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Ukrainian biogas and biomethane industry as the basis for national energy independence

Abstract. The study aimed to assess the potential of Ukraine's biomethane industry and analyse biogas production and purification technologies, economic and regulatory aspects, and opportunities for integration into the EU market. The study confirmed that Ukraine can produce more than 10 billion m^3 of biomethane per year from agricultural, livestock, food industry and household organic residues. The technological processes of production, including anaerobic digestion, purification and enrichment of biogas, as well as the efficiency of purification methods such as membrane separation, variable pressure adsorption and cryogenic distillation were analysed. The study analysed the regulatory framework of Ukraine on biomethane and its harmonisation with EU standards. The adoption of Law No. 1820-IX and DSTU EN 16723-1:2023 simplifies certification but requires further improvement to fully comply with European requirements. A comparative analysis of the costs of biomethane production in Ukraine and the EU demonstrated the competitiveness of Ukrainian products due to the lower cost of raw materials, but the limited availability of financial incentives. Key investment barriers were identified, including a lack of government subsidies, the absence of guaranteed tariffs and the complexity of certification. The study confirms that biomethane reduces carbon dioxide (CO_2) emissions by 85% compared to natural gas and is central to the circular economy. The study analysed the real indicators of biomethane production in Ukraine for 2019-2024, which demonstrated a gradual increase, but a significant lag behind the EU countries. The study assessed the prospects for Ukrainian biomethane exports to the EU, the competitive environment, logistical challenges, and the need

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to modernise the gas transmission system and harmonise standards. The practical significance of the study is determined by a comprehensive analytical framework for the formation of an effective state policy in the field of biomethane industry development in Ukraine

Keywords: renewable energy; decarbonisation; biomass gasification; circular economy; energy sustainability

INTRODUCTION

The rising cost of traditional energy carriers is affecting Ukraine's energy stability. This problem is exacerbated by fuel shortages and geopolitical threats from russia, which increase the national vulnerability in the energy supply sector. In this regard, it is necessary not only to reduce energy costs but also to actively expand the use of alternative energy sources that can ensure reliable, affordable and sustainable energy security for Ukrainian society. The development of the biogas and biomethane industry is an important component of Ukraine's energy strategy aimed at improving energy security, reducing dependence on natural gas imports and introducing low-carbon technologies. The creation of an efficient biomethane industry not only helps to strengthen energy independence but also stimulates the development of a circular economy through the utilisation of organic waste and the recovery of natural resources (Dymchuk *et al*., 2025).

I. Zamula *et al*. (2024) studied the potential of the biomethane market in Ukraine under martial law, emphasising the importance of harmonising the regulatory framework with European standards. The study noted that the prospects of biomethane as an alternative energy source are based on its chemical identity with natural gas, which enables transportation through the existing gas transmission infrastructure without the need for modernisation. M. Cierpiał-Wolan *et al.* (2021) analysed the use of regional potential for energy independence in Poland and Ukraine. The study determined that biomethane is a versatile resource suitable for use not only in the industrial and municipal sectors but also in the transport sector, which significantly expands its economic and environmental benefits. O. Kucher *et al.* (2022) assessed the energy potential of biogas production in Ukraine and stated that the use of agricultural, industrial and municipal waste can produce up to 10 billion cubic metres of biomethane per year. The study also emphasised the importance of anaerobic digestion as a key process for biogas production.

C. Esonye *et al.* (2023) examined the impact of the russian invasion on Ukrainian energy security, noting that biomethane development could be a strategic response to threats to national energy independence. M. Li *et al.* (2024) analysed the development of decentralised energy systems, noting that biogas plants can help reduce dependence on centralised natural gas supplies. The study emphasised the importance of financial incentives for biomethane producers that could increase their competitiveness. D. Mignogna *et al.* (2023) investigated the production of biogas and biomethane as feedstocks for renewable energy sources, emphasising the effectiveness of purification technologies such as membrane separation, variable pressure adsorption and cryogenic purification, which ensure high quality of the biomethane produced. F. Sher *et al.* (2024) reviewed the latest biogas production technologies and identified key challenges related to the infrastructure integration of biomethane into energy systems. N. Pryshliak & I. Bilokinna (2023) analysed the efficiency of using biogas plants in households, emphasising the potential of decentralised biomethane production for Ukraine's energy independence. M. Sesini *et al.* (2024) conducted a comparative analysis of the biogas sector in Europe and concluded that the creation of an effective biomethane certification system is a key step for its integration into the European energy market. U. Brémond *et al.* (2021) studied the trends in the development of the European biogas sector until 2030, noting that Ukraine has significant potential for integration into the European market, provided that the regulatory framework is further improved and investments in production infrastructure are attracted.

The study aimed to conduct a comprehensive analysis of Ukraine's biogas and biomethane industry as an important factor of energy independence, assess its potential to replace imported natural gas and reduce its carbon footprint, and identify strategic directions for development and integration into the national and international energy system.

The objectives of the study are comprehensive assessment of the potential of the biomethane industry as one of the key factors in ensuring Ukrainian energy independence; second, an analysis of the technological aspects of biomethane production, in particular the processes of anaerobic digestion, purification and enrichment of biogas, to identify effective technological solutions for integration into the national gas transmission system.

MATERIALS AND METHODS

The research methodology was based on the analysis of scientific sources, analytical reports and strategic documents in the field of bioenergy. For the analysis, the materials of the global report "Bioenergy in 2024: A global report is now available at SAF" (2024) on global trends in biomethane production and consumption, the analytical report of the Ministry of Agrarian Policy and Food of Ukraine (2023) on the challenges and regulatory framework of the industry were used. Additionally, the research of the Institute of Bioenergy Crops and Sugar Beet on the efficiency of growing bioenergy crops and optimising anaerobic digestion processes was covered.

The first stage of the study conducted a theoretical analysis of modern biogas and biomethane production technologies, incorporating innovative developments and their effectiveness in industrial conditions. The main processes of anaerobic digestion of organic waste, methods of biogas purification and its enrichment to the level of biomethane, which can be used as an environmentally friendly fuel, were studied. The factors affecting the efficiency of the fermentation process were analysed, including types of raw materials, temperature conditions, microflora composition, methods of stabilising gas output and methods of biomass processing. Technical possibilities of transporting biomethane through existing gas pipelines, its accumulation, long-term storage and use in various sectors of the economy, including industry and utilities, were emphasised. The experience of the following EU countries was considered: Germany, France, the United Kingdom, Sweden, Denmark, the Netherlands, Switzerland, Italy, Finland, and Austria, which are implementing innovative methods to increase biogas yields, waste processing efficiency, and improve biomethane enrichment technologies.

The second stage of the study analysed the potential for biomethane production in Ukraine and its impact on the national energy balance. The amount of available raw materials for biogas production was estimated, as well as the possibility of creating biogas clusters in regions with high agricultural potential. The economic feasibility of large-scale biomethane production was analysed, incorporating energy security, environmental aspects and the cost of technological processes. The possibilities of reducing greenhouse gas emissions by using biomethane instead of natural gas were studied. The potential of biomethane as a reserve fuel for energy needs during crises was also highlighted.

The third stage of the study analysed the prospects for biomethane exports from Ukraine to the EU in the context of the European decarbonisation and energy security goals. The key requirements of the European market were studied, including biomethane certification mechanisms, a system of guarantees of its origin, and technical standards for transportation that determine the possibilities of integrating Ukrainian biomethane into the EU gas transmission system. The legislative framework for the development of the biomethane market in Ukraine. The economic incentives and regulatory mechanisms in place in the EU, including the system of subsidies, feed-in tariffs and tax benefits that promote the production and export of biomethane, were studied. The study analysed the possibility of adapting similar financial instruments in Ukraine to support biomethane producers, including cheaper loans for the purchase of equipment, subsidies and state co-financing of bioenergy projects. The projected volumes of biomethane production in Ukraine were estimated.

RESULTS

Biogas and biomethane are among the key elements of modern renewable energy production technology that contribute to the decarbonisation of the economy and increase energy independence. Biogas is produced as a result of anaerobic digestion of organic raw materials, the main components of which are methane (CH_4) and carbon dioxide (CO_2). The composition of biogas depends on the type of feedstock and fermentation conditions, but the typical CH_4 content ranges from 50-70%. The technological process of biogas production includes several key stages: feedstock preparation, anaerobic digestion, purification of the resulting gas and its further use. The initial stage involves the collection of organic waste (agro-industrial, food, municipal) and its mechanical or thermal treatment to improve the efficiency of the fermentation process. The next step is the anaerobic decomposition of biomass by microorganisms, which produces biogas with an optimal CH_4 content. Biogas purification involves the removal of impurities such as hydrogen sulphide (H_2S), ammonia (NH_3), water vapour and siloxanes, which increases its energy value and expands its applications. The sequence of the main stages of biogas production is shown in Figure 1, which demonstrates the key technological processes and the possibilities of its further use.

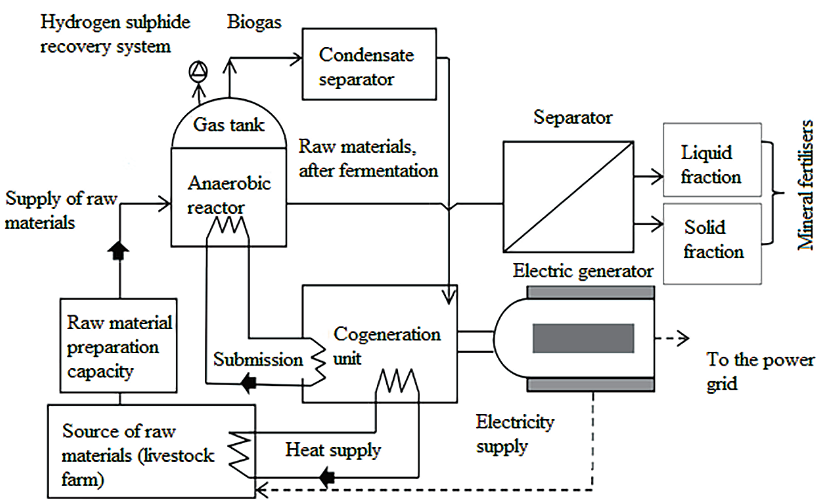

Figure 1. Flow chart of biogas production

Source: N. Pryshliak & I. Bilokinna (2023)

Following the Figure 1, the biogas production process involves several key stages that ensure the efficient conversion of organic feedstock into energy-rich gas. The initial stage involves the collection and preparation of organic feedstock, which may include agricultural, food and livestock waste and municipal biowaste. Preparation involves grinding, hydrothermal treatment and moisture control to improve the fermentation process. The feedstock is then transferred into an anaerobic digester, where microorganisms break down organic compounds and produce biogas, the main components of which are CH_4 and CO_2. Fermentation takes place in several phases, including hydrolysis, acetogenesis, acidogenesis and methanogenesis, which ensure the gradual conversion of complex organic substances into CH_4.

Once the fermentation process is complete, the biogas is passed through a purification system to remove unwanted impurities such as H_2S, NH_3 and water vapour. Various technologies are used at this stage, including membrane separation, variable pressure adsorption, cryogenic purification and absorption methods, to achieve a high level of gas purity. The final stage is the use of biogas or its further enrichment to biomethane levels that meet natural gas standards. Biomethane is biogas purified from impurities, with a CH_4 concentration of more than 95%, which ensures its compliance with the requirements for use in gas transmission networks and industrial consumers. The technological process of converting biogas into biomethane involves the removal of CO_2, H_2S, NH_3, moisture and other impurities. Biomethane can be transported through existing gas networks, used in industry, transport or as a backup fuel for power generation.

Figure 2 demonstrates the technological chain of biomethane production, purification and transportation, starting from the supply of raw materials to final consumption. The process involves the logistical supply of organic waste to a biogas plant, where anaerobic digestion takes place to produce biogas. The biogas is then transferred to an enrichment plant where it is purified from impurities (CO_2, H_2S, NH_3, moisture) to meet biomethane standards. The purified biomethane can be used in several ways: supply to medium or low-pressure gas networks, transportation through high-pressure gas pipelines, and use as a motor fuel through automotive gas-filling compressor stations. Depending on the scale of production, there are different organisational models: centralised plants operating from a single source of feedstock, networked complexes of several biogas plants, or distributed systems with biogas pipelines connecting several production sites to a single processing station.

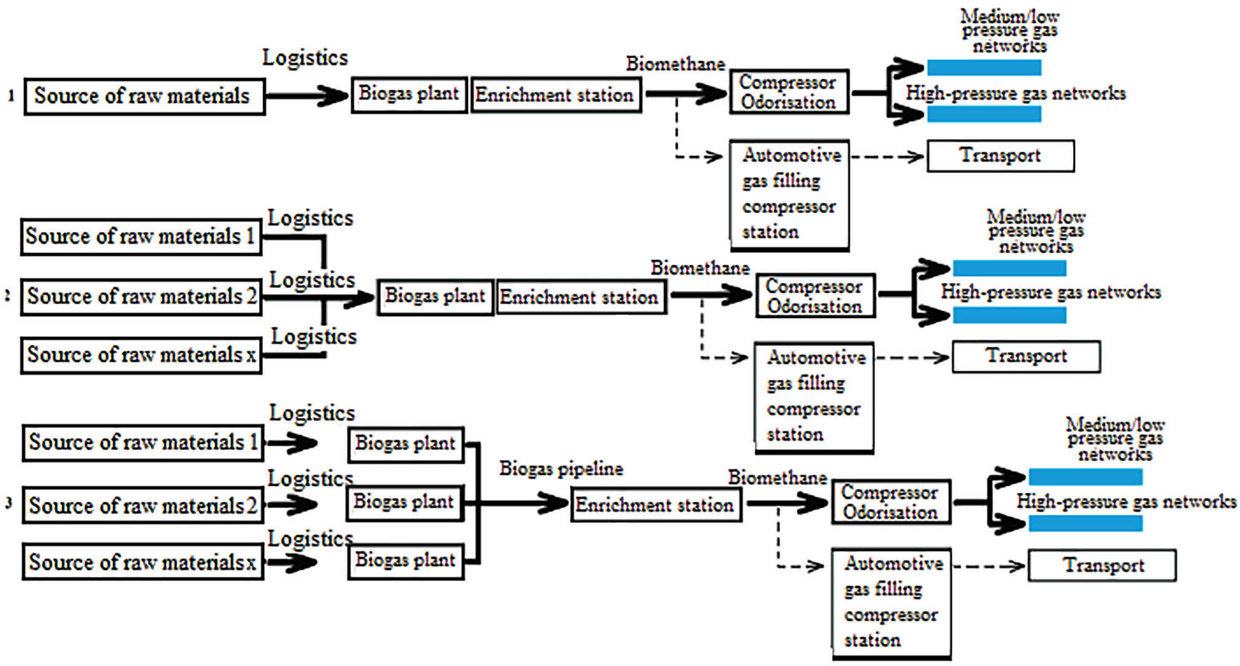

Figure 2. Scheme of biomethane production, purification and transportation
Source: Yu. Okhota (2023)

As shown in Figure 2, the biomethane production process involves several key steps. First, the organic feedstock is transported to a biogas plant where anaerobic digestion and biogas production take place. The biogas is then sent to an enrichment plant, where undesirable components (CO_2, H_2S, NH_3, water vapour) are removed, resulting in biomethane with a high CH_4 concentration (>95%). The analysis of the biomethane production and transportation process chain identified the key factors that affect the efficiency of the fermentation process and the subsequent use of biogas. The main parameters that determine the performance of anaerobic digestion are the type of feedstock, temperature conditions, microflora composition and biomass pre-treatment methods. The study by Yu. Okhota (2023) demonstrated that the use of mixed substrates (e.g., a combination of agricultural waste and food residues) increases biogas yield and stabilises its quality composition. At the same time, the high content of lignocellulose in biomass requires additional hydrolysis or mechanical grinding steps to increase the availability of organic compounds for microorganisms.

Temperature conditions are crucial in fermentation processes. The mesophilic regime (35-40°C) ensures a stable fermentation process with minimal energy consumption, while the thermophilic regime (50-60°C) increases the decomposition rate of organic raw materials, but requires careful control of conditions to maintain microflora activity. The optimal ratio of nitrogen to carbon in biomass is also a critical parameter that affects the quality of the final biogas.

The process of biogas enrichment to biomethane involves the removal of CO_2, H_2S, NH_3 and water vapour. As shown in Table 1, different purification technologies are used, including membrane separation, variable pressure adsorption, absorption (chemical, physical, aqueous) and cryogenic distillation. Membrane technology is the most common due to its efficiency and low operating costs, although variable pressure adsorption and cryogenic separation provide higher purity of the final product.

Table 1. Technical characteristics of the main technologies for biogas purification to biomethane

Cleaning technology	Degree of CH_4 purification (%)	Energy consumption (kWh/1000 m³)	Main impurities removed	Advantages	Limitations
Membrane separation	96-98	0.15-0.3	CO_2, H_2O	Low costs, compactness, simplicity	Does not completely remove H_2S and NH_3
Variable pressure adsorption	97-99	0.2-0.5	CO_2, partially H_2S	High product purity	High capital expenditures, moisture sensitivity
Chemical absorption	98-99.5	0.3-0.6	CO_2, partially H_2S	Extremely high CO_2 efficiency	Corrosion, reagent costs
Physical absorption	95-97	0.2-0.4	CO_2	Efficient at high pressure	Limited efficiency at low-pressure
Water absorption	90-96	0.25-0.4	CO_2, H_2S, NH_3, H_2O	Environmentally friendly, does not require chemicals	Low efficiency at low-pressure
Cryogenic distillation	98.5-99.9	0.5-0.8	CO_2, H_2S, H_2O, NH_3	Maximum purity of biomethane	High energy costs, the complexity of the process

Source: compiled by the authors based on Yu. Okhota (2023)

Following Table 1, each of the biogas treatment technologies has advantages and limitations that determine their feasibility depending on specific production conditions. Membrane separation demonstrates a balanced ratio between energy efficiency (0.15-0.3 kWh/1000 m³) and high CH4 removal (96-98%), making it the most popular for small and medium-sized plants. Variable pressure adsorption technology provides even higher purity (up to 99%) and better CO_2 removal but is sensitive to humidity and requires significant investment. Chemical absorption provides extremely high CO_2 removal efficiency but is accompanied by corrosive effects and reagent costs. Physical and aqueous absorption are inferior in terms of purification but remain simple and environmentally acceptable solutions for medium-sized facilities. Cryogenic distillation shows the highest quality of biomethane purification (up to 99.9%) and can remove all major impurities simultaneously, but requires the highest energy costs and complex infrastructure. Thus, the choice of a particular technology should be based on the optimal balance between the required biomethane quality, the investor's economic capacity and the technical conditions of the plant.

The biomethane produced can be used in various sectors of the economy. It is supplied to medium and low-pressure gas networks, transported to high-pressure gas pipelines, or used to fuel vehicles through automotive gas-filling compressor stations (Table 2). Depending on the scale of production and logistics, there are three possible approaches to creating biomethane complexes: centralised plants based on a single biogas plant; multi-level systems combining several sources of raw materials; and distributed biogas networks with biogas pipelines transporting raw materials to a single processing complex.

Table 2. Technical parameters of biomethane transportation and storage in the gas transmission system

Parameter	Values/units of measurement	Comment
Operating supply pressure in the gas transmission system	1.2-7.5 MPa	Depending on the category of the pipeline
Minimum CH_4 content	≥96%	Requirement for compliance with DSTU EN 16723-1:2023

Continued Table 1.

Parameter	Values/units of measurement	Comment
Maximum CO_2 content	≤2%	Ensuring the quality of gas for transportation
Biomethane temperature range	-5°C...+50°C	Safe transport temperature
Efficiency of the compressor station for supply	85-92%	Determines the energy loss on compression
Possibility of storage in UGS facilities	Yes	Technical compatibility of biomethane with underground natural gas storage facilities
Estimated losses during transport	0.1-0.5% per 100 km	Depending on the quality of the seals, the condition of the pipelines

Source: compiled by the authors based on Yu. Okhota (2023), Bioenergy in 2024: A global report is now available at SAF (2024)

Table 2 highlights the key technical parameters that are crucial for the integration of biomethane into the Ukrainian gas transmission system and can be used for a preliminary engineering assessment of its compatibility with the existing infrastructure. In particular, the operating supply pressure in the range of 1.2-7.5 MPa indicates the need for compressor equipment capable of compressing gas to a level that corresponds to the category of the gas pipeline. This affects electrical calculations, in particular electricity consumption at compressor stations, where an efficiency of 85-92% can estimate energy losses during the supply process and justify the feasibility of using different types of compressors (turbo compressors, reciprocating, screw, etc.). The minimum CH_4 content of ≥96% and the maximum CO_2 content of ≤2% meet the requirements of DSTU EN 16723-1:2023, which ensures the appropriate calorific value of the gas and compatibility with combustion systems. This is critical for safety, and combustion efficiency in industrial and domestic installations, as well as for the accuracy of gas calorific value calculations in commercial metering. The range of permissible temperatures for biomethane (-5°C...+50°C) demonstrates its reliability in transportation in different climatic zones of Ukraine, which avoids thermal deformation or the risk of water vapour condensation in networks. Estimated transmission losses (0.1-0.5% per 100 km) are an indicator of the technical condition of gas pipelines and the quality of sealing joints, which determines the need for periodic maintenance and modernisation of the gas transmission system. Special attention should be paid to the technical feasibility of biomethane accumulation in underground gas storage facilities, which indicates its full interoperability with natural gas if it meets the standards. This opens up the prospects for balancing demand, creating strategic reserves, and using biomethane as an element of flexible energy supply.

An analysis of European practice demonstrated that the adaption of the infrastructure to receive biomethane requires the development of a system of guarantees of origin and the modernisation of compressor stations to stabilise gas pressure in the networks. The use of biomethane as a motor fuel is also actively developing, as evidenced by the growing number of automotive gas-filling compressor stations adapted to receive biomethane. The EU experience demonstrates the effectiveness of strategies to expand the use of biomethane. Table 3 demonstrates the dynamics of the biomethane industry in the EU in 2019-2024, reflecting the number of biomethane plants in the leading countries of the industry.

Table 3. EU countries with the largest number of biomethane plants

Country	2019	2020	2022	2023	2024
Germany	232	242	250	260	270
France	123	214	400	500	550
Great Britain	99	107	120	130	135
Sweden	70	70	75	78	80
Netherlands	51	60	68	72	75
Denmark	42	52	60	65	70
Switzerland	37	39	45	50	55
Italy	12	23	30	35	40
Finland	17	22	25	27	30
Austria	15	15	18	20	22
Norway	13	13	15	18	20
EU (total)	725	880	1400	1510	1600

Source: compiled by the authors based on Yu. Okhota (2023), Bioenergy in 2024: A global report is now available at SAF (2024)

According to the European Biogas Association, at the end of 2023, there were 1510 biomethane plants in operation in Europe, which is 201 more than in 2022. In 2024, the total installed capacity of biomethane plants reached 6.4 billion m^3 per year. Table 3 shows the dynamics of growth in the number of biomethane plants in the EU in

2019-2024, which demonstrates the gradual but steady expansion of the renewable gas sector. Germany traditionally holds the lead in terms of the number of biomethane plants: from 232 in 2019, their number increased to 270 in 2024. However, it is France that is showing the highest growth rate, from 123 plants in 2019 to 550 in 2024, as a result of consistent government policy to support biomethane production and build the relevant infrastructure. The UK also demonstrates stable dynamics: the number of its biomethane plants has increased from 99 to 135 over the five years. The Nordic countries of Sweden, Denmark and Finland have shown gradual growth, which is in line with the strategic course of these countries towards decarbonisation and expansion of the renewable energy sector. In particular, the number of plants in Sweden increased from 70 to 80, in Denmark from 42 to 70, and in Finland from 17 to 30. Similar positive dynamics can be observed in the Netherlands (from 51 to 75), Switzerland (from 37 to 55) and Italy (from 12 to 40), which indicates the modernisation of bioenergy infrastructure and increased investment in the sector. Biomethane capacity developed at a more moderate pace in Austria (from 15 to 22) and Norway (from 13 to 20), which can be explained by the structure of their energy mix, particularly the high share of hydropower in Norway. Overall, in 2019-2024, the number of biomethane plants in the EU increased from 725 to 1600, which confirms the high interest in biomethane as a key component of the energy transition strategy and strengthening the region's energy security.

Thus, these data confirm the positive dynamics of the biomethane industry in Europe, which is the result of active environmental policy, financial incentives and growing demand for renewable energy resources. The EU plans to significantly expand the production of renewable gases. In this context, the European Commission (2025) has developed the REPowerEU programme aimed at strengthening the resilience of the EU energy system. The strategy is based on two key pillars: diversification of gas supplies by increasing imports of liquefied natural gas and pipeline gas from alternative suppliers, and active development of biomethane and renewable hydrogen production and imports. The REPowerEU includes urgent measures to mitigate the effects of high energy prices, ensure the stability of gas supplies and accelerate the transition to clean energy sources. Figure 3 shows the projected growth of biogas and biomethane production in Europe in 2020-2050, in billion m^3. Production is projected to increase from around 15 billion cm^3 in 2020 to over 120 billion cm^3 in 2050.

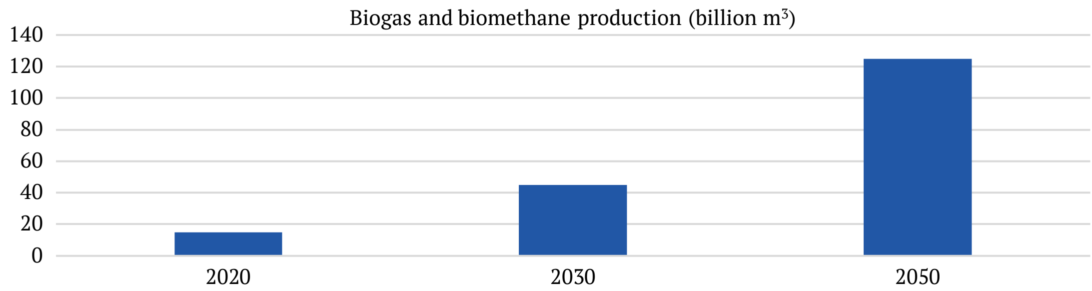

Figure 3. Forecast of biogas and biomethane production in Europe until 2050
Source: compiled by the authors based on Yu. Okhota (2023), Bioenergy in 2024: A global report is now available at SAF (2024)

Data demonstrates a significant increase in production volumes: while in 2020 this number was relatively low, by 2030 it is expected to grow significantly, due to increased investment in the bioenergy sector and the active implementation of renewable technologies. By 2050, biogas and biomethane production is projected to reach its maximum levels, driven by the implementation of global decarbonisation initiatives, including the REPowerEU programme, which promotes the development of bioenergy and the integration of renewable sources into the overall energy balance. In the EU, the biomethane industry is regarded as one of the possible ways to achieve climate goals and reduce greenhouse gas emissions, which underlines its strategic importance in the transition to sustainable energy. Given these trends, biomethane is also a prominent way to ensure Ukrainian energy security, as it is a potential renewable energy source that can partially replace imported natural gas and help reduce dependence on fossil fuels. Its production is based on the use of local organic waste, which could theoretically reduce dependence on external energy suppliers and contribute to the development of the domestic energy sector. If the necessary economic and regulatory conditions are created in Ukraine, biomethane could be integrated into the national energy system, potentially stabilising gas supplies, especially in times of crisis when access to traditional energy resources is limited or unstable. Ukrainian current energy policy prioritises gradual diversification of energy sources, development of renewable resources and reduction of dependence on fossil fuels. Given global trends in decarbonisation, biomethane may become one of the most promising areas for improving national energy sustainability. European experience shows that political support, incentive mechanisms and regulatory frameworks are key to the development of the biomethane market. In Ukraine, these factors can also help accelerate the introduction of biogas enrichment technologies and their integration into the gas transmission network. In addition, biomethane may have export potential, which opens additional opportunities for the Ukrainian energy market, especially given the active development of renewable gases within the EU.

The potential for biomethane production in Ukraine largely depends on the availability of a feedstock base, which is formed from agricultural, industrial and household organic residues. An analysis of the resource potential demonstrated that the country has sufficient biomass to produce more than 10 billion cubic metres of biomethane per year, which is equivalent to approximately a third of current Ukrainian natural gas consumption. The main sources of biomass are agricultural waste, including cattle, pig and poultry manure, straw, corn stalks, silage and beet pulp. Industrial waste also has significant energy potential, especially residues from the food, sugar, brewing and dairy industries. An additional source of biomass is municipal organic waste, including solid household waste, catering residues and sewage sludge. According to analytical studies, the agricultural sector has the greatest potential for biomethane production, generating significant volumes of organic residues suitable for anaerobic digestion. Table 4 shows the potential of biomethane production based on different types of feedstocks.

Table 4. Potential for biomethane production from different types of feedstocks in Ukraine

Source of biomass	Potential biomethane yield (m^3/t)	Annual production potential (billion cm^3)
Cattle manure	55	2.5
Pig manure	60	1.8
Poultry manure	70	1.2
Corn silage	200	3.5
Wheat straw	120	2.0
Beet pulp	150	1.7
Remnants of the meat industry	800	0.9
Remnants of the dairy industry	500	0.8
Solid household waste	100	0.6
Wastewater	50	0.5

Source: compiled by the authors based on Yu. Okhota (2023), Bioenergy in 2024: A global report is now available at SAF (2024)

The distribution of raw materials is a key factor in the formation of biogas clusters, which contribute to efficient logistics and optimisation of production processes. The greatest opportunities for biomethane production are concentrated in regions with a high concentration of agricultural production, which ensures a stable supply of organic waste for processing. Figure 4 illustrates the regional distribution of biomethane production potential in Ukraine, covering the availability of feedstock and the concentration of agricultural enterprises.

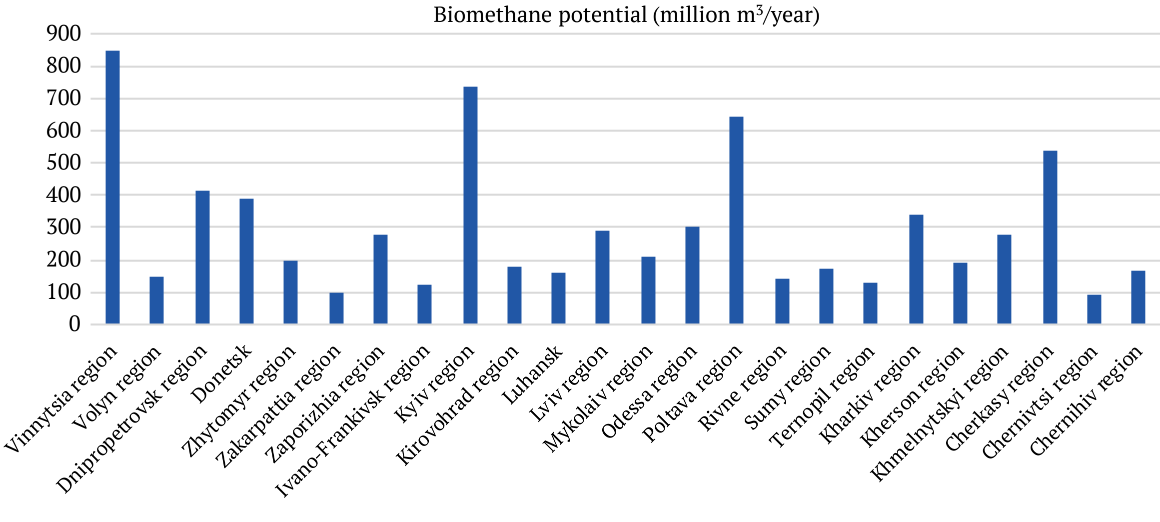

Figure 4. Regional distribution of biomethane production potential as of 2024
Source: I. Zamula *et al*. (2024)

The potential for biomethane production in Ukraine is estimated at 21.8 billion m^3 per year, which is higher than the country's natural gas production in 2023 (18.7 billion m^3). The most promising regions for biomethane production are Kyiv, Vinnytsia, Poltava and Cherkasy regions, which have a significant raw material base for processing organic waste. The regional distribution of biomethane production potential in Ukraine is uneven. The highest potential is in Vinnytsia, Kyiv, Cherkasy, Poltava, Dnipro and Donetsk regions, where the potential for CH_4 production ranges from 38 to 846 million m^3 per year.

These data demonstrated significant opportunities for the development of the biomethane industry in Ukraine, especially in regions with a developed agricultural sector and the availability of raw materials for biogas production. The economic feasibility of large-scale biomethane production largely depends on the cost of raw materials, the cost of biogas purification and enrichment processes, and the level of government support for the sector. Analysis of the European experience determined that countries with developed biogas infrastructure actively use subsidies, tax benefits and systems of guarantees of origin to stimulate biomethane production. In this context, Ukraine needs to develop and implement similar instruments that will help attract investment in the sector and create a stable biomethane market. From the perspective of energy security, biomethane is seen as a key element in the strategy of replacing imported natural gas. Biogas can diversify energy sources and reduce dependence on volatile international markets. In addition, the transportation of biomethane through existing gas networks makes it a beneficial option for ensuring the stability of energy supply in regions with access to an extensive gas transmission infrastructure.

The use of biomethane also reduces greenhouse gas emissions, as its production is based on a closed carbon cycle. The use of agricultural waste and industrial and household residues in biogas plants reduces CH_4 and CO_2 emissions generated by their uncontrolled decomposition. This is especially important in the context of European climate commitments and the gradual decarbonisation of the energy sector.

The potential of biomethane as a backup fuel for energy needs in times of crisis is notable. Military operations and the deliberate destruction of Ukrainian energy infrastructure create an urgent need to develop decentralised energy sources that can ensure uninterrupted gas and electricity supply independently of centralised systems. Biomethane has significant potential in this context, as it can be produced and used locally, reducing the vulnerability of regional energy systems to attacks on major gas pipelines and power generation facilities. Figure 5 demonstrates that biomethane is one of the most promising energy sources for ensuring energy security in times of crisis.

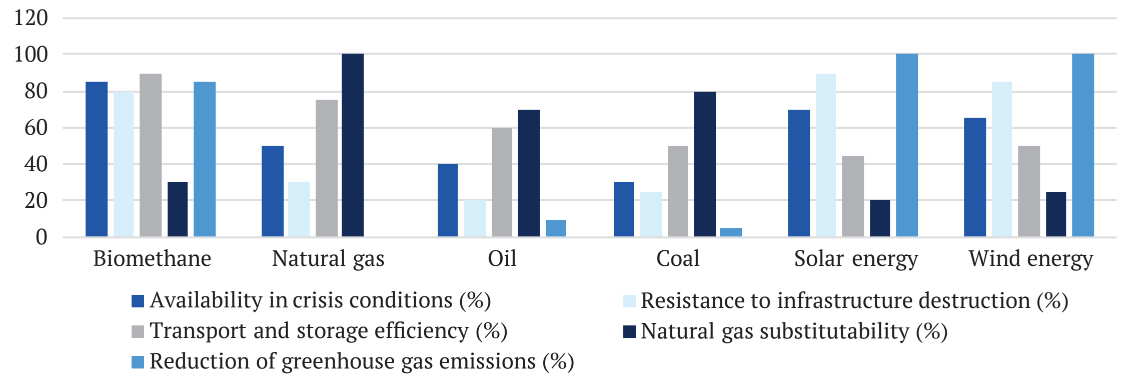

Figure 5. Comparative analysis of energy sources by energy security and environmental efficiency criteria
Source: compiled by the authors based on Law of Ukraine No. 1820-IX (2021)

Figure 5 demonstrates that biomethane has one of the highest availability rates in a crisis at around 85%, which is significantly higher than the respective rates for natural gas (50%) and oil (40%). This is determined by the decentralisation of biomethane production, and gas can be generated without being tied to imported supplies or main gas pipelines. Resilience to infrastructure destruction. In the event of targeted destruction, it is critical to maintain uninterrupted energy supply. Biomethane has 80% resilience, which means that even if the main gas transmission networks are damaged, its production and use can be carried out locally. This is a significant advantage compared to centralised gas systems, which have only 30% resilience as they are dependent on large trunk pipelines. Biomethane can be easily transported through existing gas networks and stored in storage facilities, with an efficiency of up to 90% in this regard. By comparison, storing electricity from solar and wind power plants is much less efficient, as they require battery storage or special energy conversion systems, making them only 45-50% efficient.

The diagram also demonstrated that biomethane can replace up to 30% of the total volume of natural gas in Ukraine, which is equivalent to about 9-10 billion m^3 per year. For comparison, imported natural gas covers about 40-50% of the country's total gas consumption. Thus, increasing biomethane production will significantly reduce dependence on imports. Biomethane has a significant positive environmental impact, reducing greenhouse gas emissions by around 85% compared to natural gas. While the combustion of coal, oil and conventional gas generates significant amounts of CO_2, biomethane has a near-neutral emissions balance due to the use of organic waste. Table 5 shows the projected volumes of biogas and biomethane production in Ukraine by 2050, considering the prospects for their use in various sectors of the economy.

Table 5. Forecast of biogas and biomethane production in Ukraine until 2050

Years	Biogas for heat and power generation	Biomethane, total	Biomethane for thermal power plants	Biomethane for transport	Biomethane for heat production and industrial use	Biomethane for export
2020	0.13	0	0	0	0	0
2025	0.36	0.44	0.11	0.01	0.1	0.22
2030	0.6	1	0.23	0.08	0.2	0.5
2035	0.83	1.69	0.35	0.18	0.31	0.84
2040	1.06	2.5	0.49	0.34	0.43	1.25
2045	1.28	3.44	0.63	0.54	0.55	1.72
2050	1.5	4.5	0.79	0.79	0.68	2.25

Source: compiled by the authors based on Bioenergy in 2024: A global report is now available at SAF (2024)

According to forecasts, the total volume of biomethane could increase to 4.5 billion m^3 per year in 2050, while biogas for heat and power production could reach 1.5 billion m^3. The main growth in biomethane production is expected to come from exports, which could grow from 0.22 billion m^3 in 2025 to 2.25 billion m^3 in 2050. Domestic consumption of biomethane will also gradually increase, for thermal power plants, transport, industry and heat production. In 2030, 0.23 billion m^3 of biomethane is expected to be used for thermal power plants, which will account for approximately 23% of the total projected volume, and by 2050 this figure will increase to 0.79 billion m^3. The use of biomethane for transport will also have an upward trend: in 2030, the production of 0.08 billion m^3 is forecasted, and in 2050, 0.79 billion m^3. This indicates the prospect of widespread use of biomethane as an environmentally friendly motor fuel. In general, the projected increase in biomethane production in Ukraine could significantly reduce dependence on natural gas imports and promote the development of renewable energy.

The prospects for biomethane exports from Ukraine to the EU are an important area of development for the bioenergy industry, which is in line with the European goals of decarbonisation and energy security. Ukraine's integration into the European energy area requires that the national biomethane market comply with EU requirements, including certification mechanisms, a system of guarantees of origin and transportation standards. In 2019-2024, several measures were taken at the legislative level to promote the development of the biomethane market and its exports. In particular, the Law of Ukraine No. 1820-IX (2021) was adopted. The implementation of this mechanism will enable export of biomethane to Europe by Ukrainian producers, as the availability of a relevant certificate will confirm its compliance with environmental standards. In addition, the Procedure for the Functioning of the Biomethane Register was approved, which defines the procedures for registration, verification and accounting of the fuel produced.

An additional step was the adoption of the Law of Ukraine No. 2320-IX (2022), which promotes the use of organic waste as a feedstock for biomethane production. This correlates with European approaches to the circular economy and resource utilisation strategies. Another important achievement was the adoption of State Standard of Ukraine No. 16723-1:2023 (2023), which regulates the technical requirements for biomethane for injection into gas networks. This standard was developed following the European norms, which greatly simplifies the integration of Ukrainian biomethane into the EU gas supply system. Financial incentives are key in the development of the biomethane industry, as they ensure the economic attractiveness of production and help attract investment. As the experience of EU countries shows, government support in the form of biomethane tariffs and feed-in tariffs for biomethane electricity is an effective mechanism for stimulating this sector (Table 6).

Table 6. Financial support for biomethane in EU countries

Country	Biomethane tariff (EUR/m^3)	Green tariff for electricity (EUR/kWh)
Denmark	0.735	-
France	0.45-0.95 (municipal solid waste), 0.85-1.25 (agriculture)	0.15-0.175
Italy	0.796	-
Netherlands	0.483-1.035	-
Germany	-	0.134-0.237 (+0.03 bonus for biomethane)
Great Britain	-	0.1-0.116 (FIT scheme, RHI until 2021)
Switzerland	-	0.146-0.233 (depending on the source and power)
Sweden	-	No fixed tariffs; support through tax incentives
Finland	-	State investment grants, certificates of origin
Austria	-	Regional subsidies, tax instruments
Norway	-	Support through Enova SF, fiscal incentives, no fixed tariff

Source: compiled by the authors based on Ministry of Agrarian Policy and Food of Ukraine (2023), Bioenergy in 2024: A global report is now available at SAF (2024)

As shown in Table 6, there are two main mechanisms of financial support for the biomethane sector in the EU and associated countries: direct tariffs for biomethane injected into the gas transmission network and feed-in tariffs for electricity produced from biomethane or biogas. Several countries (France, Denmark, Italy, and the Netherlands) have clearly defined tariff incentives for biomethane: for example, in Denmark, it is 0.735 EUR/m^3, in France 0.45-0.95 EUR/m^3 for biomethane from municipal solid waste and 0.85-1.25 EUR/m^3 for agricultural feedstock. In Italy, the tariff is fixed at 0.796 EUR/m^3, and in the Netherlands in the range of 0.483-1.035 EUR/m^3, which creates long-term financial attractiveness for investors. At the same time, in countries such as Germany, the UK, France, Switzerland and partially Austria, priority is given to tariffs for electricity produced from biomethane. In Germany, the tariff ranges from 0.134-0.237 EUR/kWh with an additional bonus of 0.03 EUR/kWh for the use of biomethane. In France, the tariff is 0.15-0.175 EUR/kWh, in the UK 0.1-0.116 EUR/kWh, and in Switzerland 0.146-0.233 EUR/kWh. In Sweden, Finland, Austria and Norway, fixed tariff rates are generally absent, but alternative support mechanisms are used: tax breaks, guarantees of origin, investment grants or support from government agencies, such as Enova SF in Norway. This diverse approach to financing reflects national energy strategies and market development in each country. At the same time, the availability of financial incentives in any form significantly enhances the economic feasibility of investing in the biomethane industry, ensuring its competitiveness against traditional energy resources.

Ukraine, which is developing the biomethane sector, can use the experience of EU countries to develop its financial support mechanisms. Even though the legal framework for biomethane production has already been established through the introduction of a register of guarantees of biomethane origin, it is necessary to create a system of economic incentives that will help attract investment and increase production. Possible support instruments include the introduction of a guaranteed tariff for biomethane, tax benefits, and a feed-in tariff for electricity produced from biomethane. Such measures could stimulate the construction of new biomethane plants and increase investor interest in the Ukrainian renewable gas market. Projected estimates show that by 2050, Ukraine could produce up to 4.5 billion m3 of biomethane per year, much of which could be exported. This will not only reduce dependence on fossil fuel imports but will also contribute to the decarbonisation of the economy, which is in line with the European trends of energy transformation. Ukraine is actively working to integrate the biomethane market into the European energy space, which requires harmonising its regulatory framework with EU legislation. The Law of Ukraine No. 1820-IX (2021) establishes the legal framework for biomethane certification and the functioning of an electronic register of guarantees of origin. The document provides a legal basis for the implementation of biomethane guarantees of origin that meet EU requirements. An important addition is the Law of Ukraine No. 2320-IX (2022), which defines the principles of organic residue management as a valuable raw material for bioenergy, for biomethane production. In the context of the technical integration of biomethane into the gas transmission system, the State Standard of Ukraine No. 16723-1:2023 (2023). In particular, the document regulates the permissible content of CH_4, CO_2, H_2S, NH_3 and water vapour, as well as pressure and temperature parameters. At the EU level, the regulation is based on the Directive of the European Parliament and of the Council No. 2018/2001 (2018), which defines mandatory shares of energy from renewable sources in final consumption, in particular in the transport sector, and provides for the use of a system of guarantees of origin for biomethane and other renewable gases. In addition, Regulation (EU) No. 2019/942 of the European Parliament and the Council Establishing a European Union Agency for the Cooperation of Energy Regulators (2019) defines the mechanisms for European monitoring and verification of renewable gas guarantees of origin, including carbon footprinting requirements, which is key for biomethane trade in the EU single market.

Despite the adoption of relevant legislative changes, Ukrainian biomethane exports require further development of certification mechanisms in line with EU standards and integration of the Ukrainian Register of Guarantees of Origin with the European Renewable Gas Registry. Despite its high export potential, the Ukrainian biomethane market faces several barriers. One of the key ones is customs and administrative restrictions: the lack of clear mechanisms for certification and confirmation of biomethane origin following EU standards makes it difficult for it to enter the European market. In addition, Ukraine currently has limited access to the European biomethane transportation infrastructure, as not all gas operators recognise the possibility of integrating Ukrainian biomethane into their gas transmission system. An additional barrier is the lack of long-term supply contracts, as European buyers require guarantees of stable production, which is not yet sufficiently supported by the state in Ukraine.

Calculations of biomethane production costs show a significant advantage for Ukraine due to the lower cost of raw materials. CAPEX (capital expenditures) in Ukraine is 900-1200 EUR/kW of installed capacity, which is lower than in the EU (1500-2000 EUR/kW). OPEX (operating costs) for Ukrainian biogas plants are estimated at 25-35 EUR/MWh, while in the EU this figure reaches 40-55 EUR/MWh due to higher labour and administrative costs (Geletukha *et al.*, 2022). Despite economic competitiveness, low levels of investment support and lack of government incentives remain key constraints to the development of the biomethane sector. The most effective support mechanisms that can be implemented in Ukraine are tax incentives for biomethane producers, feed-in tariffs similar to European programmes, and state subsidy programmes for the modernisation of biogas plants. In 2019-2024, biogas production in Ukraine grew at a steady pace. In 2024, about 1 billion m^3 of biogas was produced, although this is significantly lower than the projected growth rate of the sector. The main risks include the lack of government support in the form of a feed-in tariff for biomethane, the high cost of connecting to the gas transmission system, and military risks that limit investment activity in the sector. However, with proper support, the forecast for 2050 remains optimistic: 2 billion m^3/year in 2030, 6 billion m^3/year in 2040, and 10 billion m^3/year in 2050.

Comparison of biogas treatment methods shows that the most appropriate for Ukrainian biogas plants are variable pressure adsorption and membrane technology. The membrane technology is the most common in the EU due to its high efficiency but requires significant investment. Variable pressure adsorption is the best option for Ukraine due to lower implementation costs and easier operation. Cryogenic separation, although providing the highest level of purification, is too energy-intensive and expensive for Ukrainian producers. The logistical possibilities for transporting biomethane from Ukraine are currently limited, but there are two main export routes. Ukraine's gas transportation system, which is one of the largest in Europe, could theoretically be used to transport biomethane but needs to be adapted to accept this type of fuel. Liquefied natural gas exports are another promising option, enabling the transportation of biomethane in liquefied form to European terminals. Given the European experience, the most effective model would be to create biomethane hubs in Ukraine's border regions, which would simplify its further transportation to the EU.

The integration of Ukrainian biomethane into the European energy system requires further improvement of the regulatory framework, adaptation of infrastructure and introduction of support mechanisms, including tax benefits and feed-in tariffs. By actively attracting investment and implementing relevant reforms, Ukraine has every opportunity to become a key supplier of biomethane to the EU market. Given the strategic importance of biomethane for the country's energy security, the development of financial support mechanisms will be an important step towards creating a competitive biomethane market in Ukraine and its further integration into the European energy space.

DISCUSSION

The results of the study confirm the significant potential of biomethane production in Ukraine as a strategic resource for energy security and economic development. According to the study by G. Geletukha & Y. Matveev (2021), the use of local agricultural and industrial waste can produce more than 10 billion m^3 of biomethane per year, which can replace a significant share of imported natural gas. The study results correlated with the findings of M. Zupančič *et al.* (2022), who analysed waste to biogas technologies in European countries, proving that decentralised biomethane production contributes to increased energy independence and reduced fossil fuel use. The introduction of modern biogas to biomethane technologies is crucial to ensure that the product meets EU technical standards (Kucher *et al.*, 2022). An important stage of this study was the comparison of biogas purification technologies for its enrichment to biomethane. The analysis of different purification methods demonstrated that variable pressure adsorption and membrane separation are the most efficient and economically feasible for Ukrainian production conditions, which is confirmed by similar studies by B. de Souza Moraes *et al.* (2022) and M. Gustafsson *et al.* (2024). Variable pressure adsorption technology ensures high biomethane purity by efficiently removing CO_2, H_2S and other impurities, while membrane separation is less energy-intensive and reduces operating costs. Studies also indicate that cryogenic distillation has the highest level of purification but is less accessible due to high capital and operating costs. The results of this study confirm the significant potential of biomethane production in Ukraine as a strategic resource for energy security and economic development. Analysis of the Ukrainian market has shown that the use of local agricultural and industrial waste can produce more than 10 billion m^3 of biomethane per year, which can replace a significant share of imported natural gas. The regional analysis confirmed that the most promising regions for the development of biomethane clusters are Vinnytsia, Kyiv, Poltava, Khmelnytskyi, Cherkasy, and Lviv regions, which is consistent with the findings of G. Trypolska (2023a; 2023b).

An analysis of the costs of biomethane production in Ukraine has demonstrated the competitiveness of the industry compared to the EU. CAPEX for Ukrainian biogas plants is 900-1200 EUR/kW, which is significantly lower than the European figures (1500-2000 EUR/kW). OPEX is estimated at 25-35 EUR/MWh, while in the EU this figure reaches 40-55 EUR/MWh due to higher labour and administrative costs. This is in line with the findings of N.P. Reznik *et al.* (2024), emphasise the impact of financial incentive mechanisms on the development of the biomethane industry.

From an environmental point of view, the use of biomethane can reduce CO_2 emissions by 85% compared to natural gas, as confirmed by the study by S. Belinska *et al.* (2024). In addition, biomethane is in line with the European Green Deal strategy, which defines it as a key resource for decarbonising the economy, as noted by M. Zablodskiy *et al.* (2024). The analysis of the export potential of Ukrainian biomethane has revealed several barriers, including customs and administrative restrictions, lack of clear certification mechanisms, and limited access to the European gas transmission infrastructure. At the same time, this study demonstrated that the introduction of mechanisms of origin and the adaptation of the regulatory framework to EU standards could significantly improve the export potential of Ukrainian biomethane, which is supported by the findings of B. Cahill & L. Palti-Guzman (2023).

A separate aspect of this study was an assessment of the stability of biomethane as an energy source in crises. Our analysis has shown that decentralised biomethane production can minimise the risks of gas supply disruptions, which is consistent with the findings of M. Farghali *et al.* (2022) and O. Kucher *et al.* (2024). An important factor was the study of biomethane's resistance to attacks on energy infrastructure, which is critical in times of war and unstable geopolitical situations. The agricultural sector, which generates large volumes of organic waste suitable for anaerobic digestion, has significant potential for biomethane production (Golub *et al*., 2018). This was confirmed by Y. Chernysh *et al.* (2022), who identified agricultural waste as the main source of raw materials for the development of the biomethane industry in Ukraine. In addition, the analysis of G. Ahamer (2021) confirmed that the use of agricultural residues is a key factor in ensuring the country's energy independence.

The assessment of the logistical possibilities for biomethane exports from Ukraine showed that there are two main routes of transportation the Ukrainian gas transmission system and the export of liquefied natural gas. Transportation through the gas transmission system is the most obvious and potentially cost-effective option, as Ukraine has one of the most extensive gas networks in Europe (Danylyshyn & Koval, 2023). However, this requires infrastructure upgrades, including the adaptation of compressor stations, the introduction of biomethane quality control systems, and the integration of the Ukrainian certification system for guarantees of origin with European standards of the European Renewable Gas Registry. In addition, one of the key challenges is the lack of a regulatory framework for the commercial transportation of biomethane through the gas transmission system, which requires harmonisation with EU legislation.

The second promising route is the export of liquefied natural gas, which enables transportation of biomethane in liquefied form through specialised terminals (Lisovyk *et al*., 2024). This option is particularly relevant for entering the global market and supplying biomethane to countries that do not have direct gas connections with Ukraine. However, the export of liquefied natural gas requires significant investments in the creation of relevant infrastructure, including liquefied biomethane plants, terminals for loading it, and logistics chains for transportation. Despite the high initial costs, LNG exports could become a strategic area of development, especially in the context of the growing demand for renewable gases in Europe.

To implement the export potential, it is necessary to modernise gas networks, which was confirmed by Y. Furdas *et al.* (2024) and E. Shahini *et al.* (2024). The authors emphasised that the adaptation of the gas transmission system for biomethane includes both technical improvements (installation of purification systems, control of biomethane mixing with natural gas) and regulatory changes (harmonisation of certification rules, harmonisation of transportation tariffs). International cooperation is also an important aspect of Ukraine's integration into the European biomethane market, which involves synchronising standards, mutual recognition of guarantees of origin and harmonisation of export procedures (Andreitsev *et al*., 2024). Given the successful experience of Germany, Denmark and France in expanding the biomethane sector, Ukraine has the potential to become a significant supplier of renewable gas to the European market, but this requires a clear strategy for developing logistics infrastructure and overcoming existing regulatory barriers.

In summary, it is worth noting that the results of this study are closely intertwined with the work of other authors, confirming the complex nature of the topic of biomethane development in Ukraine. This applies to both the assessment of the technical potential of production and the analysis of the economic feasibility, technological efficiency and environmental significance of biomethane. The research results demonstrate a common vision of the need for a transition to decentralised energy, where biomethane plays a key role in ensuring energy sustainability and independence. There is also a common perception that the development of the biomethane sector requires simultaneous modernisation of infrastructure, adaptation of the regulatory framework to EU standards, introduction of financial support mechanisms, and integration into the European renewable gas certification and metering system. The importance of cross-sectoral cooperation between agriculture, energy, environmental policy and international trade is also confirmed.

CONCLUSIONS

The study confirmed that the Ukrainian biogas and biomethane industries are important components of energy independence and decarbonisation of the country's economy. An analysis of the Ukrainian regulatory framework shows the gradual implementation of EU standards, through the adoption of Law of Ukraine No. 1820-IX on the development of biomethane production and the creation of an electronic register of guarantees of its origin. This creates the preconditions for biomethane exports to the EU. However, further alignment with the RED II Directive and the Gas Guarantees Regulation is required for full integration. The production potential of biomethane in Ukraine is estimated at over 10 billion m^3 per year, which can replace a significant portion of imported gas, ensuring energy stability. The results obtained demonstrate that biogas production from agricultural, industrial and municipal waste is a promising area that not only reduces dependence on natural gas imports but also contributes to environmentally sound waste management.

The introduction of modern purification technologies, such as membrane separation, variable pressure adsorption and cryogenic distillation, ensures the production of high-quality biomethane that meets EU requirements and can be integrated into gas transmission networks. A comparison of biomethane production costs (CAPEX, OPEX) in Ukraine and the EU showed the competitiveness of domestic products due to the lower cost of raw materials. CAPEX for Ukrainian biogas plants is estimated at 900-1200 EUR/kW, which is significantly lower than in the EU (1500-2000 EUR/kW). OPEX is estimated at 25-35 EUR/MWh, which is also more favourable compared to Europe (40-55 EUR/MWh). However, the development of the biomethane industry is hampered by the lack of financial support mechanisms. The most effective incentives that can be introduced in Ukraine are tax benefits for biomethane producers, "green" tariffs and government subsidies for the modernisation of biogas plants. An analysis of the EU's competitive environment has shown that the most dynamically developing biomethane market is in France, Germany and Denmark, where favourable financial support mechanisms are in place.

Ukraine has the potential to integrate into this market but faces logistical challenges. The main barriers to exports include customs and administrative restrictions, lack of clear certification mechanisms, and limited access to the European biomethane transport infrastructure. An estimate of real biomethane production in Ukraine for 2019-2024 shows slow growth in the industry. In 2023, about 300 million m^3 of biogas was produced, which is only 3% of the potential volume. The main factors limiting production are the lack of government support in the form of a feed-in tariff for biomethane, the high cost of connecting to the gas transmission system, and military risks. The resilience of biomethane to crises and the possibility of its local production minimises the risks associated with gas supply interruptions, which is especially important in times of energy instability. Biomethane can ensure a stable supply of energy even in the event of the destruction of the main infrastructure, making it a strategically important resource for Ukraine.

Further research should address the improvement of biomethane purification and transportation technologies, developing a regulatory framework for its certification following EU standards, and creating favourable economic conditions for attracting investment in the renewable gas sector. Ukrainian integration into the European biomethane market opens additional opportunities for the development of this industry, which will contribute to economic growth and increase national energy security.

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CONFLICT OF INTEREST

None.

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Біогазова та біометанова промисловість України як основа енергетичної незалежності країни

Анотація. Метою дослідження було провести оцінку потенціалу біометанової промисловості України, аналіз технологій виробництва та очищення біогазу, економічних та нормативно-правових аспектів, а також можливостей інтеграції у ринок ЄС. Дослідження підтвердило, що Україна має ресурсний потенціал для виробництва понад 10 млрд м^3 біометану на рік завдяки використанню відходів агропромисловості, тваринництва, харчової промисловості та побутових органічних залишків. Проаналізовано технологічні процеси виробництва, включаючи анаеробне зброджування, очищення та збагачення біогазу, а також ефективність методів очищення, таких як мембранна сепарація, адсорбція при змінному тиску та кріогенна дистиляція. Досліджено нормативно-правову базу України щодо біометану та її гармонізацію зі стандартами ЄС. Прийняття Закону № 1820-IX та ДСТУ EN 16723-1:2023 спрощує сертифікацію, однак потребує подальшого удосконалення для повної відповідності європейським вимогам. Порівняльний аналіз витрат на виробництво біометану в Україні та ЄС показав конкурентоспроможність української продукції через нижчу вартість сировини, проте обмежену доступність фінансових стимулів. Виявлено ключові інвестиційні бар'єри, серед яких нестача державних субсидій, відсутність гарантованих тарифів та складність сертифікації. Результати дослідження підтверджують, що біометан сприяє скороченню викидів вуглекислого газу (CO_2) на 85 % порівняно з природним газом та відіграє ключову роль у циркулярній економіці. Проаналізовано реальні показники виробництва біометану в Україні за 2019-2024 роки, що демонструють поступове зростання, але значне відставання від країн ЄС. Оцінено перспективи експорту українського біометану до ЄС, конкурентне середовище, логістичні виклики, необхідність модернізації газотранспортної системи та гармонізації стандартів. Практичне значення проведеного дослідження полягає у наданні комплексної аналітичної бази для формування ефективної державної політики у сфері розвитку біометанової промисловості України

Ключові слова: відновлювана енергетика; декарбонізація; газифікація біомаси; циркулярна економіка; енергетична стабільність