ARCHITECTURE CIVIL ENGINEERING ENVIRONMENT
The Silesian University of Technology No. 4/2020

doi: 10.21307/ACEE-2020-036

MODELING OF ENVIRONMENTAL-ENERGY EFFICIENCY OF THE BIOGAS INSTALLATION WITH HEAT SUPPLYING OF THE BIOMASS FERMENTATION PROCESS

Georgiy RATUSHNIAK [a], Yuriy BIKS [b], Olena LYALYUK [c], Olga RATUSHNYAK [d], Andriy LYALYUK [e]

[a] PhD, Prof.; Department of Engineering Systems in Construction, Vinnytsia National Technical University, Voiniv Internatsionalistiv, 7. Vinnytsia, 21000 Ukraine
*E-mail address: *ratusnakg@gmail.com*

[b] PhD, Assosiated Prof.; Department of Construction, Architecture and Municipal Economy, Vinnytsia National Technical University, Voiniv Internatsionalistiv, 7. Vinnytsia, 21000 Ukraine
*E-mail address: *biksyuriy@gmail.com*

[c] PhD, Assosiated Prof.; Department of Construction, Architecture and Municipal Economy, Vinnytsia National Technical University, Voiniv Internatsionalistiv, 7. Vinnytsia, 21000 Ukraine
*E-mail address: *lyalyuk74@gmail.com*

[d] PhD, Assosiated Prof.; Department of Enterprise Economics and Production Management, Vinnytsia National Technical University, Khmelnyts'ke shosse, 95. Vinnytsia, 21000 Ukraine
*E-mail address: *ogratushnyak@gmail.com*

[e] Master's student; Department of Construction, Architecture and Municipal Economy, Vinnytsia National Technical University, Voiniv Internatsionalistiv, 7. Vinnytsia, 21000 Ukraine
*E-mail address: *1b16b.lyalyuk@gmail.com*

Received: 3.05.2020; Revised: 8.10.2020; Accepted: 9.10.2020

Abstract

The determinants of profitability and environmental friendliness of bioconversion are noted in the paper. As one of the major factors the reduction of thermal energy costs for the fermentation of organic wastes in their utilization is proposed to take into consideration. The expediency of using renewable energy sources for thermal stabilization of the fermentation process, especially in the thermophilic mode of organic fermentation, is emphasized. The energy efficiency biogas installation with structural and technological scheme is given as an example. It receives thermal energy to increase its efficiency from a solar collector and a heat pump. It is proposed to evaluate the energy efficiency of a biogas plant taking into account the cost of bioconversion products and the costs of providing this process. A mathematical model was proposed to substantiate the environmental-economic efficiency of a biogas installation with the minimum energy costs for the thermal stabilization of the biomass fermentation process. The model is based on fuzzy set theory which uses linguistic variables. Linguistic variables take into account the influence of quantitative and qualitative factors on the objective function.

Keywords: **Biogas installation; Biomass; Eco-energy efficiency; Fermentation; Fuzzy logic; Renewable energy sources; Thermal stabilization.**

1. INTRODUCTION

Sustainable development of society implies the greening of the industrial process in solving the problem of preserving the natural environment. The introduction of biogas technologies allows reducing waste and increasing production intensification by utilizing organic waste, to maintain ecosystem balance. This is achieved through the production of gaseous energy and high quality organic fertilizers to maintain soil fertility. The clean power of solar, wind and bioelectric power installations in Ukraine allows producing over 8.4 billion kilowatt-hours of electricity annually [1]. This will reduce over 9 million tons of greenhouse gas emissions [2]. The profitability and environmental friendliness of biogas installations is determined by the energy costs of the fermentation process under optimal thermal stabilization conditions [3].

The fermentation of biomass, depending on the temperature interval can be carried out in cryophilic, mesophilic and thermophilic modes of digestion [4]. The cryophilic regime of biomass digestion takes place at a temperature of the medium T = 10–20°C and does not require additional consumption of thermal energy. It flows slowly, does not provide high productivity of biogas production, so it is used in the warm season. The mesophilic fermentation process takes place at a temperature T = 25–45° and requires structural and technological measures to maintain a stable temperature regime in the biogas installation. The maximum amount of biogas, when reduced almost twice as long as it is in the biogas reactor, than in the mesophilic one, is provided by the thermophilic fermentation regime at a temperature T = 45–55°C [3, 4]. Providing this mode of fermentation requires additional heat supply, including the compensation for heat losses.

An environmental-energy efficient means of providing thermal stabilization of the fermentation process in the utilization of organic waste is the use of renewable sources of solar energy and low potential heat energy in bioconversion systems. The environmental-energy efficiency of using bioconversion can be ensured by the use of structural and technological schemes of combined biogas installations with the system of heat providing thermal stabilization of the organic waste fermentation process. The biogas installation receives heat from the solar collector and the heat pump. The low-potential energy of the pump is the thermal emissions of waste biomass [3].

2. LITERARY ANALISYS AND PROBLEM STATEMENT

The growing scarcity of energy resources and the exacerbation of environmental pollution by organic wastes of the agro-industrial complex are pushing for the introduction of biogas installations to obtain an alternative source of energy – biogas and environmental fertilizers [1]. The share of bioenergy in the total of renewable energy sources in Ukraine does not exceed 20% [1, 7, 10] and tends to increase gradually.

According to the results of theoretical and experimental studies of ways of increasing, the energy efficiency of biogas installations [10, 11, 13], the expediency of using solar energy and other renewable energy sources for heat supply of the process of fermentation of organic substances has been revealed. Several authors [1, 11, 14] have proposed energy-saving designs of biogas installations with alternative sources of energy for thermal stabilization of the methane formation process. Physical and mathematical modeling methods substantiate the feasibility of improving the design and technological solutions of biogas installations [15–18].

Environmental-economic evaluation of the bioconversion performance implementation by energy criterion was investigated in [11, 15, 19]. But it was made without considering the use of alternative energy sources for the heat supply of the biomass fermentation process, by taking into account the dynamic environment of the project.

Various mathematical methods (statistical, analytical, analogues, expert evaluations, fuzzy logic and artificial neural networks) have been used to evaluate the efficiency of biogas plants [3, 4, 6, 12, 14, 20, 21, 24, 25, 26]. According to the results of existing literary sources analysis, no mathematical models were found for substantiation of environmental-energy efficiency of the installation with renewable energy sources of heat supply by means of biomass fermentation technological process with quantitative and qualitative factors of alternative energy sources.

Over the last 20 years, interest in the modeling processes using fuzzy logic in the field of renewable energy has only increased [20, 25, 26]. In the field of bioenergy, this trend is not as noticeable as in the field of wind, solar and other renewable energy sources, as evidenced by the analysis of the data shown in Fig. 1 [26].

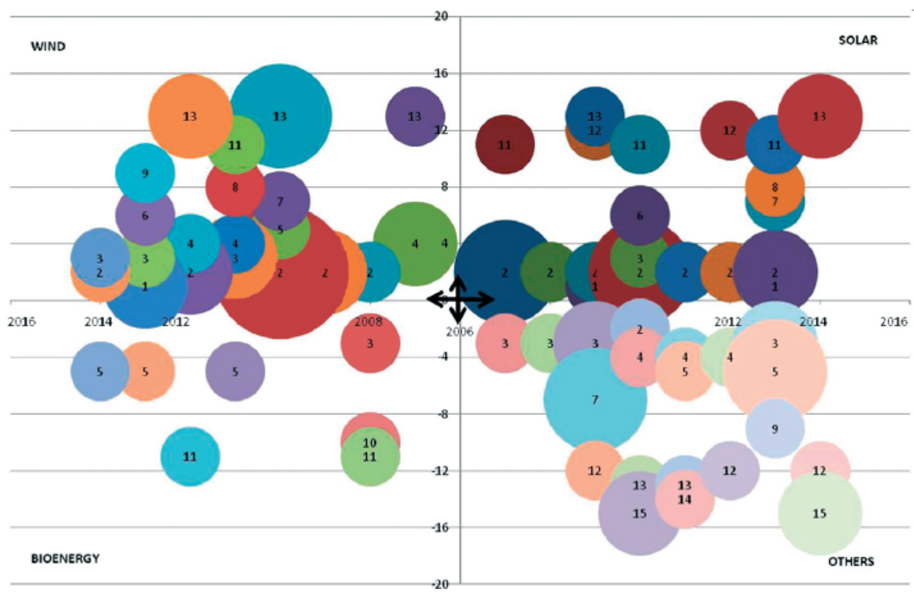

Figure 1.
Extent of fuzzy based research in renewable energy modeling. "x" axis – denotes year; the origin is [2006,0]. "y" axis – denotes the techniques in increasing complexity. The techniques are 1 – fuzzy regression, 2 – neuro-fuzzy, ANFIS, 3 – fuzzy AHP, ANP, 4 – fuzzy clustering, 5 – fuzzy optimization, 6 – neuro-fuzzy DEA, 7 – fuzzy GA, 8 – neuro-fuzzy GA, 9 – fuzzy expert, 10 – neuro-fuzzy expert, 11 – fuzzy MCDM, 12 – fuzzy TOPSIS, VIKOR, 13 – fuzzy PSO, 14 – fuzzy honey bee optimization, 15 – fuzzy PSO, QPSO, Cuckoo optimization.
Note: the number inside the bubble indicates the technique and size of the bubble indicates the no. of research publication

Supporting the authors thesis [26], it can be noted that the use of mathematical modeling based on the fuzzy logic is mentioned in various fields of bioenergy research papers, in particular related to biogas plants. Thus, fuzzy logic is successfully used in modeling the yield of biogas [3, 25, 31], for the management decisions support system [27], for prediction of biogas production [28], for a comprehensive environmental-economic assessment of the process of anaerobic fermentation food waste [29], etc.

It should be noted that the use of fuzzy logic for the biogas production process prediction has a high correlation with experimental data. For example, the authors of the study [31] obtained a high value of the coefficient of determination $R^2 = 0.98$ in modeling of the biogas yield kinetics. Turkdogan-Aydınol, F. I. when have modelled the yield of biogas and methane in his research [25] obtained $R^2 = 0.98$ for the fuzzy model, while for another model (regression analysis) this value was lower in both cases: $R^2 = 0.87$ for biogas and $R^2 = 0.89$ for methane, respectively.

The results of the conducted analysis [1, 3, 6, 8, 10, 13, 16, 17, 21, 26, 29] indicated the feasibility of mathematical models developing to substantiate the complex criterion of biogas installations environmental-energy efficiency. In particular, biogas plants with renewable energy sources for heat supply of the biomass fermentation process is mentioned. Therefore, in this article the authors proposed a mathematical model to substantiate the environmental-energy efficiency of a biogas installation. This model allows to take into account quantitative and qualitative factors which affects the thermal stabilization of the biomass fermentation process.

Meanwhile, the environmental-economic efficiency of the innovative bioconversion project could be determined as the minimal total cost of implementing the technological process of this project, i.e.

$$\sum S = \left(\sum S_c + \sum S_o - \sum S_d - \sum S_s\right) \rightarrow \min, \qquad (1)$$

where $\sum S_c$, $\sum S_o$ – the capital and operating costs

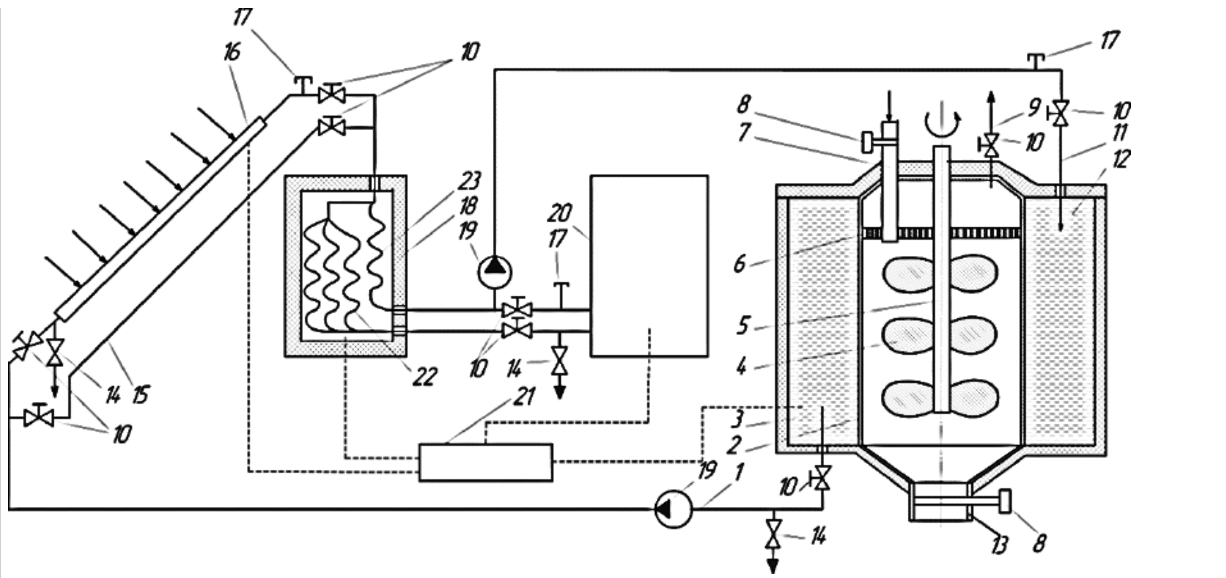

Figure 2.
Biogas installation with combined system of heat supply for thermal stabilization of the bioconversion process [3]

for the implementation of the bioconversion project;

$\sum S_d$, $\sum S_s$ – the profit from the reduction of compensation for environmental damage and from the sale of bioconversion products, respectively.

The most variable parameters of the bioconversion project are the operating costs to ensure the technological process of biogas production, i.e.

$$\sum S_o = \left(\sum S_m + \sum S_r + \sum S_u + \sum S_i + \sum S_t\right) \rightarrow \min, \quad (2)$$

where $\sum S_m$, $\sum S_r$, $\sum S_u$, $\sum S_i$, $\sum S_t$ – the maintenance costs for service personnel, raw materials, utilization of raw materials, intensification of biomass fermentation and thermal stabilization of the fermentation process, respectively.

The cost of thermal stabilization of the fermentation process could be defined as

$$\sum S_t = S \cdot \sum S_T \rightarrow \min, \quad (3)$$

where: S – the energy costs;

$\sum S_T$ – the total energy consumption for thermal stabilization.

Analysis of formulas (1), (2), (3) shows that increasing the environmental-energy efficiency of bioconversion processes can be achieved by reducing the cost of thermal stabilization of the biomass fermentation process. One of the ways to reduce these costs is to use renewable energy sources [11].

3. PURPOSE AND TASKS OF RESEARCH

One of the reasons for the insignificant implementation of innovative energy-saving biogas plants in Ukraine climate is the high energy consumption of bioconversion processes. As well the insufficient study of intensification means of organic agro-industrial waste fermentation also could be mentioned [10, 11, 13]. It should also be mentioned that there is lack of methodology to substantiate the effectiveness of the renewable energy sources used for thermal stabilization of biomass fermentation processes. The aim of the present paper is to develop a mathematical model to substantiate the environmental-energy efficiency of a biogas installation with renewable energy sources. Moreover, it is necessary to take into account quantitative and qualitative parameters that are decisive in assessment of the environmental-energy efficiency of fermentation processes in the bioreactor.

To achieve this the following tasks should be solved:

1. To substantiate the expediency of using renewable energy sources for thermal stabilization of the biomass fermentation process.
2. To propose a principal design scheme for thermal stabilization of biomass in biogas installation using renewable energy sources.
3. To develop a mathematical model of substantiation of environmental-energy efficiency of biogas plants with renewable energy sources using the fuzzy set theory and linguistic variables. This mathematical apparatus allows to take into account the influence of quantitative and qualitative factors.

4. MATERIALS AND METHODS

In Fig. 2 it is shown a principal design scheme of a combined biogas installation with a system of thermal stabilization of bioconversion process. The biogas installation receives heat from the solar collector and the heat pump [3].

The installation contains a reservoir 2, inside, which a vertical propeller mixer 4 is mounted on the hollow shaft 5. In the upper part of the reservoir 2 above the protective gas distribution grate 6 is placed a biomass-loading shaft 7 with a slide valve 8, as well as a biogas outlet pipe 9 with shut-off valve 10. At the bottom of the reservoir 2 there is a removal opening for the substrate 13 with a gate valve 8. The reservoir 2 is wrapped in a heating jacket 12, which is covered with insulation 3. The heat extraction circuit 1 and heat supply circuit 11 is connected to the heating jacket 12. The heat extraction circuit 1 connects the solar collector 16 with the storage tank 18 and through the second heat exchanger 23 passes into the heat supply circuit 11. The heat supply circuit 11 is connected to the heating jacket 12. The storage tank 18 comprises a first heat exchanger 22 and a second heat exchanger 23 which are interconnected. The heat extraction circuit 1 and heat supply circuit 11 are equipped with a circulating pump 19, shut-off valve 10, water drain valve 14 and air drain valve 17. The solar collector 16 contains a bypass line 15. The heat pump 20 is connected in parallel with the network of isolated pipelines through the first heat exchanger 22. The network of isolated pipelines consists of equipment for heat extraction circuit 1 and heat supply circuit 11. The temperature control unit 21 is connected to the solar collector 16, the storage tank 18, the heat pump 20 and the heating jacket 12.

The installation works like this.

The substrate of biomass is fed to the reservoir 2 through the loading shaft of biomass 7. Inside the reservoir 2 the substrate is agitated by means of a hollow shaft 5 with a vertical propeller mixer 4. The biogas outlet is being occurred in the upper part of the reservoir 2 through the protective gas distribution grate 6. The gas enters the outlet pipe 9 with shut-off valve 10. The heating jacket 12 maintains the required temperature inside the reservoir 2. The heat transfer agent's circulation and heating of the reservoir 2 are proceeded by the heating jacket 12 with the heat extraction circuit 1 and the heat supply circuit 11 connected. The heat transfer agent for heating receives thermal energy from the heat pump 20. The accumulation of thermal energy from the heat pump 20 is carried out by the storage tank 18.

When utilizing the thermal energy of the solar collector 16 and the heat pump 20 in a biogas plant with a combined thermal stabilization system of the bioconversion process, the heat transfer equations for the surface of the reservoir 2 with biomass and the heating jacket 12 have the form [24]

$$dQ = k \cdot F \cdot \Delta T_{av} d\tau = m_w \cdot C_w \cdot \Delta T_w d\tau = m_m \cdot C_m \cdot \Delta T_m, \quad (4)$$

where k – the heat transfer coefficient from the water in the heating jacket 12 through the surface F of the reservoir 2 to the biomass mixture at time τ (the value of this coefficient is quite variable and is determined by empirical equations), $\frac{W}{m \cdot K}$;

ΔT_{av} – the average temperature difference between the heat transfer agents at time τ, K;

C_w, C_m – the specific heat capacity of water and biomass mixture, respectively, at time τ, $\frac{J}{kg \cdot K}$;

m_w, m_m – the mass of water and biomass mixtures, respectively, kg;

ΔT_w – the water temperature difference between the inlet and outlet in the heating jacket 12, K;

ΔT_m – temperature difference of biomass mixture, K.

It should be mentioned, that thermal stabilization process of bioconversion systems is characterized by uncertainty of the input conditions, variable thermo-physical properties of equation (4) components and the influence of a large number of factors. These factors cannot always be reliably taken into account. Furthermore, in the reference literature there is a shortage of available data about the thermo-physical properties of various organic raw materials used in a biogas installation.

The most rational mathematical method for determining the value of an objective function, which characterizes the efficiency of a biogas installation, taking into account the input quantitative and qualitative environmental-energy information, are methods of fuzzy logic and linguistic variables [3, 20, 25, 26]. The fuzzy inference is the approximation of the dependence $X = f(X_1, X_2, \ldots, X_n)$ by means of fuzzy "IF - THEN" rules and fuzzy logic operations AND ($\wedge$), OR (v). The factors influencing the objective function are considered as linguistic variables, given on the corresponding universal sets and evaluated by fuzzy terms. Quantitative expressions "High" (H), "Average" (A), "Low" (L) or, if necessary, their corresponding modifications are used as fuzzy terms for

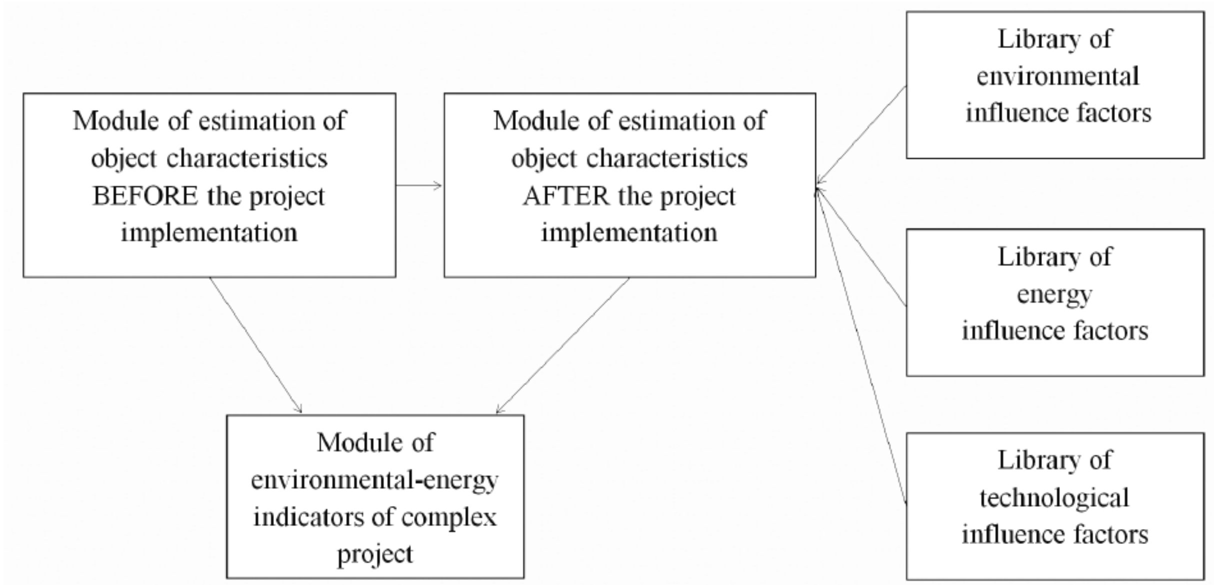

Figure 3.
The simplified model structure of complex assessment of the environmental-energy efficiency of a biogas installation

evaluating linguistic variables.

When modeling the structure of the hierarchy of factors influencing the value of the objective function X, their classification is performed and a tree of logical inference is built. The objective function X in this paper is the environmental-energy efficiency of a biogas installation, with given input variables that characterize the quantitative and qualitative factors of renewable energy sources used for thermal stabilization of biomass fermentation [3].

5. DEVELOPMENT OF MATHEMATICAL MODEL FOR SUBSTANTIATION OF ENVIRONMENTAL-ENERGY EFFICIENCY OF BIOGAS INSTALLATION WITH USE OF FUZZY LOGIC AND LINGUISTIC VARIABLES

According to the literature analysis results [3, 6, 12, 14], variable environmental, energy and technological factors of influence have been identified. These factors of influence are variables of the objective function X – environmental-energy efficiency of the biogas installation. The model structure of the complex assessment of environmental-energy efficiency of biogas plant is proposed in Fig. 3. The model contains modules for assessing the characteristics of the object before (1) and after (2) project implementation of renewable energy sources for heat stabilization of biomass fermentation, module of

Table 1.
Classification of influence factors on the environmental-energy efficiency and term values as linguistic variables

Influence factors	Designation and name of the linguistic variable		Terms for evaluating linguistic variables
Environmental, X_1	The effect of reducing carbon monoxide emissions in exergy units, x_{11}		Low (L) Average (A) High (H)
	The effect of preventing environmental pollution in exergy units, x_{12}		Low (L) Average (A) High (H)
	The effect of using biofuels in exergy units, x_{13}		Low (L) Average (A) High (H)
	The effect of the use of organic fertilizers in exergy units, x_{14}		Low (L) Average (A) High (H)
Influence factors	Designation and name of the linguistic variable		Terms for evaluating linguistic variables
Energy, X_2	Exergy effect from receiving additional thermal energy from traditional sources, x_{21}		Low (L) Average (A) High (H)
	Exergy effect of obtaining additional solar energy, x_{22}		Low (L) Average (A) High (H)
	Exergy effect of receiving additional thermal energy from the heat pump, x_{23}		Low (L) Average (A) High (H)
Fermentation temperature regimes, X_3	Exergy effect at:	Thermophilic mode, x_{31} Mesophilic mode, x_{32} Cryophilic mode, x_{33}	Low (L) Average (A) High (H)

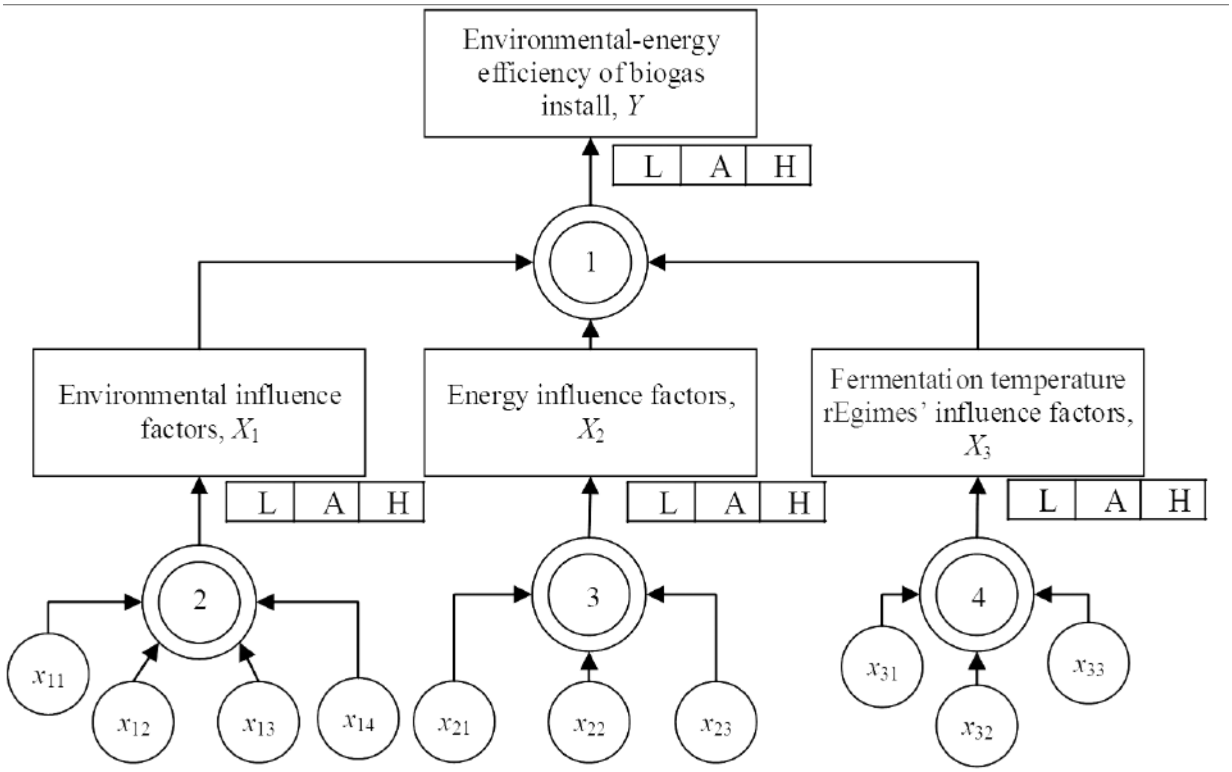

Figure 4.
Inference tree for assessing the environmental-energy efficiency of a biogas installation

environmental and energy indicators of complex project (3) and a library of linguistic variables describing environmental (4), energy (5) and technological (6) factors.

The implementation of the model of complex assessment of the environmental-energy efficiency of the biogas installation (Fig. 3) involves a comprehensive study of the linguistic variables data (factors of influence) by creating appropriate mathematical models. In assessing the environmental-energy efficiency, the exergy criterion was used, which makes it possible to quantify the efficiency of energy conversion. It allows to evaluate the benefits of individual elements of the installation and pre-identify the effectiveness of the entire installation. The classification of the factors of influence by the exergy criterion on the environmental-energy efficiency of the biogas installation and a meaningful interpretation of the relevant terms as input and output linguistic variables are shown in Table. 1.

The system of fuzzy equations corresponds to the linguistic statement that characterizes the fuzzy matrix of knowledge (Table 1), which simulates the influence of environmental and energy factors on the objective function Y:

$$\mu_L(Y)=\mu_L(X_1)\wedge\mu_L(X_2)\wedge\mu_L(X_3)\vee\mu_L(X_1)\wedge\mu_L(X_2)\wedge\mu_A(X_3)\vee \mu_A(X_1)\wedge\mu_L(X_2)\wedge\mu_L(X_3)\vee\mu_L(X_1)\wedge\mu_A(X_2)\wedge\mu_L(X_3). \quad (5)$$

$$\mu_A(Y)=\mu_A(X_1)\wedge\mu_A(X_2)\wedge\mu_A(X_3)\vee\mu_L(X_1)\wedge\mu_A(X_2)\wedge\mu_A(X_3)\vee \mu_A(X_1)\wedge\mu_L(X_2)\wedge\mu_A(X_3)\vee\mu_A(X_1)\wedge\mu_A(X_2)\wedge\mu_L(X_3)\vee \mu_H(X_1)\wedge\mu_A(X_2)\wedge\mu_A(X_3)\vee\mu_A(X_1)\wedge\mu_H(X_2)\wedge\mu_A(X_3). \quad (6)$$

$$\mu_H(Y)=\mu_H(X_1)\wedge\mu_H(X_2)\wedge\mu_H(X_3)\vee\mu_H(X_1)\wedge\mu_A(X_2)\wedge\mu_H(X_3)\vee \mu_A(X_1)\wedge\mu_H(X_2)\wedge\mu_H(X_3)\vee\mu_H(X_1)\wedge\mu_H(X_2)\wedge\mu_A(X_3). \quad (7)$$

where $\mu_L(Y)$, $\mu_A(Y)$, $\mu_H(Y)$ – is a membership grade of vector Y to fuzzy set "High" (H), "Average" (A), "Low" (L), of objective function Y according to [20]; $\wedge$ – denotes t-norm (multiplication in this paper).

According to the proposed classification of influence factors (Table 1), the objective function (*Y*) which is represented as an inference tree of hierarchical fuzzy model, is shown in Fig. 4.

The numbers in doubled circles in Fig. 4 are referred to the equations (8–11), which demonstrates dependencies between the objective function (Y) which is represented as an inference tree in the form of hierarchical fuzzy model and abovementioned influence factors (X_1, X_2, X_3) which are estimated by the relevant linguistic variables and the terms of their evaluation. In accordance with the proposed hierarchical fuzzy model, the assessment of the environmental-energy efficiency of the biogas install (Fig. 4) is described as:

$$Y = f(X_1, X_2, X_3, W_Y, B_Y, C_Y), \quad (8)$$

$$X_1 = f(x_{11}, x_{12}, x_{13}, x_{14}, W_{X1}, B_{X1}, C_{X1}), \quad (9)$$

$$X_2 = f(x_{21}, x_{22}, x_{23}, x_{24}, W_{X2}, B_{X2}, C_{X2}), \quad (10)$$

$$X_3 = f(x_{31}, x_{32}, x_{33}, W_{X3}, B_{X3}, C_{X3}), \quad (11)$$

where $-W_Y, W_{Xi} = (W_{X1}, W_{X2}, W_{X3})-$ fuzzy weights vector for linguistic estimation of objective function and influence factors respectively; $B_Y, B_{Xi} = (B_{X1}, B_{X2}, B_{X3})$ and $C_Y, C_{Xi} = (C_{X1}, C_{X2}, C_{X3})$ – the membership functions' parameter vectors for the respective influence factors.

6. DISCUSSION OF THE RESULTS OF THE STUDY

The use of additional sources of thermal energy to provide thermal stabilization contributes, as noted by Baader W. (1978), "…to the metabolic activity and reproductive capacity of microorganisms, because it is functionally dependent on temperature".

The temperature in the biogas reactor affects the volume of biogas produced and the technological time of biomass fermentation. Use of the renewable energy sources to cover the heat demand in cold period, particularly to ensure the mesophilic and thermophilic fermentation process as acceptable measure in the context of sustainable development. Studies carried out by a number of authors [1, 11, 14, 18] indicate the feasibility of using renewable energy sources for heat supply of the biogas production process. This is especially necessary in the cold season in areas with low temperatures (in Ukraine, etc.). The presented design of a biogas installation that receives additional heat energy from a solar collector and a heat pump ensures an efficient fermentation process meets this objective.

The results of the analysis of costs for the technological process of biogas production [13] show that the efficiency of bioconversion can be increased by reducing energy consumption (up to 42 kWh to heat biogas before purification in the mesophilic process [3]) for thermal stabilization of biomass fermentation.

In the case of thermal stabilization of the biomass fermentation process using a solar collector and a heat pump that supply additional heat energy to the biomass through a heating jacket, it is impossible to reliably estimate the effect of combined heat supply sources using heat transfer equations and heat balance. This is due to the uncertainty of the input conditions, the variability of the thermophysical properties of the parameters of these equations, namely biomass.

Revealed analysis of fuzzy logic experience using [3, 4, 6, 12, 14, 20, 21, 24, 25, 26] strengthens and substantiates authors feasibility of applying this mathematical method (apparatus) in energy efficient processes in bioconversion. Therefore, a mathematical model of eenvironmental-energy efficiency of a biogas installation with renewable heat sources of the bioconversion process is proposed. The model performs the classification of environmental, energy and temperature factors with the appropriate terms of their qualitative assessment. Linguistic statements that characterize the fuzzy matrix of the influence of environmental and energy factors on the objective function Y are described by a system of fuzzy logical equations (5), (6), (7). The structure in terms of inference tree for assessing the environmental-energy efficiency of a biogas installation is proposed (Fig. 4).

Further evaluation and verification of environmental-energy efficiency assessment of the proposed model of biogas installation with alternative energy sources for thermal stabilization of the biomass fermentation process can be proceeded by fuzzy logic apparatus as well by artificial neural network (ANN), genetic algorithms (GA), etc. All of the abovementioned assessment methods require real data about installation performance to be collected for model learning, fine tuning and optimization. The relations (8), (9), (10), (11) will allow to adapt (to make a fine tuning) the proposed mathematical model for assessing the environmental-energy efficiency of a biogas installation.

As a consequence, the proposed model allows to take into account the quantitative and qualitative parameters of renewable heat sources of the biomass fermentation process by appropriate adjustment of the fuzzy knowledge network that affects the objective function.

7. CONCLUSIONS

1. Implementation of structural and technological schemes for bioconversion of organic waste with renewable heat sources to provide thermal stabilization of biomass fermentation for the production of alternative energy sources – biogas and environmentally friendly fertilizers will significantly reduce the use of traditional energy sources and will contribute to the environmental improvement.
2. The proposed mathematical model using the fuzzy set theory apparatus and linguistic variables is the basis for creation of an expert-modeling system of intellectual decision support in the objective assessment of biogas installation environmental-energy efficiency. It is especially important in alternative evaluation's procedure of the biogas installation projects with heat stabilization of the biomass fermentation.

REFERENCES

[1] Geletuha, G. G., Zheleznaya, T. A., Kucheruk, P. P., & Olejnik, E. N. (2014). Sovremennoe sostoyanie i perspektivy razvitiya bioenergetiki v Ukraine (Modern state of the art and prospects of bioenergy development). *Analiticheskaya zapiska BAU* 9, (*Analytical note of Bioenergy Association of Ukraine* 9), 25.

[2] Kudria, S. O. (2015). Sostoyanie i perspektivy razvitiya vozobnovlyaemoj energetiki v Ukraine (State and prospects for development of renewable energy in Ukraine). *Visnyk Natsionalnoi akademii nauk Ukrainy (Bulletin of the National Academy of Sciences of Ukraine*), 12, 19–26.

[3] Ratushniak, H. S., Lialiuk, O. H., & Koshcheiev, I. A. (2017). Biohazovi ustanovky z vidnovliuvanymy dzherelamy enerhii termo-stabilizatsii protsesu fermentatsii biomasy (Biogas installations with renewable energy sources of thermo-stabilization biomass fermentation) Vinnytsia: VNTU, 110.

[4] Baader, W. (1978). Technische Voraussetzungen und Konsequenzen fur Biogasgewinnung im landwirtschaftlichen Bereich. *Landtechnik*.

[5] Dubrovin, V. O., Melnichuk, M. D., & Melnik, Y. F. (2009). Bioenergiya v Ukrayini – rozvitok silskih teritorij ta mozhlivosti dlya okremih gromad. (Bioenergy in Ukraine-rural development and opportunities for individual communities) K: NUBiP Ukrainy. (Kyiv: The National University of Life and Environmental Sciences of Ukraine), 111.

[6] Serbin, V. A. (2003). Netradicijni ta ponovlyuvani dzherela energiyi v sistemah TGP. (Non-conventional and renewable systems in HVAC) Makiyivka: Donbas National Academy of Civil Engineering and Architecture, 153.

[7] Drukovanyi, M. F. (2010). Suchasni tekhnolohii pererobky biomasy v biohaz ta orhanichni dobryva (Modern technologies of biomass processing into biogas and organic fertilizers). Zb. nauk. prats Vinnytskoho nats. ahrar. un-tu (Coll. of Science Works of Vinnytsia National Agrarian University), 42, 125–140.

[8] Joshua, O. S., Ejura, G. J., Bako, I. C., Gbaja, I. S., & Yusuf, Y. I. (2014). *Fundamental principles of biogas product. Int J Sci Eng Res (IJSER), 2*(8), 47–50.

[9] Golub, N., Kozlovets, O., & Voyevoda, D. (2016). Technology of anaerobic-aerobic purification of wastewater from nitrogen compounds after obtaining biogas. *Eastern-European Journal of Enterprise Technologies, 3*(10), 35–40.

[10] Geletuha, G. G., & Kobzar', S. G. (2002). Sovremennye tekhnologii anaerobnogo sbrazhivaniya biomassy (Obzor) (Modern technologies of anaerobic digestion of biomass (Review)). *Ekotekhnologii i resursosberezhenie* (*Ecotechnologies and resource conservation*), 4, 3–10.

[11] Zhelykh, V. M., & Furdas, Yu. V. (2013). Pidtrymannia teplovoho rezhymu bioreaktora pid chas zastosuvannia soniachnoi enerhii (The bioreactor thermal regime maintaining when using solar energy). *Suchasni tekhnolohii, materialy i konstruktsii v budivnytstvi* (*Modern Technology, Materials and Design in Construction*), 1, 142–148.

[12] Borovska, T. M., & Severilov, P. V. (2009). Modeliuvannia y optymizatsiia system vyrobnytstva biohazu (Modeling and optimization of biogas production systems). *Naukovi pratsi VNTU* (*Scientific works of VNTU*), 2, 1–9.

[13] Ratushnyak, G. S. (2012). Intensification of Biogas Production By Means of Mechanical Mixing of The Substrate. *Tap Chi Khoa hoc & Cong nghe*, 8, 57.

[14] Redko, A. O., Bezrodnyi, M. K., Zahoruchenko, M. V., Redko, O. F., Ratushniak, H. S., & Khmelniuk, M. H. (2016). Nyzkopotentsiina enerhetyka (Low-potential energy). Kharkiv: TOV "Drukarnia Madryd", 412.

[15] Tkachenko, S. Y., Stepanov, D. V., & Stepanova, N. D. (2020). Analiz sotsialnoi ta enerho-i pryrodozberezhnoi efektyvnosti realizatsii biohazovoi tekhnolohii (Analysis of social and energy-environmental efficiency of biogas technology's realization). *Visnyk Vinnytskoho politekhnichnoho instytutu* (*Herald of Vinnytsia politechnical institute*), 2, 34–41.

[16] Ziemiński, K., & Frąc, M. (2012). Methane fermentation process as anaerobic digestion of biomass: Transformations, stages and microorganisms. *African Journal of Biotechnology, 11*(18), 4127–4139.

[17] Zemlianka, O. O., & Hubynskyi, M. V. (2009). Vybir ratsionalnykh rezhymiv roboty reaktora biohazovoi ustanovky. (The choice of rational modes of operation of the biogas installation reactor). *Tekhnichna teplofizyka ta promyslova teploenerhetyka* (T*echnical thermophysics and industrial thermal power engineering*), 1, 112–120.

[18] Weiland, P. (2003). Production and energetic use of biogas from energy crops and wastes in Germany. *Applied biochemistry and biotechnology*, *109*(1-3), 263–274.

[19] Zuiev, O. O. (2009). Ekonomichni aspekty vprovadzhennia suchasnykh biohazovykh ustanovok (Economic aspects of modern biogas installations implementation). *Proceedings of the Tavria State agrotechnological university, 5*(9), 88–92. Retrieved from: http/www.nbuv.gov.ua/portal/chem.biol/ptdan/2009_9_5/5113.pdf.

[20] Rotshtein, O. P., Lariushkin, P., & Mitiushkin, Yu. I. (2008). Soft computing v biotekhnolohii: bahatofaktornyi analiz i diahnostyka (Soft computing in biotechnology: multivariate analysis and diagnostics). Vinnytsia: UNIVERSUM-Vinnytsia, 144.

[21] Baral, S., Pudasaini, S., Khanal, S., & Gurung, D. (2013). Mathematical modelling, finite element simulation and experimental validation of biogas-digester slurry temperature. *International Journal of Energy and Power Engineering, 2*(3), 128–135.

[22] Megonigal, J. P., Hines, M. E., & Visscher, P. T. (2004). Anaerobic metabolism: linkages to trace gases and aerobic processes. *In Biogeochemistry*, 317–392.

[23] Pham, C. H., Vu, C. C., Sommer, S. G., & Bruun, S. (2014). Factors affecting process temperature and biogas production in small-scale rural biogas digesters in winter in northern Vietnam. *Asian-Australasian journal of animal sciences, 27*(7), 1050–1056.

[24] Tkachenko, S. Y., & Rezydent, N. V. (2011). Teploobmin v systemakh biokonversii (Heat transfer in bioconversion systems). Vinnytsia: VNTU.

[25] Turkdogan-Aydınol, F. I., & Yetilmezsoy, K. (2010). A fuzzy-logic-based model to predict biogas and methane production rates in a pilot-scale mesophilic UASB reactor treating molasses wastewater. *Journal of hazardous materials, 182*(1–3), 460–471.

[26] Suganthi, L., Iniyan, S., & Samuel, A. A. (2015). Applications of fuzzy logic in renewable energy systems – a review. *Renewable and sustainable energy reviews*, 48, 585–607.

[27] Finzi, A., Oberti, R., Riva, E., & Provolo, G. (2014). A Simple Fuzzy Logic Management SupportSystem for Farm Biogas Plants. *Applied Engineering in Agriculture, 30*(3), 509–518.

[28] Blesgen, A., & Hass, V. C. (2010). Efficient biogas production through process simulation. *Energy & fuels, 24*(9), 4721–4727.

[29] Chen, T., Shen, D., Jin, Y., Li, H., Yu, Z., Feng, H., ... & Yin, J. (2017). Comprehensive evaluation of environ-economic benefits of anaerobic digestion technology in an integrated food waste-based methane plant using a fuzzy mathematical model. *Applied Energy*, 208, 666–677.

[30] Djatkov, D., Effenberger, M., & Martinov, M. (2014). Method for assessing and improving the efficiency of agricultural biogas plants based on fuzzy logic and expert systems. Applied energy, 134, 163–175.

[31] Latinwo, G. K., & Agarry, S. E. (2015). Modelling the kinetics of biogas production from mesophilic anaerobic co-digestion of cow dung with plantain peels. *International Journal of Renewable Energy Development, 4*(1), 55.

[32] Yordanova, S. N. E. J. A. N. A. (2007). Single input fuzzy control for nonlinear and time-varying plant. In Proc. of the 11th WSEAS international conference on Systems, 189–193.

[33] Wahmkow, C., Knape, M., & Konnerth, E. (2013, June). Biogas Intelligence-operate biogas plants using Neural Network and Fuzzy logic. In 2013 Joint IFSA World Congress and NAFIPS Annual Meeting (IFSA/NAFIPS), 1483–1488. IEEE.