



Yaroslav HONTARUK¹, Irina FURMAN², Valerii BONDARENKO³, Alla RIABCHYK⁴,
Oleksandr NEPOCHATENKO⁵

Production of biogas and digestate at sugar factories as a way of ensuring the energy and food security of Ukraine

ABSTRACT: The necessity of developing the production of biogas and digestate at Ukrainian sugar factories focused on the further sale of biomethane in the energy market and for its own needs is substantiated, which will partially ensure the energy security of the state under martial law. The volumes of sugar beet cultivation are determined, and the potential volumes of biogas production from the waste of Ukrainian agro-industrial complexes are investigated. A model of the functioning of a production bioenergy cluster based on a sugar factory has been developed and proposed. As a result of the study, it was found that a tangible way to increase the level of energy autonomy of the processing industry of the agro-industrial complex of Ukraine is the production of biogas by

✉ Corresponding Author: Yaroslav Hontaruk; e-mail: e050122015@gmail.com

¹ Vinnytsia National Agrarian University, Ukraine; ORCID iD: 0000-0002-7616-9422; e-mail: e050122015@gmail.com

² Vinnytsia National Agrarian University, Ukraine; ORCID iD: 0000-0002-9923-555X; e-mail: irina_furman@ukr.net

³ National University of Life and Environmental Sciences of Ukraine, Ukraine; ORCID iD: 00000-0002-5929-7158; e-mail: ondarenkovalm@gmail.com

⁴ National University of Life and Environmental Science of Ukraine, Ukraine; ORCID iD: 0000-0001-6290-3609; e-mail: alla2110@ukr.net

⁵ Uman National University of Horticulture, Ukraine; ORCID iD: 0000-0001-5049-983X; e-mail: nepochatenko2@gmail.com



© 2024. The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution-ShareAlike International License (CC BY-SA 4.0, <http://creativecommons.org/licenses/by-sa/4.0/>), which permits use, distribution, and reproduction in any medium, provided that the Article is properly cited.

anaerobic digestion and its subsequent purification to the state of biomethane. To produce this type of biofuel, the use by-products of agriculture, agro-industrial processing enterprises, and organic waste from territorial communities where sugar factories are located is advisable. At the same time, as the analysis of resource potential shows, modern methane generation technologies allow using a wide range of biomass as a raw material base, which can be obtained both from production activities (non-core (non-target) products) and from household waste in general, which is one of the methods of solving the problems of their utilization.

It has been determined that the use of advanced technologies for the transportation of liquid digestate and its injection will reduce the cost of application, increase the absorption in the soil, and the use of biodiesel will reduce transportation costs.

KEYWORDS: biogas, biomethane, sugar plants, cluster, digestate

Introduction

Since the beginning of Russia's military aggression, Ukraine has resolutely declared its refusal to buy energy from the aggressor country. Russia responded by launching a "gas war," namely, by stopping gas transit to the EU through the Sohranivka gas compressor station and later sabotaging the Nord Stream 1 and Turkish Stream pipelines.

Given the refusal to import natural gas from the aggressor country and the sharp rise in energy prices in the European market, the use of biomass potential from agricultural waste and the organic fraction of household waste for biomethane production is an urgent issue for ensuring Ukraine's energy security and the creation of specialized production facilities on the basis of sugar factories can be organized in the short term.

1. Literature review

Research shows that Ukraine and Russia are the two most important producers and exporters of grain in the world, accounting for 12 and 17% of global wheat exports, respectively (Lin et al. 2023).

It should be noted that Ukraine's agro-industrial complex has implemented the fight against climate change through sustainable production and protection of bioresources, processing of food waste, plant residues, and animal manure for biofuel production (Honcharuk et al. 2023).

At present, Ukraine is facing a severe fuel shortage and prices have increased by almost 50%. In addition, rising fuel prices have contributed to rising food prices (Tokarchuk et al. 2022).

Overall, the conflict in Ukraine has highlighted the importance of energy security as a key component of Europe's geopolitical strategy (Pryshliak et al. 2023).

Biogas production in the world is developing quite dynamically. It should be noted that the study by Bharadwaj B. determined that there is a huge potential for biogas that can be developed through the development of communications through the territorial communities of Australia and relevant government agencies to minimize emissions of harmful gases into the atmosphere (Bharadwaj et al. 2023).

Ukraine's significant potential in the agro-industrial sector and the availability of a substantial raw material base can become the basis not only for our country's energy security but also for the EU through the production of biogas with its subsequent purification to the level of bi-methane.

However, the difficult price situation in the energy market and the rise in fuel and mineral fertilizers require the search for cheaper and more efficient tillage systems before fertilizing the soil, as the total area of land fertilized with mineral fertilizers in 2021 was more than 16.7 million hectares, while organic fertilizers amounted to only 1.03 million hectares (Official website of the State Statistics Service of Ukraine).

Based on the research conducted (Lohosha et al. 2023), it was found that the use of bioorganic fertilizers in modern technologies for growing corn and open-field vegetables is an effective measure for obtaining additional products.

Today in Ukraine, the first steps of Ukrainian agricultural enterprises towards the introduction of waste-free production are presented in the example of Organic-D LLC; it heats and electrifies the complex, dries crops, and uses organic fertilizers (digestate) by recycling waste at a biogas plant (Kaletnik et al. 2020).

Consider the importance of using rapeseed as a raw material for biodiesel production in order to ensure the country's energy independence and fulfill obligations under international agreements to reduce CO₂ emissions (Pryshliak et al. 2022).

Despite the numerous scientific achievements in the field of biogas production, it is necessary to study the prospects for the production of this type of energy raw material and digestate at sugar factories in order to ensure the energy and food security of the state under martial law, which determines the relevance of the study.

2. Materials and methods

The methodological basis for the study of the efficiency of processing agricultural waste in Ukraine into biogas and digestate is a structural-functional and systemic approaches. The study used a combination of general scientific and special methods:

- ◆ monographic – to analyze the achievements of scientists on the subject of the study, which allowed to establish the cause-and-effect relationships of the development of phenomena

and processes arising in the system of production and processing of agricultural waste into biomethane and digestate with a focus on the further sale and use of this energy resource for the own needs of sugar factories;

- ◆ deductive – to project the situation with the creation of biomethane and digestate production on the basis of sugar factories with the subsequent use of these products at agricultural enterprises and the creation of own biogas filling stations;
- ◆ inductive – the study from the individual to the general allowed us to develop recommendations for the creation of clusters on the basis of sugar factories;
- ◆ economic analysis – in collecting, systematizing and researching information on sugar beet and by-products production in Ukraine and in determining the economic and environmental efficiency of individual enterprises specializing in biogas and digestate production;
- ◆ graphical and tabular – for visual display of certain indicators of waste generation in the form of pulp and molasses and their processing into biogas and, subsequently biomethane;
- ◆ statistical – in the process of processing information to analyze and evaluate the potential for biogas production.

The research methodology involves the following tasks: (1) analysis of the state of formation of the main raw materials for biogas and digestate production; (2) study of the potential for biomethane production in Ukraine; (3) analysis of successful practices of individual enterprises that implement advanced technological solutions in the field of biogas production from agricultural waste and organic fraction of municipal solid waste; (4) development of proposals for the formation of bioenergy clusters on the basis of sugar factories in close cooperation with territorial communities and agrarian formations; (5) formulation of proposals for the prospects of development of relevant clusters and use of the system.

3. Results and discussion

As a close analog of natural gas, biomethane can be used for heat and electricity production, as a fuel for transportation, and as a raw material for the chemical industry. The conversion of biogas to biomethane can become the main source of energy security for the country in the medium term.

Beet pulp is a by-product of the sugar industry. It is the primary feedstock for biogas production at the respective plants. Given the low cost of this feedstock and the absence of transportation costs to the processing site, it is an optimal basis for biogas production.

According to (Kaletnik 2018), the production of biofuels from biomass would solve not only the problem of energy security but also stabilize the agricultural sector of the economy. This is also relevant for Ukraine, especially for the sugar industry.

Today, biogas production is mainly focused on electricity generation with the subsequent sale at a “green tariff” SE “Guaranteed Buyer”, but the sale of biomethane on the energy mar-

ket should be considered more economically feasible. It should be noted that the state buys electricity from renewable energy sources through the state enterprise Guaranteed Buyer. The purchase of “clean” electricity is carried out on a priority basis and in full. The purchase price for electricity at special tariffs is higher than the market price for electricity and amounts to UAH 5.90/kWh as of the beginning of 2024. The scheme for stimulating electricity production through the feed-in tariff is set to last until January 1, 2030. It applies to entities that produce electricity from renewable energy sources at power plants commissioned during its validity period.

By the end of 2022, 68 industrial biogas plants were built and commissioned in Ukraine, with the industry’s total capacity reaching 105 MW and total gas production reaching 230 million cubic meters. The biogas plants commissioned in 2020 are classified by type of feedstock as follows:

- ◆ 28 stations produce biogas from agricultural raw materials;
- ◆ 27 stations operate on biogas from solid waste landfills;
- ◆ 9 stations produce biogas as a result of anaerobic treatment of industrial wastewater, and another one produces biogas from domestic wastewater;
- ◆ 3 plants are designed to produce generator gas (classified as biogas plants) (Annual Report of the Association of Gas Producers of Ukraine).

In 2022, the total consumption of natural gas in Ukraine, according to the Association of Gas Producers of Ukraine, amounted to more than 20.8 billion m³, with domestic production of 18.5 billion m³ and imports of 1.54 billion m³ (Table 1).

TABLE 1. Structure of natural gas supply in Ukraine in 2022 [billion cubic meters³]

TABELA 1. Struktura dostaw gazu ziemnego na Ukrainie w 2022 roku [mld m³]

Consumption.	Mining	Import
20.8	18.5	1.54

Source: Official website of the State Statistics Service of Ukraine 2023.

At present, the Law of Ukraine “On Amendments to the Law of Ukraine “On Alternative Fuels” on the Development of Biomethane Production” No. 5464 of 5/5/2021 has been adopted in the legal field. The law solved two main tasks: it legally regulated the concept of biomethane and created an electronic system of accounts “Biomethane Register” aimed at providing access to the sale of this type of product in the energy market (Law of Ukraine “On Amendments to the Law of Ukraine “On Alternative Fuels”). Sugar beet cultivation had a clear upward trend and in 2021 amounted to more than 1.8 million tons, including 10.3 million tons grown by agricultural enterprises (Table 2). In 2022, 23 sugar factories operated, producing 1.33 million tons of sugar. Including the production of 542.7 thousand tons of pulp based on the planned biogas yield of 64 m³/t. and in the process of purification from carbon dioxide, more than 20.8 billion m³ of biomethane can be obtained.

TABLE 2. Sugar beet production by categories of farms [thousand tons]

TABELA 2. Produkcja buraków cukrowych według kategorii gospodarstw [tys. ton]

2015	2018	2019	2020	2021	Deviations, +/-
Farms of all categories					
10,330.8	13,967.7	10,204.5	9,150.2	10,853.9	523.1
Enterprises					
9,553.8	13,316.6	9,658.3	8,627.1	10,353.7	799.9
including farms					
618.9	961.2	459.7	422.5	517.1	-101.8
households					
777.0	651.1	546.2	523.1	500.2	-276.8

Source: Official website of the State Statistics Service of Ukraine 2023.

It should be noted that the use of biogas production technologies in Ukraine is promising for solving the problems of processing agricultural waste, ensuring the environmental safety of the state, improving soil fertility through the use of digestate, and increasing the level of energy security in rural areas (Honcharuk 2020).

It should be noted that in the structure of biogas production potential, the main raw material is post-harvest residues and corn silage, which in the future will amount to more than 9.6 billion m³ (Fig. 1). This figure can cover half of the natural gas consumption in 2022 and provide agriculture with organic fertilizers.

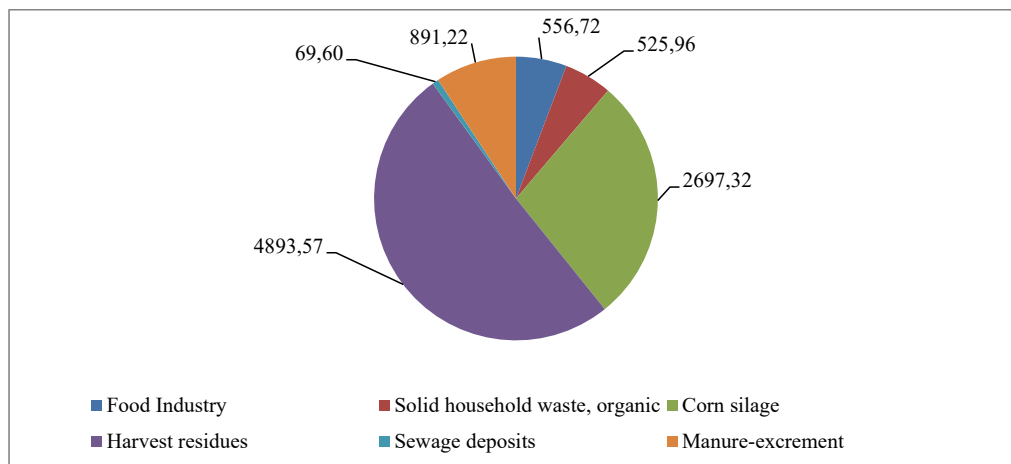


Fig. 1. Potential volume of biomethane production in Ukraine [million. m³]
(Website of the Bioenergy Association of Ukraine)

Rys. 1. Potencjalna wielkość produkcji biometanu na Ukrainie [mln m³]

Sugar factories can achieve the greatest efficiency by creating biogas production facilities on their own material and technical base, focused on processing their own by-products (molasses, pulp) and agricultural waste (crop and livestock waste).

For sustainable biogas production and utilization, a number of aspects need to be taken into account in Ukraine, namely:

- ◆ the main raw material for biogas production should be agricultural waste, agricultural processing enterprises, and organic household waste;
- ◆ to reduce production costs, the distance for transportation of raw materials should be optimal at a distance of a maximum of 20 km;
- ◆ bringing surplus biogas to the state of biomethane with subsequent sale to the national gas transportation system is an economically more feasible option than electricity production;
- ◆ the use of heat recovery from electricity production for one's own needs can contribute to bioeconomy and the development of new industries – bioethanol, heating of production facilities, etc;
- ◆ the use of digestate for soil fertilization will enable the production of organic products and reduce the costs of fertilizers for agricultural enterprises;
- ◆ the use of injection technologies for the application of liquid digestate will minimize the cost of drying these products;
- ◆ biogas contains carbon dioxide, which can be used in the chemical industry as industrial carbon dioxide, which will reduce the cost of biogas production.

The schematic diagram of the modernized sugar factories should include a fairly large amount of high-tech equipment. It is proposed that the by-products from the sugar plant should be transferred to a biogas reactor. After processing, a part of the biogas would be supplied to the plant's own power plant to meet production needs and to carry out the electrolysis process for the production of "green" hydrogen. The biogas purification plant cleaned this product from carbon dioxide and transported it for further processing to create synthetic methane. The purified biomethane and synthetic gas were sold through pumping stations to the general Ukrainian gas transportation system. Thus, sugar factories will be able to become producers of gas instead of consumers (Fig. 2).

It should be noted that during the period of martial law, Ukraine banned the export of natural gas, but biomethane is not subject to these restrictions and can be sold for export. This will make exporting part of the biomethane and synthetic methane possible when the sugar industry's capacities are fully utilized.

It should be noted that on August 2, 2022, the NEURC adopted a Resolution to reduce the requirements for the molar fraction of oxygen in biomethane that can be sold to the national gas transmission system and increased the corresponding indicator from 0.02 mol% to 0.2% mol%, which allowed to ensure the access of biomethane to the Ukrainian gas market (Annual Report of the Association of Gas Producers of Ukraine). This decision simplified the access of biomethane producers to the energy market.

Due to the presence of excess heat energy in the proposed scheme of modernization of sugar factories, it would be advisable to improve it by focusing on the development of bioethanol production at the relevant complexes (Fig. 3).

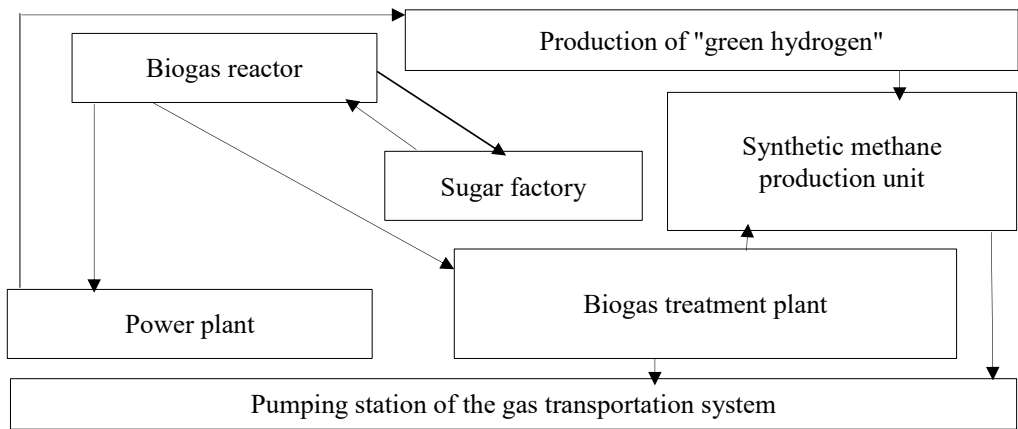


Fig. 2. Schematic diagram of modernized sugar factories
Source: own study

Rys. 2. Schemat ideowy modernizacji cukrowni

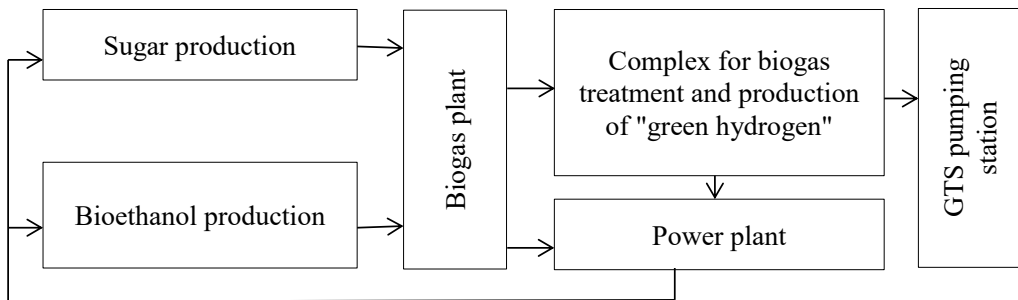


Fig. 3. Scheme of functioning of a production bioenergy cluster on the basis of a sugar plant
Source: own study

Rys. 3. Schemat funkcjonowania produkcyjnego klastra bioenergii na bazie cukrowni

The creation of bioethanol production will make it possible to utilize the thermal energy that remains unused during the power plant operation. It should be noted that the respective production will increase biogas production through the use of alcohol bard in combination with beet pulp.

The formation of bioenergy clusters according to the developed algorithm will allow for solving a significant number of problems in the agro-industrial complex of Ukraine, namely:

- ◆ ensure the creation of additional jobs in rural areas;
- ◆ stimulate the growth of the state's GDP;
- ◆ increase energy independence and development of alternative energy production in Ukraine;
- ◆ partially meet the demand for energy resources through the production of biomethane;

- ◆ promote the development of new biogas technologies;
- ◆ give impetus to the development of related industries, such as bioethanol production.

It is worth noting that according to the European Green Deal, hydrogen energy should become a major component of the EU's integrated energy system in 2025-2030, and the capacity of electrolysis plants will increase. Ukraine is an integral part of the EU's future hydrogen energy. Thus, the Hydrogen Strategy envisages cooperation with Ukraine in the development of renewable energy sources (RES) and the production of "green" hydrogen, as well as Ukraine's involvement in the industrial European Clean Hydrogen Alliance. The Hydrogen Europe Association, as part of the 2x40 GW initiative, envisages the construction of 9.8 GW of electrolyzers for the production of "green" hydrogen in Ukraine (Ukrainian Energy ua-energy.org, 2023). Thus, Ukraine can become an integral part of the implementation of the ambitious goals of the European Green Deal, and sugar factories can provide a significant part of green hydrogen production through the creation of bioenergy clusters.

In addition to the ideas and recommendations formulated by Kupchuk et al. (2022), it should be noted that solving the problems of increasing the level of energy independence of agro-industrial processing enterprises should be based primarily on the application of an integrated approach to the design of relevant bioenergy clusters. Thus, the organization of such clusters should be considered in the context of a macro-level technological system consisting of the following components: agricultural enterprises, agro-industrial processing enterprises (sugar, alcohol plants) and waste sorting lines of specialized organizations of communal ownership, territorial communities (municipalities) and the biogas complex itself. It should be noted that further improvement of such a cluster should be based on the application of the basic principles of technological systems development:

- ◆ the law of transition from the macro to the micro level – considering each of the four elements as a separate lower-level technological system with its own elements and connections between them;
- ◆ the law of increasing the degree of veplicity of the system, which consists in dividing the structural elements of subsystems into separate, smaller elements (veps) at all levels and forming an extensive network of complete and mutually consistent links between them, which allows for high maneuverability, flexibility and sensitivity of the technological macro system (production cluster).

In our opinion, the relevant cluster should be formed on the basis of the development of cooperation between territorial communities and the population in the field of sorting and processing of the organic component of solid waste and sugar factory waste (Fig. 4):

- ◆ the city council conducts explanatory work with the population in order to form the environmental awareness of citizens;
- ◆ a sorting plant is being set up at the landfill maintenance company to sort waste and partially incinerate it;
- ◆ organic waste from the sorting plant and agaric formations of the territorial community is transferred to the biogas complex for further processing into biogas, biohumus and digestate;

- ◆ digestate and biohumus are transferred for further purification and sale by an agricultural enterprise as fertilizers;
- ◆ a gas station complex is being set up to sell liquefied biomethane to the public and enterprises.

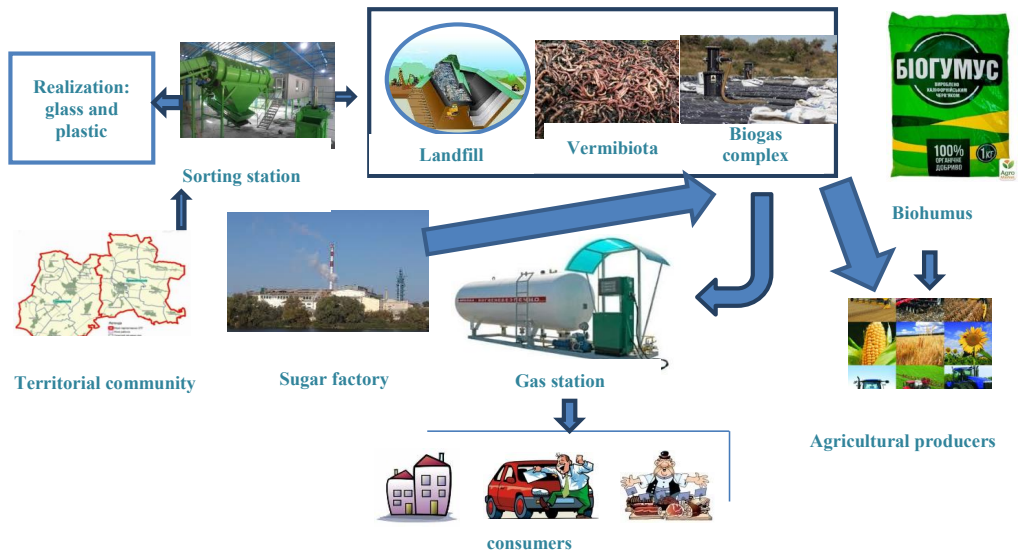


Fig. 4. Model of a territorial cluster focused on biogas production from waste from enterprises and households (based on sugar factories)
Source: own study

Rys. 4. Model klastra terytorialnego skupionego na produkcji biogazu z odpadów przedsiębiorstw i gospodarstw domowych (na podstawie cukrowni)

The implementation of this scenario will make it possible to:

- ◆ provide community agricultural producers with organic fertilizer at moderate prices;
- ◆ partially provide feed in the form of vermibiota to fisheries and poultry processing enterprises;
- ◆ increase crop yields through vermicompost fertilization;
- ◆ increase employment through the creation of additional jobs in communities;
- ◆ a significant increase in tax revenues to local budgets, which is quite relevant in the context of the shortage of funds caused by martial law.

The total cost of the complex will be UAH 3.9 million per year. The cost of liquefied biomethane production will be UAH 21.49/l with a planned realization cost of UAH 30/l (it should be noted that the market value of natural liquefied methane is UAH 41.64/l). The volume of industrial CO₂ will amount to 136.1 tons, which is planned to be sold at a market price of UAH 5586/t for a total of UAH 760 thousand (Table 3).

TABLE 3. Structure of costs and sales of liquefied biomethane to the population

TABELA 3. Struktura kosztów i sprzedaży skroplonego biometanu dla ludności

Indicator	
In terms of biomethane [m ³ /1t]	72
In terms of LBG [l]	216
Total LBG yield [l]	181,400
Construction cost [UAH million]	57.0
Operating costs [UAH million]	0.9
Depreciation of the complex [UAH million/year]	3.0
Cost price, 1 liter of LBG [UAH]	21.49
Realizable value, 1 liter of LBG [UAH]	30
Realizable value, LBG [UAH million]	5.4
Total cost of LBG [UAH million]	3.89
Cost of liquefied natural methane [UAH/l]	41.64
CO ₂ yield per 1 ton of organic waste [kg]	162
Total CO ₂ yield [tons]	136.1
CO ₂ sales price [UAH/t]	5,586
Total cost of CO ₂ [UAH thousand]	760.25
Total production cost of CO ₂ and LBG [UAH million]	3.9
Planned revenue from sales	5.76
Profit [UAH million]	1.86
Payback period – pessimistic scenario [years]	21
Optimistic scenario [years]	10

Source: own research.

The basic principles of a waste-sorting plant management system should be as follows:

1. Prevention of waste, creating conditions for manufacturers to ensure that their products generate the minimum amount of waste that can end up in a landfill after use.
2. Reuse. This means reusing products or their components that have not become waste for the same purpose (e.g., auto parts, electrical appliances, furniture, clothing, etc.). Such items are collected in special centers where used goods are updated and sold on a second-hand basis.
3. Recycling, or the processing of waste material into another product. This principle is used to recycle glass, ferrous and non-ferrous metals, paper, textiles, plastic, and wood. Sorting waste into fractions (glass, paper, metal, plastic) is necessary to facilitate recycling.
4. Waste to energy. Waste is converted into thermal energy through incineration plants. Today, from 23 to 58% of solid waste in the European Union is subject to incineration. Biogas plants operating at landfills or agricultural waste sites are also becoming widespread.
5. Landfilling. Only waste that cannot be disposed of in any other way should be disposed of at landfills. Modern landfills in the European Union are very different from the ones we are

used to, as they involve a complex engineering system that prevents the penetration of harmful substances into the soil or groundwater.

According to the data (Official website of the State Statistics Service of Ukraine 2023), liquefied methane sales in Ukraine amounted to more than 31.7 thousand tons per year. The capacity of the proposed gas station based on the bioenergy cluster is 181 thousand liters of liquefied biomethane or 91,000 kg. Based on the planned capacity and consumption of liquefied methane in Ukraine, it can be stated that the creation of 348 similar filling stations will make it possible to completely replace the methane produced by the gas station with biomethane.

The creation of appropriate clusters within the territorial communities will provide an opportunity to boost industrial production and employment, significantly improve the level of environmental protection and optimize the production costs of sugar factories.

It has been established that a very real way to increase the level of energy independence of processing enterprises of the agro-industrial complex of Ukraine is to use biogas obtained from agricultural waste and by-products of these organizations, and organic waste from local communities can also become an additional source of raw materials. At the same time, as the analysis of the resource potential shows, modern methane generation technologies allow using a wide range of biomass as a raw material base, which can be obtained both from production activities (non-core (non-target) products) and from household waste in general, which is one of the methods of solving the problems of their utilization. Thus, it can be stated that a promising way is to create clusters focused on biogas production from waste within territorial communities, which will allow for a number of potential effects:

- ◆ increasing the level of energy independence of the sugar industry of the state;
- ◆ reduction of costs for energy resources of sugar factories;
- ◆ positive effect on the ecological state of the environment;
- ◆ sharp reduction of greenhouse gas emissions by these enterprises;
- ◆ provide agricultural producers with organic fertilizers;
- ◆ create additional jobs;
- ◆ solve problems with household waste disposal.

Today, the main constraint to the development of biogas production in the form of cluster associations in Ukraine is the high cost of implementing these projects. Stimulating the development of biogas production at sugar factories should be aimed at increasing the tax burden on CO₂ emissions and developing a system of state support for the creation of relevant clusters. The implementation of the proposed projects can provide a partial solution to the problem of energy independence of the Ukrainian agro-industrial complex and provide agricultural enterprises with organic fertilizers in the short term. To increase biogas and digestate production at sugar factories, it is advisable to take the following steps:

- ◆ modernize existing biogas complexes to produce biomethane;
- ◆ establish cooperation with agricultural producers focused on purchasing waste from this sector of the economy for biogas production;
- ◆ develop biomethane liquefaction technologies for use as a fuel for automotive vehicles;
- ◆ Ukraine's gradual accession to the European Biomethane Trading System.

It should be noted that the Regional Gas Company, which controls about 70% of gas distribution networks in Ukraine, began conducting the first field experiments in 2020 to transport a mixture of natural gas and hydrogen. This will provide an opportunity to analyze the infrastructure capabilities to ensure reliable supplies of gas/hydrogen mixtures to end users in different regions. Preliminary findings, according to official reports of RGC, demonstrated the possibility of using 10–15% hydrogen mixed with natural gas for delivery to the company's customers, which indicates the possibility of exporting a mixture of hydrogen and natural gas or bi-methane even without modernizing the domestic gas transmission system (UNECE website 2023).

Therefore, modernizing the Ukrainian gas transportation system and establishing the production of biomethane and “green” hydrogen at sugar factories, nuclear power plants, and other ways will ensure the energy security of Ukraine and partially the entire European continent.

It should be noted that surface application of digestate is not feasible due to the high cost of transportation and the need to use large containers.

The use of injection systems in combination with hose transportation using diesel pumping stations with their adaptation to the use of biodiesel as a fuel will reduce the cost of fertilizer transportation. According to previous studies, the cost of biodiesel is UAH 33 /kg or UAH 28.44/l (Telekalo et al. 2022).

Also, the use of an injection system will ensure more efficient distribution of the liquid fraction in the soil, and the use of flexible active harrows with ripper teeth will improve the absorption of organic matter. Exclusion of the digestate drying process from the technological cycle will reduce the cost of biogas production.

Today, Ukraine already has the appropriate technologies and adapted systems for transferring liquid digestate directly from biogas plants to agricultural land at a distance of up to 20 km. It should be noted that these technologies were developed by the engineering staff of this company. Still, some foreign-made components are used to implement the relevant complexes (Simol jack (Italy), Sornell pump (USA), DOOSAN diesel engine (South Korea) (Website of the company A.TOM 2023).

The use of advanced technologies for the transportation of liquid digestate and its injection will reduce the costs of agricultural enterprises and increase the humus content in the soil. At the same time, the use of a flexible active harrow with loosening teeth, which has shown the benefits of loosening and crumbling the soil compared to conventional harrows, will improve soil cultivation after digestate application (Bulgakov et al. 2019).

The use of the proposed technology of soil application and tillage in the complex will make it possible to reduce the production costs of biogas plants by reducing the cost of digestate drying, increase the absorption of fertilizers through the use of injection systems, and the use of biodiesel will significantly reduce the cost of fuel and lubricants.

To increase the production and use of biomethane at sugar factories, the following measures should be taken to stimulate the development of the industry, namely: reorientation of existing biogas plants to biomethane production through subsidies (compensation from the budget for up to 40% of the cost of the relevant modernization); application of biomethane liquefaction technologies for use in transport (compensation for the cost of construction of the proposed gas stations

by compensating 30% of the cost of equipment); gradual accession of Ukraine to the European (improvement of relevant regulatory and legal support).

Conclusions

The development of biomethane production at sugar factories will make it possible:

- ◆ reduce the volume of natural gas imports and partially sell the surplus on the energy market;
- ◆ give impetus to the development of high-tech equipment for biogas plants;
- ◆ create additional jobs at sugar industry enterprises;
- ◆ provide agricultural producers with organic fertilizers (digestate);
- ◆ significantly reduce the cost of biomethane production by using the developed algorithm for the functioning of a bioenergy cluster based on a sugar plant.

At the same time, biogas production at sugar industry enterprises will have positive consequences for the functioning of the economy under martial law:

- ◆ increase the energy independence of the agro-industrial processing industry while increasing the share of renewable energy in the overall energy supply structure;
- ◆ improve the ecological condition of the country's water bodies, as the use of sedimentation tanks with subsequent discharge of wastewater will be unnecessary;
- ◆ provide agricultural producers with an environmentally friendly and cheap fertilizer – digestate, which will optimize the cost of agricultural production and improve its quality.

References

- Annual Report of the Association of Gas Producers of Ukraine. [Online] https://www.agpu.org.ua/images/pdf/Annual_Report-2022.pdf [Accessed: 2023-12-06].
- BHARADWAJ et al. 2023 – BHARADWAJ, B., KAMBO, A., ARRATIA-SOLAR, A. and ASHWORTH, P. 2023. Awareness of biogas increases its social acceptance. *Journal of Cleaner Production* 421, DOI: 10.1016/j.jclepro.2023.138432.
- BULGAKOV et al. 2019 – BULGAKOV, V., KALETNIK, H., GONCHARUK, I., IVANOV, S. and USENKO, M. 2019. Results of experimental investigations of a flexible active harrow with loosening teeth. *Agronomy Research* 17(5), pp. 1839–1845, DOI: 10.15159/AR.19.185
- HONCHARUK, I. 2020. Biogas production in the agricultural sector is a way to increase energy independence and soil fertility. *Agrosvit* 15, pp. 18–29, DOI: 10.32702/2306-6792.2020.15.18.
- HONCHARUK et al. 2023 – HONCHARUK, I., TOKARCHUK, D., GONTARUK, I. and HRESHCHUK, G. 2023. Bio-energy recycling of household solid waste as a direction for ensuring sustainable development of rural areas. *Polityka Energetyczna – Energy Policy Journal* 26(1), pp. 23–42, DOI: 10.33223/epj/161467.
- KALETNIK, G. 2018. Diversification of biofuels production development is the basis for ensuring food, energy, economic and environmental security of Ukraine. *Bulletin of Agrarian Science* 11, pp. 169–176, DOI: 10.31073/agrovisnyk201811&21.

- KALETNIK et al. 2020 – KALETNIK, G., HONCHARUK, I. and OKHOTA, Yu. 2020. The Waste-Free Production Development for the Energy Autonomy Formation of Ukrainian Agricultural Enterprises. *Journal of Environmental Management and Tourism* XI(3 (43)), pp. 513–522, DOI: 10.14505/jemt.v11.3(43).02.
- KUPCHUK et al. 2022 – KUPCHUK, I.M., GONTARUK, Y.V. and PRYSYAZHNYUK, Y.S. 2022. Prospects for increasing the level of energy autonomy of processing enterprises of the agro-industrial complex of Ukraine through biogas production. *Technique, energy, transport of the agro-industrial complex* 3(118), pp. 59–73, DOI: 10.37128/2520-6168-2022-3-8.
- Law of Ukraine “On Amendments to the Law of Ukraine “On Alternative Fuels” on the Development of Biomethane Production” No. 5464 of 05.05.2021. [Online] http://w1.c1.rada.gov.ua/pls/zweb2/webproc4_1?pf3511=71839 [Accessed: 2023-12-06].
- LIN et al. 2023 – LIN, F., LI, X., JIA, N., FENG, F., HUANG, H., HUANG, J., FAN, S., CIAIS, P. and SONG, X.-P. 2023. The impact of Russia-Ukraine conflict on global food security. *Global Food Security* 36, DOI: 10.1016/j.gfs.2022.100661.
- LOHOSHA et al. 2023 – LOHOSHA, R., PALAMARCHUK, V. and KRYCHKOVSKIY, V. 2023. Economic efficiency of using digestate from biogas plants in Ukraine when growing agricultural crops as a way of achieving the goals of the European Green Deal. *Polityka Energetyczna – Energy Policy Journal* 26(2), pp. 161–182, DOI: 10.33223/epj/163434.
- Official website of the State Statistics Service of Ukraine. [Online] <http://www.ukrstat.gov.ua> [Accessed: 2024-05-05].
- PRYSHLIAK et al. 2022 – PRYSHLIAK, N., BONDARENKO, V., SOKOLIUK, S. and BROVARETS, O. 2022. The formation of a bioenergy cluster for the production of biofuels from agricultural crops and waste: the experience of Ukraine. *Polityka Energetyczna – Energy Policy Journal* 25(4), pp. 149–164, DOI: 10.33223/epj/156210.
- PRYSHLIAK et al. 2023 – PRYSHLIAK, N., DANKEVYCH, V., TOKARCHUK, D. and SHPYKULIYAK, O. 2023. The sowing and harvesting campaign in Ukraine in the context of hostilities: challenges to global energy and food security. *Polityka Energetyczna – Energy Policy Journal* 26(1), pp. 145–168, DOI: 10.33223/epj/161794.
- TELEKALO et al. 2022 – TELEKALO, N.V., KUPCHUK, I.M. and GONTARUK, Y.V. 2022. Efficiency of growing and processing of winter rape for biodiesel. *Agrarian innovations* 13, pp. 149–154, DOI: 10.32848/agrar.innov.2022.13.23.
- The Law of Ukraine “On Accession of Ukraine to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal” 803-XIV of July 01, 1999. [Online] <https://zakon.rada.gov.ua/laws/show/803-14#Text> [Accessed: 2023-12-06].
- TOKARCHUK et al. 2022 – TOKARCHUK, D., PRYSHLIAK, N., BEREZYUK, S. and SHYMKOVYCH, A. 2022. Food security and biofuel production: solving the dilemma on the example of Ukraine. *Polityka Energetyczna – Energy Policy Journal* 25(2), pp. 179–196, DOI: 10.33223/epj/150496.
- UNECE website. Project Roadmap for the production and use of hydrogen in Ukraine. [Online] https://unece.org/sites/default/files/2021-03/Hydrogen%20Roadmap%20Draft%20Report_UKR%20March%202021.pdf [Accessed: 2023-12-06].
- Website of the Bioenergy Association of Ukraine. [Online] <https://uabio.org/> [Accessed: 2024-02-06].
- Website of the company A.TOM. [Online] <https://atom-attachments.com/en/direction/sistemy-vneseniya-organicheskikh-udobreniy> [Accessed: 2023-12-06].
- Website “Ukrainian Energy ua-energy.org”. Available capacities and potential of exporting “green” hydrogen from Ukraine to the EU. [Online] <https://ua-energy.org/uk/posts/naiavni-potuzhnosti-ta-potentsial-eksportu-zelenoho-vodniu-z-ukrainy-do-yes> [Accessed: 2023-12-06].

Produkcja biogazu i pofermentu w cukrowniach jako sposób na zapewnienie bezpieczeństwa energetycznego i żywnościowego Ukrainy

Streszczenie

W artykule uzasadniono konieczność rozwoju produkcji biogazu i pofermentu w ukraińskich cukrowniach, ukierunkowanej na dalszą sprzedaż biometanu na rynku energetycznym i na własne potrzeby, co częściowo zapewni bezpieczeństwo energetyczne państwa w stanie wojennym. Określono wielkość uprawy buraków cukrowych i zbadano potencjalne wielkości produkcji biogazu z odpadów ukraińskich kompleksów rolno-przemysłowych. Opracowano i zaproponowano model funkcjonowania produkcyjnego klastra bioenergetycznego opartego na cukrowni.

W wyniku badań stwierdzono, że konkretnym sposobem na zwiększenie poziomu autonomii energetycznej przemysłu przetwórczego kompleksu rolno-przemysłowego Ukrainy jest produkcja biogazu w procesie fermentacji beztlenowej i jego późniejsze oczyszczanie do stanu biometanu. Do produkcji tego rodzaju biopaliwa wskazane jest wykorzystanie produktów ubocznych rolnictwa, przedsiębiorstw przetwórstwa rolno-przemysłowego oraz odpadów organicznych ze społeczności terytorialnych, w których zlokalizowane są cukrownie. Jednocześnie, jak pokazuje analiza potencjału zasobów, nowoczesne technologie wytwarzania metanu pozwalają na wykorzystanie szerokiej gamy biomasy jako bazy surowcowej, którą można pozyskać zarówno z działalności produkcyjnej (produkty niezwiązane z podstawową działalnością), jak i ogólnie z odpadów z gospodarstw domowych, co jest jedną z metod rozwiązywania problemów związanych z ich utylizacją.

Ustalono, że zastosowanie zaawansowanych technologii transportu płynnego pofermentu i jego wtrysku obniży koszty aplikacji, zwiększy absorpcję w glebie, a zastosowanie biodiesla obniży koszty transportu.

SŁOWA KLUCZOWE: biogaz, biometan, cukrownie, klaster, odpady pofermentacyjne