

Development of bioenergy enterprises as a sustainable energy solution for urban micro-methanisation

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■ **Abstract.** A serious argument for the need to develop bioenergy enterprises and micro-methanisation of cities is, first of all, the need to quickly rebuild the energy sector and fulfil commitments regarding the transformation to clean energy. Second, it is the fact that Ukraine, like most European Union countries, has significant areas of low-yield land that could potentially be used for growing perennial energy crops and, consequently, for replacing energy imports with biofuel. The purpose of the article was to conduct theoretical research and practical testing of approaches to forming directions for the development of bioenergy enterprises as sustainable energy solutions for micro-methanisation of cities. The results of this study were obtained using the following methods: analysis and synthesis for problem formulation, research task formulation, and identification of promising technologies for the production of electrical and thermal bioenergy; scientific abstraction, comparison, and generalisation for defining a roadmap for the development of bioenergy enterprises and urban micro-methanisation. Timely completion of tasks related to the development of bioenergy enterprises and urban micro-methanisation is only possible if state support policies and incentives for energy decentralisation are revised. The article discussed theoretical and practical aspects of implementing technologies for producing electrical and thermal bioenergy. It systematised the use of biomass-fired thermal power plants and combined heat and power plants in European countries. A roadmap for the development of bioenergy enterprises and micro-methanisation of cities has been developed, which includes such key areas as the creation of a regulatory framework for micro-methanisation of cities, the demonopolisation and decentralisation of heat and power supply, intensification of international cooperation and partnership, development of bioenergy infrastructure, establishing dialogue with stakeholders, financial support and subsidies, creation of public information platforms, risk insurance, and state guarantees. The advantages of switching to alternative fuels have been identified. The achievement of the expected result in energy and heat supply to territories and cities has been substantiated. The study has high practical value and can be used in the formation of a sustainable development strategy for communities and as a strategic alternative for bioenergy supply

■ **Keywords:** management; sustainable development strategy; decarbonisation; biomass; generation; sustainable development; technological development

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■ Introduction

In the context of adhering to the principles of sustainable development, growing challenges to ensuring energy security, overcoming environmental instability due to active hostilities, and the need to decarbonise Ukraine's economy, the development of bioenergy enterprises and the micro-methanisation of cities are of particular importance. Micro-methanisation is one of the promising areas in the process of converting organic waste into biogas and its subsequent use as a source of thermal and/or electrical energy. The introduction and application of innovative micro-methanisation technologies in cities allows several pressing issues to be addressed: first, reducing waste volumes; second, reducing greenhouse gas emissions; third, enabling local energy production; and fourth, increasing the energy independence of cities and urban communities. Bioenergy enterprises can become catalysts for sustainable economic development through innovative technological development, job creation, and diversification of energy supplies. From this perspective, justifying the need to introduce modern mechanisms for the effective functioning of such enterprises, assessing their potential in the current conditions of Ukrainian cities and communities, and developing a roadmap and models of support from the state and local government are relevant in both scientific and practical terms. The need to develop a roadmap is dictated by the importance of phased implementation of micro-methanisation technologies in cities, investment planning and searching for funding, coordinating the actions of state authorities, businesses and the public, reducing risks by taking into account legal, technical, and economic aspects, as well as the need to communicate with international partners and adapt best practices.

Ukraine faced serious consequences of the destruction of the country's energy sector due to the destruction of most of its power generation facilities, namely thermal power plants and power stations (Order of the Cabinet of Ministers of Ukraine No. 1082-r, 2023). According to O. Sikorska *et al.* (2023), there are four objective factors contributing to the sustainable development of the bioenergy sector in Ukraine: significant biomass resources generated by the agricultural sector and vast land areas; favourable climatic conditions; the availability of labour resources that can quantitatively and qualitatively solve the tasks of developing bioenergy; the availability of an extensive transport and logistics network integrated with the EU.

The issue of developing bioenergy enterprises and urban micromethanisation is becoming particularly relevant. M.R. Errera *et al.* (2023) made a forecast for the supply of primary bioenergy until 2050 and determined its place in the global energy matrix. The characteristics of bioenergy generation and energy use have shown that the global supply of primary bioenergy could increase six-fold by 2050, accounting for 37% of demand. A full adaptation scenario could meet 100% of global energy demand, and bioenergy can and should play an important role in the global energy supply. This will result in a shift in the

composition of bioenergy supplies, from wood to energy crops and biowaste. The available technical potential for fuel and electricity largely matches the trends in primary bioenergy supplies and takes into account the potential for avoiding greenhouse gas emissions. The heuristics and level of transparency of the new model will allow for adjustments and exploration of other scenarios over time. The results of the study by S. Manikandan *et al.* (2023) on the biochemical conversion of biomass waste into bioenergy prove that energy is traditionally produced first, by wood biomass combustion and second, using anaerobic oxidation, enzymatic hydrolysis and microbial fuel cells. The circular economy preserves the value of its by-products, anaerobic digestion and microbial fuel cells help achieve sustainable biomass use. Moreover, alternative fuels are increasing energy demand worldwide.

E.B. Ramirez *et al.* (2024) investigated the potential of renewable energy generation in plant-based microbial fuel cells through metabolic reactions of microorganisms in their interaction with a substrate. Microbial fuel cells, in addition to direct energy production, have a stable and self-sustaining workflow, as microorganisms are self-generated and demonstrate resistance to environmental stress factors. The production of energy from non-traditional sources is a matter of social utility, public interest and national economy, which enables global energy demand to be met and constantly increases interest in the development of new technologies that provide access to alternative, inexpensive energy with minimal impact on the environment. According to O. Ovcharenko *et al.* (2021), taking into account the conditions of sustainable development, the importance of developing bioenergy enterprises and micro-methanisation in Ukrainian cities, which are the subject of this study, is significantly increasing. It is the development of bioenergy enterprises and micro-methanisation of cities that will make it possible to maintain and increase a certain level of economic security by enabling economic entities to choose the most effective of the available development alternatives, which will allow them to effectively withstand internal and external threats.

Despite the significant attention of scientists to this issue, the problems of developing bioenergy enterprises as a sustainable energy solution for urban micromethanisation remain unresolved. The aim of the article was to develop a theoretical and methodological approach to the formation and development of opportunities, mechanisms and prospects for the creation and development of enterprises in the bioenergy industry that implement micromethanisation technologies through local processing of organic waste into biomethane directly within urban areas.

■ Materials and Methods

The study covered the period from 2010 to 2023, which made it possible to track the dynamics of renewable energy development and, in particular, the bioenergy segment. It should be noted that the data used in the graphics was

only available up to and including 2022, as the official statistical series for 2023 had not yet been published in full as of the time of writing. Another limitation of the study was that data for 2024 could not be taken into account, as it was still preliminary and unverified by the time the study was conducted.

The study used a set of materials covering regulatory and legal acts of Ukraine and the EU in the field of renewable energy, waste management and tariff setting, in particular documents Order of the Cabinet of Ministers of Ukraine No. 1082-r (2023), Order of the Cabinet of Ministers of Ukraine No. 373-r, Global bioenergy statistics report (2023), Bioenergy Europe (2022), as well as reporting data on the volume of organic waste generated in cities and towns (Garbage processing in Ukraine, 2024; Prospects of micromethanisation in cities, 2024), municipal waste management programmes and energy strategies (Order of the Cabinet of Ministers of Ukraine No. 587-r, 2024). In addition, statistical data series on the share of renewable energy sources and biomass power generation in previous periods were taken into account, as well as data on the technical characteristics of the world's leading biomethane and micro-biog plants.

Various methods were used to achieve the set objectives. The roadmap method was used to determine the sequence of actions for creating a favourable environment for the development of bioenergy enterprises and micro-methanisation of cities, and made it possible to structure a set of measures in key areas such as regulatory and legal support, infrastructure, financing, international partnerships, insurance, communications and legislative analysis. The analysis method was used to process statistical data on electricity production from renewable sources, the share of electricity produced from biomass, electricity generation capacity and the structure of biomass potential in Ukraine and EU countries. The synthesis method was used to integrate the energy, environmental, economic and social aspects of micro-methanisation to ensure the formation of sustainable, decentralised solutions for the development of energy-efficient cities. The generalisation method made it possible to compile a list of promising technologies for the production of electrical and thermal bioenergy, while the comparison method was used to compare the rates of bioenergy development in Ukraine and EU countries, as well as to assess the cost of energy carriers and equipment. To quantitatively assess development trends, a forecasting method based on building trend models using the least squares method was used, which made it possible to extrapolate existing statistical series and assess the reliability of models using the coefficient of determination (R^2). In addition, tabular and graphical methods were used to ensure clarity and visualisation of the results.

■ Results and Discussion

Micro-methanisation of cities is the reconstruction of the energy sector in Ukraine and European Union countries in accordance with the declared Sustainable Development

Goals (Transforming Our World..., 2015) and the Paris Agreement (2015), which have increased attention to bioenergy and gradual transition of thermal power plants (TPPs) and combined heat and power plants (CHP plants) to biomass. The Sustainable Development Goals (SDGs) are a universal framework adopted by the UN General Assembly in 2015 as part of the 2030 Agenda, which includes 17 goals and 169 targets and integrates the economic, social and environmental dimensions of human development. The SDGs are being implemented through national strategies and local policies, and monitoring is ensured by a system of global and national indicators, which makes it possible to assess progress and compare results. Micromethanisation is possible with the implementation of technological solutions that combine circular economy approaches, decarbonisation, energy efficiency improvements, resource recovery and reuse, greenhouse gas emission minimisation, local energy balance optimisation, and the integration of renewable energy sources into municipal infrastructure.

Micro-methanisation projects should be aligned with relevant SDG indicators, namely Goal 7, "Affordable and clean energy", with a direct contribution to targets 7.2 (increasing the share of renewable energy), 7.3 (improving energy efficiency), 7.a and 7.b (investment and infrastructure for modern energy services). In addition, micro-methanisation of cities is supported by Goal 11, "Sustainable cities and communities" (11.6, 11.b), Goal 12, "Responsible consumption and production" (12.2, 12.5), Goal 13 "Climate Action" (13.2), as well as related Goal 6.3 (reuse of wastewater and sludge) and Goal 9 "Industry, Innovation and Infrastructure" (9.4). Alignment with the SDGs also facilitates inter-municipal cooperation and scalability of solutions, reducing transaction costs for implementation. For the reconstruction of the energy sector in Ukraine and EU countries, this means local, flexible energy generation, increased energy resilience of communities, and reduced dependence on fossil gas. In the reconstruction phase, such a link forms the basis for prioritising investments, accessing green financing and assessing the social value of projects within the principles of the circular economy (Global bioenergy statistics report, 2023). Figure 1 illustrates the growing role of bioenergy. Based on the share of electricity from biomass, a linear trend line has been constructed with a forecast for future periods, which shows that there is an 87.47% probability that its share in all other renewable energy sources will grow. An example of successful and systematic micro-methanisation is Belgium, where all thermal power plants have been completely converted to biomass. A striking example is the CHP plant in Ghent, which has been converted to use biomass, in particular wood pellets and other organic waste (Geletukha, 2021). Austria is another example of a European country that is actively developing the use of biomass. Many small and medium-sized towns in Austria have already switched to using wood chips and waste for centralised heat supply. The country uses its large forest resources to produce biomass, replacing fossil fuels (Pechenyuk, 2024).

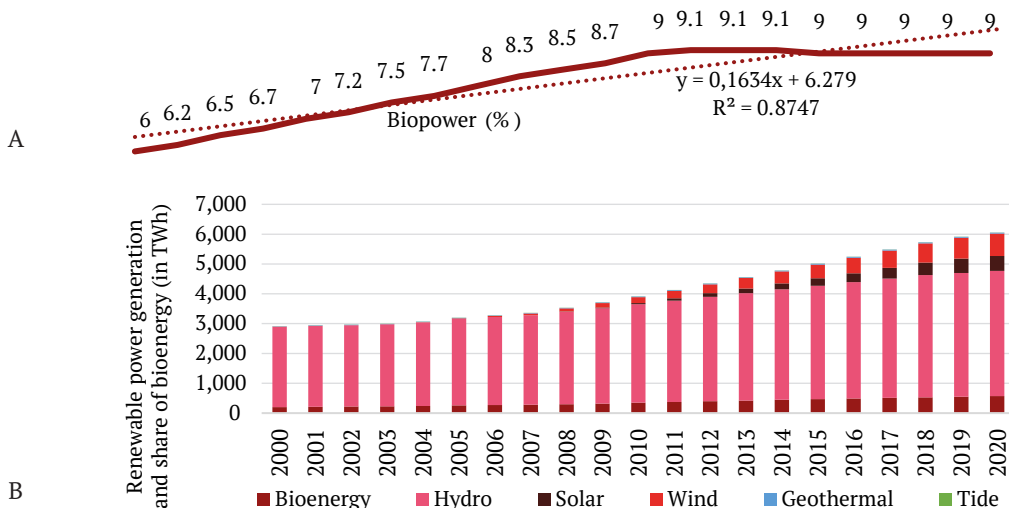


Figure 1. Electricity generation from RES (a) and share of electricity from biomass (b), TWh/year

Source: Global bioenergy statistics report (2023)

Finland also demonstrated a successful transition from coal-based energy to biomass. A significant portion of electricity and heat in Finland is produced by biomass power plants that use wood from the country’s forests (The largest biomethane plants in Europe, 2022). Denmark’s thermal power plants and combined heat and power plants are not lagging behind in the transition to biomass. In particular, the Avedøre TPP, which has been converted to biomass, provides 90% of the electricity and heat supply for Copenhagen, with a population of over 1.4 million (Epik, 2021). The United Kingdom has also successfully transformed its

coal-fired power plants. Drax Power Station, formerly the largest coal-fired power station in the country, has largely switched to biomass. Instead of coal, the station now uses wood pellets (Epik, 2021; The largest biomethane plants in Europe, 2022). The growth in biomass power generation capacity between 2000 and 2022 contributed to a nearly fourfold increase in electricity production. Further growth is confirmed by a linear trend line, which predicts further growth in biomass power generation capacity with a probability of 96.81%, which is a significant factor and highlights the relevance of the study (Fig. 2).

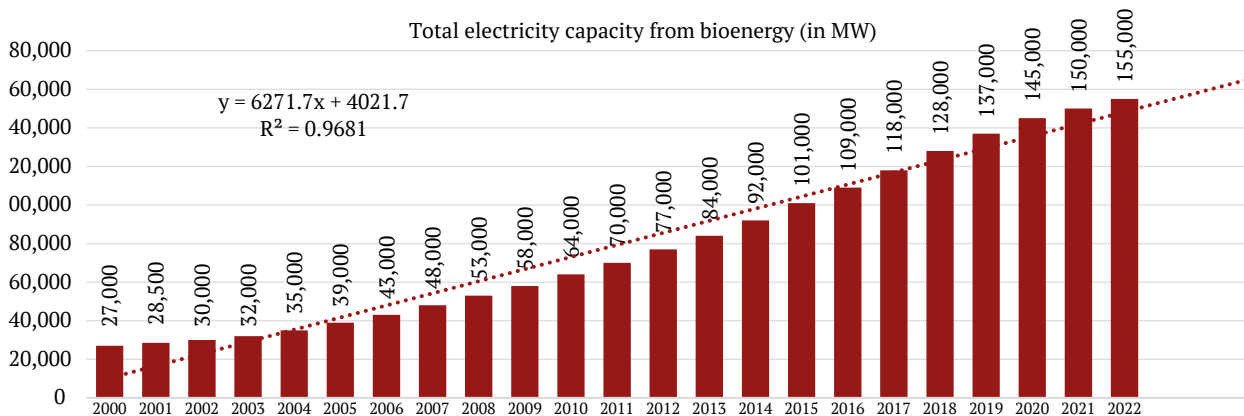


Figure 2. Biomass power generation capacity during 2000-2022, MW

Source: Global bioenergy statistics report (2023)

A serious argument for the need to develop bioenergy and micro-methanisation of cities in Ukraine and worldwide is not only the need for rapid reconstruction of the energy sector and the commitment to transform to “clean” energy, but also the fact that as of early 2022, Ukraine had almost 8 million hectares of low-yield land that could potentially be used for growing perennial energy crops. According to calculations by G. Geletukha (2021), using just

3 million hectares of low-yield land for energy crops could completely replace energy imports with biofuel, and this is only 37% of the available unused low-yield land. However, the potential of bioenergy is not merely measured by the amounts of energy crops grown. Ukraine is an agrarian country, so it has significant volumes of agricultural waste, which is a universally recognised important component of the bioenergy potential in any country.

The opinion of the European Biogas Association (EBA) needs to be taken into account, namely that the deployment of biomethane to replace fossil fuels does not require investment in additional resources for the development of new infrastructure. The existing gas infrastructure is ready for biomethane. This is key to accelerating decarbonisation and ensuring affordable renewable energy in the form of heat, electricity or transport fuel for industry and households. Indeed, anaerobic fermentation of organic materials from plant by-products, animal manure, and bio-waste from households or industry in a biogas reactor in the absence of oxygen releases a mixture of gases: 45-85 vol. % methane (CH₄) and 25-50 vol. % carbon

dioxide (CO₂). The renewable gas obtained can be used for cooking, electricity generation, and heating, replacing compressed natural gas for use in vehicles and displacing carbon dioxide at local CHP plants (Biomethane..., 2024). The total annual technically achievable energy potential of biomass in Ukraine is 37.8 million tonnes of oil equivalent (Prospects of micromethanisation in cities, 2024). According to estimates and forecasts by the Bioenergy Europe association (2022), forest wood currently accounts for 71.37% of the biomass used for bioenergy in Europe (Fig. 3a), but forecasts for 2050 show an increase in the use of agricultural biomass and waste, as well as waste streams, as shown in Figure 3.

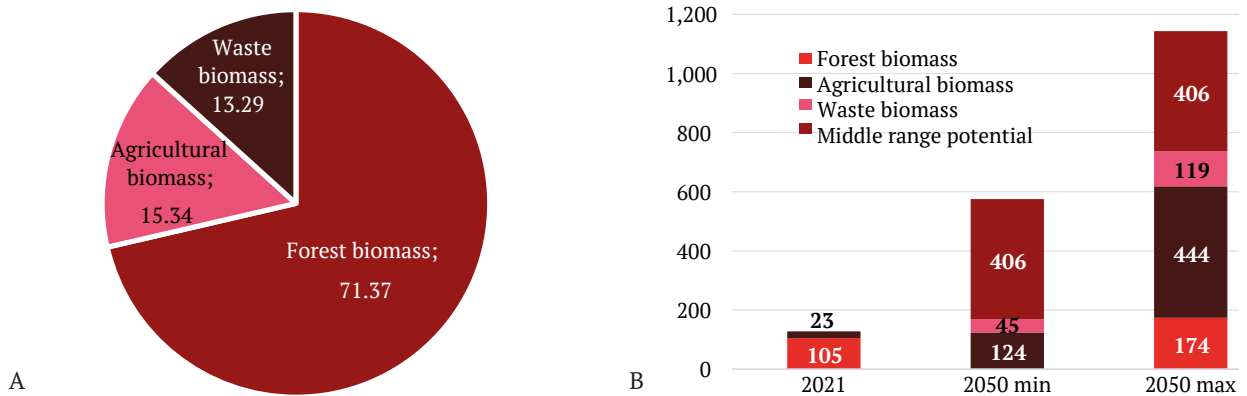


Figure 3. Biomass potential structure for the EU27 + UK (in Mtoe)

Note: a – distribution of the various biomass feedstock for energy in 2021 (%); b – Gross inland energy consumption of biomass in 2021 and potential in 2050 for the EU27 + UK (in Mtoe)

Source: Bioenergy Europe (2022)

The introduction of technologies for the production of electrical and thermal bioenergy by increasing the share of bioenergy in Ukraine’s energy balance, the development of distributed generation and energy storage facilities are recognised as one of the priority vectors of the country’s Energy Strategy (ESU) for the period up to 2050 (Energy Strategy of Ukraine, 2023)

and the National Renewable Energy Action Plan for the period up to 2030 (Order of the Cabinet of Ministers of Ukraine No. 587-r, 2024). According to the National Energy and Climate Plan (2024), it is expected that, thanks to promising technologies, the generation of electrical and thermal bioenergy in the medium and long term will change as follows (Table 1).

Table 1. Promising technologies for the production of electrical and thermal bioenergy

Technologies	Capital expenditure, €/kW						Efficiency (electrical), %	Installed capacity utilisation factor, ICUF %	Heat production coefficient
	2,025	2,030	2,035	2,040	2,045	2,050			
Wood biomass TPPs	2,750	2,700	2,650	2,600	2,550	2,500	24	50	30
Share of capital expenditures for converting TPPs to wood biomass in total expenditures, %	6.98	15.47	15.36	15.20	15.22	15.15	-	-	-
Waste incineration TPPs	2,850	2,800	2,750	2,700	2,650	2,600	23	50	30
Share of capital expenditures for converting TPPs to household waste incineration in total expenditures, %	7.23	7.11	6.98	6.85	6.73	6.60	-	-	-
Biogas TPPs	3,200	3,200	3,200	3,200	3,200	3,200	42	50	30
Share of capital expenditures for converting TPPs to biogas in total expenditures, %	8.12	8.12	8.12	8.12	8.12	8.12	-	-	-
Wood biomass TPPs + Carbon capture	3,650						24	50	30

Table 1. Continued

Technologies	Capital expenditure, €/kW						Efficiency (electrical), %	Installed capacity utilisation factor, ICF, %	Heat production coefficient
	2,025	2,030	2,035	2,040	2,045	2,050			
Share of capital expenditures for converting TPPs to wood biomass + Carbon capture in total expenditures, %	9.26	20.92	21.16	21.35	21.79	22.12	-	-	-
Biogas TPPs + Carbon Capture	5,350						42	50	30
Share of capital expenditures for converting TPPs to biogas + Carbon capture in total expenditures, %	13.58	30.66	31.01	31.29	31.94	32.42	-	-	-
Energy crop TPPs + Carbon capture	3,750						24	50	30
Share of capital expenditures for converting TPPs to energy crops + Carbon capture in total expenditures, %	9.52	21.49	21.74	21.93	22.39	22.73	-	-	-
Wood biomass CHP plants	2,850	2,800	2,750	2,700	2,650	2,600	20	50	35
Share of capital expenditures for converting CHP plants to wood biomass in total expenditures, %	7.23	16.05	15.94	15.79	15.82	15.76	-	-	-
Biomass waste-fired CHP plant	2,950	2,850	2,850	2,900	2,750	2,700	19	50	35
Share of capital expenditures for converting CHP plants to biomass from waste in total expenditures, %	7.49	16.33	16.52	16.96	16.42	16.36	-	-	-
CHP plant using energy crops	3,150	3,100	3,050	3,000	2,950	2,900	20	50	35
Share of capital expenditures for converting CHP plants to energy crops in total expenditures, %	7.99	17.77	17.68	17.54	17.61	17.58	-	-	-
Wood biomass CHPP + Carbon capture	4,450						20	50	35
Share of capital expenditures for converting CHP plants to wood biomass + Carbon capture in total expenditures, %	11.29	25.50	25.80	26.02	26.57	26.97	-	-	-
CHP plants using energy crops + Carbon capture	4,450						20	50	35
Share of capital expenditures for converting CHP plants to energy crops + Carbon capture in total expenditures, %	11.29	25.50	25.80	26.02	26.57	26.97	-	-	-
Total costs, €/kW	39,400	17,450	17,250	17,100	16,750	16,500	25	50	32

Source: supplemented by Order of the Cabinet of Ministers of Ukraine No. 587-r (2024)

A significant increase in production electricity from biomass is planned by 2030. Its total capacity is to be approximately 876 MW (Order of the Cabinet of Ministers of Ukraine No. 373-r, 2023). However, it is already clear that the pace of bioenergy development in Ukraine has been significantly behind schedule, which is explained not only by the full-scale invasion of the Russian Federation, but also by limited development due to a number of obstacles. The difficulties include insufficient funding for the sector, unregulated legislation, lack of effective incentives, technological and infrastructure constraints, complex and unstable regulatory conditions for doing business, etc. (Pechenyuk, 2024). The situation is further aggravated by the remoteness of bioenergy facilities from cities, which is typical for most EU countries and Ukraine. The facilities are mainly located in areas where there is access to agricultural waste, wood or energy crops, i.e. in rural areas and around farms. These are large closed tanks, anaerobic digestion reactors that convert biomass into energy, and biogas plants (Thermal alternative..., 2022).

The Vinnytsia region stands out in Ukraine for its large number of biogas plants that generate energy from agricultural biomass. In terms of generation volumes, it is followed by the Lviv, Ivano-Frankivsk, Volyn and Zakarpattia regions, where, due to large forest areas, bioenergy companies have significant potential with wood and forest waste (Kramar, 2023). However, most bioenergy enterprises are located far outside cities, which significantly complicates their micro-methanisation. However, everything can be changed if the value of municipal solid waste (MSW), which accumulates daily in urban landfills (Prospects of micromethanisation in cities, 2024), is taken into account and favourable conditions for micromethanisation of cities are created. In Ukraine, about 7% of the territory is polluted with MSW, and there are practically no bioenergy enterprises that can generate energy from it. Meanwhile, Sweden recycles over 99% of its waste annually, Germany over 60%, and Poland almost 43% (Garbage processing in Ukraine, 2024). A roadmap for the development of bioenergy enterprises and micro-methanisation of cities has been created. For a clear understanding

of the sequence of actions aimed at creating a favourable environment for the development of bioenergy enterprises and micro-methanisation of cities, one can follow the proposed Roadmap, which includes the creation of a favourable regulatory and legal framework, the demonopolisation

of heat supply, the development of bioenergy infrastructure, the promotion of international cooperation, and combines technical, economic and institutional instruments, including financial support, the creation of information platforms and an investment insurance system (Table 2).

Table 2. Roadmap for creating a favourable environment for the accelerated development of bioenergy enterprises and micro-methanisation of cities

Actions	Description and direction
Creating a regulatory framework for the development of micro-methanisation in cities	Legislative consolidation of tariff regulation for electricity and heat energy, creation of a favourable investment climate, etc. It is envisaged that producers of heat energy from alternative energy sources will be able to obtain tariffs on general terms and operate at economically justified tariffs.
Demonopolisation and decentralisation of heat supply	Transformation of state-owned heat supply companies into joint stock companies, minimisation of state participation and political influence, expansion of bioenergy producers and consumers of electricity and heat supply services.
Enhancing international cooperation and partnership	Consolidation of opportunities for international cooperation and partnership. Transposition and implementation of existing regulatory acts governing the trans-European energy network to facilitate Ukrainian projects obtaining the status of "project of mutual interest".
Development of bioenergy infrastructure	Construction of micro-biogas plants and installation of direct pipelines connecting plants for the production and consumption of thermal energy. Arrangement of organic waste collection.
Establishing dialogue with stakeholders	Developing stakeholder engagement policies, including dividend policy, investment policy, planning and decision-making policy.
Financial support and subsidies	Development and legislative consolidation of mechanisms and timeframes for state support for the development of bioenergy enterprises and micro-methanisation of cities. Preferential loans, state guarantees, tax and customs discounts, avoidance of multiple subsidies and tax preferences.
Establishment of public information platforms	Creation of special online resources where communities, businesses and municipal authorities can obtain information about micro-methanisation technologies, as well as opportunities for receiving state support or investments. Integration with smart city systems.
Insurance and state guarantees	Creation of state or municipal guarantee funds that will cover the financial risks of investing capital in the development of bioenergy enterprises and urban micromethanisation.

Source: developed by the authors

The advantage of using this roadmap is a comprehensive approach, promoting energy independence, attracting investment, increasing the sustainability of the energy system and environmental benefits. Disadvantages include the high cost of implementation, the need for significant changes in legislation, bureaucratic delays. The estimated implementation period in Ukraine is 3-5 years, provided that there is positive political support and stable financing. The prospect for further development of bioenergy enterprises and micro-methanisation is the transition to alternative fuels, which will reduce the vulnerability of the energy system, as damage to the gas infrastructure can immediately deprive a significant number of consumers (in some cases, part of a city or more) of heat, and the use of boiler rooms and local resources reduces such risks (Zamazeyeva, 2023); this will also reduce dependence on natural gas and, accordingly, reduce the cost of its purchase; scale up and multiply projects to install biomass boiler rooms and bio-CHP plants in communities, attract new investments, create new jobs, generate additional budget revenues, etc.

Therefore, by developing bioenergy enterprises and implementing micro-methanisation of cities, economic security of enterprises, regions and countries is achieved in terms of counteracting exogenous and endogenous factors of influence; risks are minimised or eliminated, and ecological development is ensured with the achievement of sustainable development goals (Tiutchenko *et al.*, 2024). The key recommendations for the development of bioenergy enterprises in Ukraine are improving the regulatory

framework by ensuring clear rules for bioenergy production, tariff regulation, a transparent licensing procedure, and the integration of European Directives. Accelerating the demonopolisation of heat supply and creating conditions for attracting a greater number of private and state-owned biomass heat and electricity producers. Developing infrastructure through the design and construction or procurement of micro-biogas plants, heat pipelines and organic waste collection systems. Attracting international financing to obtain investments, loans or guarantees from the EBRD, Energy Community, Ukraine-Germany Energy Partnership. Attracting investment should be based on guaranteeing stable rules and compliance with long-term energy purchase agreements; introducing public-private partnership mechanisms; providing preferential lending and investment return guarantees through state funds; attracting international donors and financial institutions that do not support fossil fuels and actively invest in RES.

Support national producers through preferential lending, tax breaks, and investment insurance; give priority to public procurement for Ukrainian producers of bioenergy equipment. Create a biomass exchange and a transparent biofuel market with quality control and supply guarantees from the state. Provide information support and training by developing public online platforms for communities and businesses, as well as training programmes for plant operators. These measures will enable the achievement of Sustainable Development Goals and generate economic benefits through energy independence, reduced imports

of natural gas and oil, a stable energy system, decentralised power generation, and the creation of new jobs in the regions through the development of the agricultural sector due to increased demand for energy crops and further GDP growth. The environmental effect will be manifested through a reduction in greenhouse gas emissions and organic waste disposal, while innovative development will be achieved through the introduction of advanced waste processing and energy storage technologies (BESS).

When making decisions on the development of micro-methanisation in Ukrainian cities, it is necessary to take into account the possible negative consequences: high investment levels and long project payback periods; risks of legislative incompleteness that reduces attractiveness for investors; significant competition for raw materials between bioenergy and other sectors of the economy (food industry, livestock farming); potential negative impact on agricultural land due to the large-scale cultivation of energy crops. Further development should be based on international experience by integrating the strategies of countries that already have successful bioenergy practices, similar climatic conditions and raw material bases, as well as common goals for decarbonisation and energy independence (Denmark, Austria, Finland, Great Britain). Good practices include setting economically sound tariffs; introducing guaranteed long-term contracts; developing local biofuel markets; and combining bioenergy with smart heating networks and energy storage facilities.

A notable achievement by M.R. Errera *et al.* (2023) was the development of a new model, whose heuristics and level of transparency allow for adjustments to be made and other scenarios to be explored over time. The author identified three future scenarios for bioenergy supply in 2050: business as usual (BUS), optimistic trends (OPT) and full adaptation (FAR). The forecast was based on four adjustment factors. Uncertainty analysis was performed using the Monte Carlo method. Bioenergy production forecasts for 2050 were compared with other forecasts available in the literature. The FAR scenario showed that it would be possible to produce 21 times more than the current supply of primary bioenergy and even meet the entire global demand for primary energy in 2050, mainly through energy crops. The assumptions made for the BUS and OPT scenarios make these forecasts more probable.

O. Evstegneeva (2024) studied the state and prospects of bioenergy use in Ukraine, identified the potential for producing biofuels from agricultural waste and biomass to replace imported natural gas and coal, and analysed the technical possibilities for attracting resources, overcoming existing barriers, determining economic feasibility, and an impact on the country's energy security. Based on the results of the study, the author outlined that Ukraine has significant technical potential for bioenergy resources, especially from agricultural waste, and that the effective use of these resources could replace a significant portion of energy imports. The effect can be seen in reduced dependence on fossil fuels, preservation of currency reserves, and

development of domestic production. The most successful cases of biomass use in heat and power generation in Ukraine have proven that bioenergy is a realistic and promising component of Ukraine's energy security, especially in conditions of war and energy shortages. Significant results in this area can be achieved by reforming the regulatory framework and mechanisms to accelerate the implementation of bioenergy projects; supporting investment in biomass processing technologies and the development of relevant infrastructure; implementing decarbonisation, creating jobs and developing local communities.

The researchers A.I. Orekhova *et al.* (2024) emphasised that the potential of bioenergy in Ukraine involves replacing imported energy resources (gas, coal) with biomass and biofuel from agricultural and forestry waste and organic waste. The study covered the economic, technical and environmental aspects of the implementation, as Ukraine has the technical potential to replace a significant portion of imported fuel (up to 20 billion m³ of gas equivalent annually). The authors argue that bioenergy can provide stable heat and electricity for communities, especially during energy crises, and provide examples of successful regional projects that have already reduced dependence on fossil fuels by using local biomass and created new jobs. These results can be achieved by involving investors and biofuel producers, stimulating decarbonisation and sustainable development in the regions. In order to strengthen Ukraine's energy independence through the use of bioenergy tools, it is necessary to remove administrative and regulatory barriers and simplify the procedure for connecting bioenergy facilities to the grid. These aspects were addressed in the article by O. Tregub (2024), who analysed tax incentives as an economic and legal tool for supporting bioenergy, in particular the possibility of a zero tax rate for CO₂ emissions from biofuel combustion. The author focused on the adequacy of the regulatory and legislative framework to the wartime crisis, which exacerbates the need for rapid adaptation of the industry despite restrictions due to martial law and the reform of EU climate legislation. The results of the study highlighted that the ecotax rate for CO₂ emissions increased from 0.41 UAH/tonne in 2018 to 30 UAH/tonne in 2022. The proposed zero rate for biomass energy production in the draft laws requires amendments to the Tax Code and the creation of a register of bioenergy plants. At the same time, an anti-corruption assessment has identified risks such as the creation of a register of plants under a resolution of the Cabinet of Ministers to prevent the non-transparent selection of beneficiary companies. The main conclusions are that the zero tax rate is a viable option during martial law to quickly boost bioenergy and support recovery. It is desirable to develop a gradual transition to the introduction of the exemption, but it is not advisable to link it to sustainability criteria due to their insufficient implementation.

M.B. Palasevich & P.A. Murdza (2024) emphasised that Ukraine has the potential to replace imported gas and coal with bioenergy by using local biomass (straw, corn stalks,

sunflower husks, wood waste, municipal organic waste). According to the authors' estimates, Ukraine's technical biomass potential is about 23 million tonnes of fuel equivalent per year, which is equivalent to approximately 20 billion m³ of natural gas. Using this resource will reduce gas imports by 60-70% in thermal power generation. The researchers cite successful examples of biomass boiler rooms in Kamianets-Podilskyi, which provide over 60% of the heat for centralised heating, and in Trostyanets, where biofuel boiler rooms have reduced the cost of heat by 25-30%. The transition to biofuel will allow the country to save approximately \$2 billion annually, which was previously spent on energy imports. The study concludes that bioenergy technologies contribute to reducing CO₂ emissions, create thousands of jobs in the regions, and that bioenergy can replace a significant portion of imported energy resources and increase Ukraine's energy independence. This is possible through the introduction of government incentives such as preferential loans, tax breaks, and simplified procedures for connecting to power grids.

Based on retrospective and forecast data, Ya. Demchenkov (2023) argues that Russia's full-scale war against Ukraine has affected the energy independence of other countries and accelerated the global energy transition. Currently, Ukraine has the potential to replace some of the energy, which the EU previously received from Russia, by creating new energy security architecture. The author's findings show that Ukraine has demonstrated better energy reform rates than other countries applying for EU membership, despite the ongoing war. All technical conditions for acquiring full ENTSO-E membership have been met, which will ensure stable electricity exchange with Europe in the future. A promising area is the development of nuclear energy and the creation of universal nuclear fuel for VVER-440 reactors, which is applicable to all reactors in the EU. Projects of common interest (PCI) for the EU include a hydrogen corridor connecting Ukraine, Slovakia, the Czech Republic, Austria and Germany. The war has turned energy into a tool of hybrid warfare and accelerated the global energy transition. Ukraine has the potential to become Europe's green energy hub, capable of producing not only clean energy, but also equipment and technologies for energy transformation. Ukraine's prospective membership in the EU will ensure that its energy will never be used against common European interests. The development of joint projects with the EU and the US (Holtec, Westinghouse, Rolls-Royce SMR; hydrogen and renewable energy projects) will increase continental security and accelerate Europe's energy independence. The Ukrainian experience can serve as an example for countries in the Global South showing that green transformation is possible even during periods of armed conflict and is beneficial for all countries. I.V. Furman & D.O. Ksenych (2024) studied the state, problems and prospects of bioenergy development in Ukraine in the context of ensuring energy security. The authors analysed the stages of the industry's development, compared Ukrainian and European experience, considered successful examples

of bioenergy clusters, and assessed the potential for using local bioresources. The study identifies the main challenges: imperfect legislation, technological limitations, insufficient funding, high competition with imported energy sources, logistical problems with raw material supply, and the need to take environmental and social aspects into account. Ukraine has significant potential for producing biofuels, biogas and electricity from biomass due to its considerable agricultural and forestry resources. It has been found that the creation of bioenergy clusters of agro-industrial enterprises and households can ensure the efficient use of resources, reduce dependence on energy imports, reduce greenhouse gas emissions, stimulate the development of rural areas and create additional jobs. The EU's experience confirms that this model promotes innovation, investment attractiveness and sustainable development. The authors conclude that the successful development of bioenergy in Ukraine requires a comprehensive approach that includes financial support (subsidies, grants, investment programmes), a stable regulatory framework, technological modernisation, infrastructure expansion, international cooperation and government incentives for the industry. Bioenergy is seen as a strategic direction that can strengthen the country's energy independence, improve environmental safety, and support regional economic development.

The results obtained are consistent with broader studies that emphasise the role of renewable energy in strengthening energy security. In particular, O. Semenko *et al.* (2025) demonstrated that energy security has become a key factor in ensuring Ukraine's economic stability during the war. This approach reinforces the relevance of expanding the network of bioenergy enterprises and introducing micro-methanisation technologies, which simultaneously contribute to the sustainable development of cities and increase the country's ability to withstand external challenges. The findings are also consistent with international studies on the use of agricultural biomass as a promising resource for bioenergy. S. Anvari *et al.* (2024) used the example of Tunisia to prove that the effective use of agricultural waste and by-products can significantly increase energy independence and promote sustainable development. This is in line with the Ukrainian context, where significant agricultural potential could form the basis for expanding bioenergy production and introducing micro-methanisation technologies.

J. Plotkin *et al.* (2023) investigated the role and prospects of thermal power plants and combined heat and power plants in Ukraine's energy system in the context of international climate commitments, national plans to reduce emissions, and the transition to renewable energy sources. The researcher have identified four key factors that justify the need to continue the operation of TPPs/CHP plants: insufficient number of electrical substations for stable reception and distribution of electricity; the inability of nuclear power plants to quickly regulate load, which creates a need for flexible generation sources, such as TPPs/CHP plants; limitations of renewable energy sources (solar, wind, etc.) due to

instability, low conversion efficiency, and the need for large land areas; the importance of CHPs for the simultaneous production of electricity and heat, as well as difficulties in financing the modernisation and gasification of these facilities. The authors concluded that the complete decommissioning of TPPs/CHP plants in the short term could threaten Ukraine's energy security, especially in the context of war. The most realistic model is a combination of renewable energy, hydroelectric power plants, modernised CHPs and new safe nuclear technologies. At the same time, effective financial mechanisms need to be developed for modernisation and reduction of emissions from thermal generation in order to meet international and national climate commitments without affecting the stability of the energy system.

By simplifying the procedures for state approval of boiler house construction projects, approval of project documentation, environmental impact assessment, land allocation, identifying of connection conditions, obtaining a licence for heat energy production, approval of tariffs, etc., it will be possible to commission up to 500 MW of distributed thermal generation capacity running on biomass and natural gas within 6-8 months. The above proposal did not receive due attention from the government and local authorities, which highlights the need for further scientific research in this area. Given the difficult situation in Ukraine's energy sector, one of the most promising ways to restore it in conditions of instability is to develop decentralised biogasification and micro-methanisation systems in cities. Decentralised biogasification is the main direction of strategic development during the Russian Federation's military aggression, due to the fact that it is a solvable task to physically protect the distributed generation facilities and associated substations (Ukrinform, 2024).

The study demonstrated a comprehensive approach to assessing the potential for micro-methanisation in Ukrainian cities, by combining legal, economic, technical and social aspects. The methods of analysis, forecasting and comparison used by the authors made it possible to quantitatively confirm the positive trends in the development of bioenergy and identify prospects for the expansion of technology at the local level. The results obtained substantiated the need for the phased implementation of a roadmap as a tool for coordinating the efforts of the government, businesses and the public.

■ Conclusions

The study provides a theoretical justification and practical testing of approaches to the development of bioenergy enterprises as a sustainable solution for micro-methanisation of urban areas. Ukraine has sufficient amounts of low-yield land; the use of additional areas for energy crops could completely replace energy imports with biofuel. The

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total technically achievable energy potential of biomass is estimated at 37.8 million tonnes of oil equivalent. European practices for conversion of TPPs/CHP plants to biomass (Belgium, Austria, Finland, Denmark, and Great Britain) have been systematised and aligned with the UN Sustainable Development Goals (Goals 7, 11, 12, 13, 6.3, and 9.4). The trend lines show that the share of bioenergy in green energy production is highly likely (87.47%) to grow, and global bioenergy capacity is even more likely to increase (96.81%). According to forecasts, electricity production from biomass in Ukraine will grow to 876 MW by 2030. A list of promising technologies and capital expenditure ranges has been compiled: wood biomass TPPs – €2,500-2,750/kW; wood biomass CHP plants – €2,600-2,850/kW; biogas TPPs – €3,200/kW; options with CO₂ capture – €3,650-5,350/kW.

A roadmap has been developed for a sequence of actions aimed at creation of a favourable environment for accelerating the development of bioenergy enterprises and micro-methanisation of cities. Subject to changes in legislation and state support, up to 500 MW of distributed heat generation from biomass/gas could be introduced within 6-8 months; given that there are more than 100 specialised companies in the country, this would allow up to 30% of lost generation to be partially restored within a year. Key barriers to the development of bioenergy enterprises and micro-methanisation of cities have been identified, including underfunding, regulatory uncertainty, technological and logistical constraints, and low waste processing rates in cities.

Decentralised bioenergy and micro-methanisation of cities have been proven to be a realistic and rapidly scalable way to increase the energy sustainability of communities, reduce gas imports and achieve climate goals. The proposed sequence of actions and agreed technological and financial benchmarks could also form the basis for state policy and local strategies. Prospects for further research consist of deepening the quantitative assessment of micro-methanisation potential at the level of specific communities (organic waste flows, heat loads, connection points); modelling financial schemes (tariff and non-tariff incentives, guarantees, BESS integration) taking into account wartime risks; assessing socio-environmental effects (jobs, emission reductions, budget revenues); and preparing packages of model solutions for rapid launch of pilots in cities.

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■ Conflict of Interest

None.

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Розвиток підприємств біоенергетики як стале енергетичне рішення мікрOMETANІЗАЦІЇ міст

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■ **Анотація.** Серйозним аргументом необхідності розвитку підприємств біоенергетики та мікрOMETANІЗАЦІЇ міст є, по-перше, потреба у швидкій відбудові енергетичного сектору та виконанні зобов'язань щодо трансформації до чистої енергетики. По-друге, той факт, що Україна, як і більшість країн Європейського Союзу, має значні площі низькопродуктивних земель, які потенційно можуть бути використані для вирощування багаторічних енергетичних рослин, а відтак, і для заміщення імпорту енергоносіїв біопаливом. Метою статті було теоретичне дослідження та практична апробація підходів до формування напрямів розвитку підприємств біоенергетики як сталих енергетичних рішень мікрOMETANІЗАЦІЇ міст. Результати даного дослідження отримано шляхом використання таких методів: аналізу і синтезу – при постановці проблеми, формулюванні завдань дослідження, визначення перспективних технологій виробництва електричної та теплової біоенергії; наукової абстракції, порівняння та узагальнення – для визначення дорожньої карти розвитку підприємств біоенергетики та мікрOMETANІЗАЦІЇ міст. Своєчасне виконання поставлених завдань з розвитку підприємств біоенергетики та мікрOMETANІЗАЦІЇ міст можливе лише за умови перегляду політики державної підтримки та стимулювання децентралізації енергетики. У статті розглядалися теоретичні та прикладні аспекти впровадження технологій виробництва електричної та теплової біоенергії. Систематизовано застосування теплових електростанцій і теплоелектроцентралей на біомасі в країнах Європи. Розроблено дорожню карту розвитку підприємств біоенергетики та мікрOMETANІЗАЦІЇ міст, яка включає такі основні напрями, як створення нормативно-правового поля з регулювання розвитку з мікрOMETANІЗАЦІЇ міст, демонополізація та децентралізація теплоенергопостачання, активізація міжнародного співробітництва та партнерства, розбудова біоенергетичної інфраструктури, встановлення діалогу із зацікавленими сторонами, фінансова підтримка та субсидування, створення публічних інформаційних платформ, страхування ризиків та державні гарантії. Визначено переваги переходу на альтернативні види палива. Обґрунтовано досягнення очікуваного результату у енерго- та теплозабезпеченні територій та міст. Дослідження має високу практичну цінність та може бути використане при формуванні стратегії сталого розвитку громад та як стратегічна альтернатива забезпечення біоенергією

■ **Ключові слова:** менеджмент; стратегія сталого розвитку; декарбонізація; біомаса; генерація; сталий розвиток; технологічний розвиток