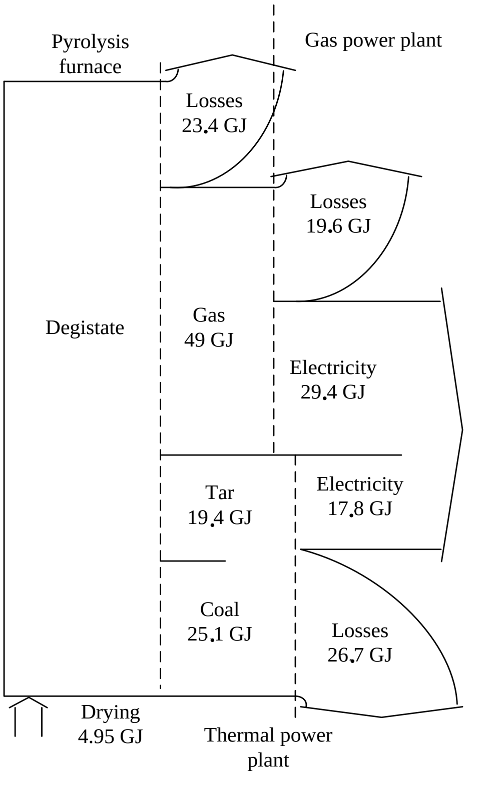

Fig. 3. Diagram of energy flows in a pyrolysis plant

Typical modules can be oriented to:

– generation of electrical and/or thermal energy;

– production of synthesis gas;

– production of methanol;

– gas accumulation;

– rectification of the liquid fraction into fuel products;

Cracking of the liquid fraction into the gas;

– gasification of the solid residue;

– production of activated carbon;

– manufacture of heating oil;

– production of carbon black;

– production of carbonic acid.

The proposed scheme allows to maximize the output from the pyrolysis furnace of the gas component.

In Fig. 2 there is shown a diagram of energy flows in a biogas digester. The diagram corresponds to the process of processing 15 tons of dry matter collected from one ha of cultivated area. As noted earlier, growing and harvesting of the original corn BM requires an average of 146 days. During this period, BM perceives from the sun an average of 865 GJ of energy. Additional costs for combustive and lubricating materials, water and electricity are 2.5 GJ or 0.3 % of the energy intensity of the raw materials.

We consider a biogas cogeneration digester, oriented to the production of electricity with an output electric power of 2 MW.

In Fig. 3 there is shown a similar diagram of energy flows in a pyrolysis plant.

Preliminary digestate must be granulated and drained. This will require 4.95 GJ or 5.3 % of the energy consumption of digestate. After processing of all the digestate received from the biogas plant, the shares of energy intensity of pyrogas, resin and coal will be 52, 21 and 27 % of the energy intensity of digestate, respectively. After the utilization of the pyrogas, 29.4 GJ or 8165 kWh of useful energy will be received, which is 3.4 % of the energy intensity of the feedstock. In this case, the yield of the useful energy of the whole process is 12.2 %, i.e. will increase by 38 % in comparison with the utilization of biogas only.

Further increase in the depth of processing is possible in the synthesis of furnace fuel from resin and coal residues obtained during pyrolysis. The energy content of this fuel is 44.5 GJ or 5.1 % of the energy intensity of the feedstock. Its utilization will additionally provide 17.8 GJ or 4945 kWh of useful energy, which is 2 % of the energy intensity of the feedstock. The yield of the useful energy of the whole process is 14.2 %, i.e. will increase by 62 %.

Thus, the use of pyrolysis technology for processing digestate will increase the yield of useful energy by 38 % in case of utilization of only the gas component, and by 62 % in the case of utilization of all pyrolysis products.

In Fig. 4 there is given a diagram showing the ratio of costs and revenues using the technology of deep processing of biogas digesters products (BDP). The data are also given for 1 ha of cultivated area. The costs of growing and harvesting are taken from the maize cultivation process sheet [12]. Maintenance of biogas digesters costs on average 4 % of the cost of the plant. The cost of considered biogas digesters with a capacity of 2MW is 10 million euros. 10.5 hours of installation will cost to the owner in 15139 UAH.

It should be recalled that this is the time required for the plant for the utilization of biogas obtained from 1 hectare. With the current green tariff for electricity, which is 5.28 UAH/kWh, the sale of electrical energy, produced on biogas digester will bring to the owner 111760 UAH. The profitability of the process is 600 %.

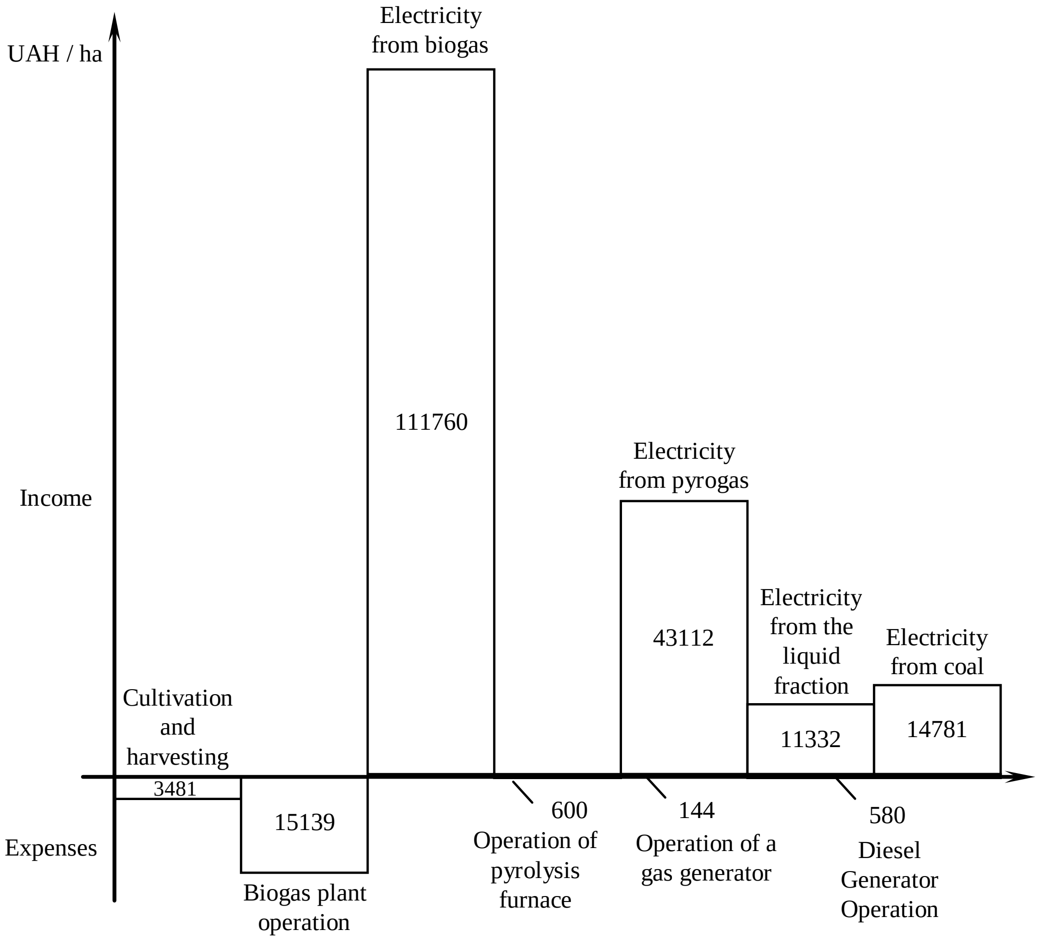

Fig. 4. Cost-benefit ratio in biogas digesters deep processing technology

It was shown in that the average cost of operation and maintenance of electric generating sets is 10% of the cost of installation for one life cycle. The average life cycle is 100.000 hours. The calculations showed that the average costs for the utilization of CO in the pyrolysis furnace, gas and diesel electric generators will be 600 UAH, 144 UAH and 580 UAH, respectively. At the same time, as before, we consider the residue obtained by processing the feedstock collected from 1 hectare.

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For the extra electricity, you can get 69225 UAH, which is 62 % of the income from the sale of biogas only. At the same time, the profitability of the process increases up to 900 %.

Discussion of technology for deep processing of biogas digesters. The proposed technology allows solve the problem of utilization of biogas plants digestate.

As practice shows, owners of biogas digesters in Ukraine are faced with a situation where there is no demand for biofertilizer or its export to the field for a number of reasons becomes unprofitable. Since fertilizer is in principle in demand only during the ripening period of plants, the use of digestate as a fertilizer automatically implies the need for its collection and storage rest of the time. This means the need to create specially equipped warehouses.

In some countries, the limits for the entry of various substances into the soil are strictly regulated. Therefore, the storage location of the CO should exclude the percolation of the residue into the ground. It should also eliminate the dilution of the remainder by rain. Given that the fermentation processes continue in CO and carbon dioxide and methane are released, the warehouse should be well ventilated.

If, however, the pyrolysis furnace is added to the complex of technical means, it is possible to significantly increase the processing depth of the initial BM and increase the yield of useful energy by 65 %. Given that the pyrolysis process is well manageable, potentially a whole range of secondary products can be obtained from digestate. In this paper, we consider a variant of the maximum production of the gas component. This will allow us to generate additional power for existing equipment. The installation of a diesel generator will also allow the utilization of furnace fuel that can be obtained by mixing the liquid and solid fractions produced at the outlet of the pyrolysis furnace.

Abstracts.

1. Corn biomass accumulates an energy potential of 865 GJ on average during the growing season. In the process of anaerobic digestion, up to 50 % of the original biomass is processed. After the utilization of biogas, 8.8% is converted into a useful electric power.

2. The chemical composition of digestate was evaluated. It can be described by expression $C_{17109.1}H_{21782.5}O_{8358}N_{889.3}$ Basically it is a mixture of cellulose, hemicelluloses, low-molecular carbohydrates, proteins and lignin.

3. Thermal treatment of digestate in a pyrolysis furnace and subsequent utilization of pyrolysis products in appropriate power plants will additionally yield 47.2 GJ of useful energy, including:

– from the pyrogas 29.4 GJ;
– from resin 7.7 GJ;
– from carbon 10 GJ.

4. Application of the proposed technology for deep digestate processing will increase the yield of useful energy by 62 %. In this case there will be no need to store and store the digestate. Also, potentially there will be an opportunity in the subsequent reorientation of production for the production of a number of products in demand in various industries. It can be the production of synthesis gas, heating oil, activated carbon, carbon dioxide, a sorbent to collect oil products from the surface of the earth and water, etc.

Thus, the proposed technology is a worthy alternative to using digestate as a fertilizer.

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