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Economic aspects of the introduction of renewable energy sources in the agro-industrial complex

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► **Abstract.** The aim of the study was to identify economic challenges to the introduction of renewable energy sources in the agricultural sector of Ukraine and to substantiate ways to overcome them, taking into account modern transformations. The methodological basis was formed by statistical analysis (in particular, trend and comparative), economic and legal analysis, as well as content analysis of scientific sources and regulatory documents. The study analysed current trends in the development of solar, wind and bioenergy in the agricultural sector. It has been established that the greatest economic effect is provided by projects based on the use of biomass, biogas and solar energy, which can reduce energy costs by up to 20-25% on average. It is found that bioenergy has the greatest prospects due to the significant amount of available agricultural raw materials; it is substantiated that the annual potential for replacing imported gas with biofuels is up to 5 billion cubic metres, which is equivalent to a reduction in costs of more than USD 2 billion. The article analyses the dynamics of solar energy implementation in the agricultural sector for the period 2018-2024, in particular, it is found that in the context of the armed conflict, the share of operating solar power plants decreased to 50-60% due to damage to infrastructure, but in the western and central regions there is a tendency to increase installed capacities. It has been found that the efficiency of the introduction of renewable energy sources depends on the level of

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government support, the availability of targeted instruments such as "green" tariffs, low-interest loans, and transparent regulatory mechanisms. The practical significance of the study is to provide recommendations for strengthening support for the introduction of renewable energy sources, which will contribute to the energy efficiency of the agricultural sector, increase the profitability of farms and the competitiveness of their products

▸ **Keywords:** innovative technologies; sustainable development; competitiveness; environmental sustainability; state support; investment incentives

▸ Introduction

The relevance of the study is stipulated by the need to develop effective economic mechanisms for the introduction of renewable energy sources (RES) in the agricultural sector, as this sector is the basis for ensuring food security, economic stability and environmental balance. Climate change, the energy crisis, rising costs of traditional energy sources and international environmental obligations require countries to adapt their economic models to new challenges, which in turn makes it necessary to analyse the economic feasibility of integrating alternative energy technologies. The introduction of RES into the production processes of the agro-industrial complex will optimise energy costs and help to increase the competitiveness of enterprises at the international level, while ensuring their energy autonomy and reducing negative environmental impact. In this context, a study of the economic aspects of renewable energy use in the agricultural sector is necessary to formulate strategic decisions that will promote the development of the industry, attract investment and implement state support mechanisms aimed at strengthening the country's energy security.

Scientific studies show that the introduction of RES in the agricultural sector is not only economically beneficial, but also strategically necessary to increase energy autonomy and reduce negative environmental impact. In the work of A. Dankevych *et al.* (2023) substantiated the effectiveness of bioenergy technologies for cost optimisation in agriculture and emphasised that government support and expansion of investment potential are the determining factors in the development of this sector. The study demonstrates that the integration of biogas plants and the use of biomass as an alternative energy source can improve the energy efficiency of agricultural enterprises and reduce their dependence on imported energy. The prospects for the development of distributed generation in the agricultural sector were considered by S. Boiko *et al.* (2023), who noted that the integration of decentralised energy systems contributes to improving the energy security of enterprises and optimising their production costs. The authors emphasised that the use of small solar and wind power plants reduces the load on centralised power grids and ensures stable energy supply even in remote regions, which is important for agricultural enterprises facing the problems of unstable energy supply and high electricity tariffs.

A separate aspect of the introduction of renewable energy in the agricultural sector was considered in paper V. Havrysh *et al.* (2022), who investigated the prospects of using sorghum as a feedstock for bioenergy production. The authors pointed out that this crop has a high energy potential and is able to provide biofuel production with minimal agricultural technology costs, which makes it attractive for farms in the southern regions of Ukraine. The issue of integrating environmental, social and governance standards into the activities of agri-food enterprises was addressed in the work of T. Voronko-Nevidnycha *et al.* (2023). They emphasised that compliance with ESG principles (environmental, social and corporate governance) in the functioning of the agricultural sector helps to attract investment and increase the capitalisation of companies. The importance of regional peculiarities in the implementation of renewable energy was considered by M. Averkyna (2023). She analysed the sustainable development of the Polissya economic region from the perspective of environmental modernisation and energy transformation and stressed that a differentiated approach to the implementation of RES allows taking into account the specifics of each region and creating adaptive models of energy development. In the study, she substantiated the need to expand government support for farmers seeking to invest in RES, in particular through a system of tax incentives and grant programmes.

The scientific work of K. Anshu *et al.* (2023) clearly demonstrated that the successful integration of innovative energy technologies into various industries, including the agricultural sector, requires not only financial support but also the formation of a balanced public policy, including regulatory frameworks and incentives to attract investment in modern technologies. The authors emphasise that sustainable energy development is possible only if regional specifics and the needs of individual farms are taken into account, as well as active cooperation between the state and private initiatives. The authors also emphasise that only a harmonious combination of state regulation and private entrepreneurship can ensure the effectiveness of such initiatives. A study by F.J. Miranda *et al.* (2023) analysed in detail the importance of integrating solar energy into the functioning of the agro-industrial complex. The researchers emphasised that the introduction of these technologies contributes to a significant reduction in the costs associated with the use of energy resources, while ensuring a more environmentally friendly nature of production processes. In addition, the authors drew attention to the dependence of the effectiveness of such investments on the existence of state subsidies, as well as the importance of creating a transparent and clear regulatory environment that would regulate activities in the field of renewable energy.

The economic feasibility of using RES in the agricultural sector has been thoroughly explored in the works of researchers, but a number of aspects have remained outside the scope of comprehensive analysis, which highlights the need for further comprehensive research on this topic. The aim of this study was to assess the economic aspects of the use of RES in the agricultural sector of Ukraine and to identify the main challenges and prospects in this area. The objectives of the study were to analyse the current state of implementation of RES in the agricultural sector of Ukraine, assess the economic feasibility of using certain types of RES and develop recommendations for optimising state policy in the field of stimulating investment in environmentally friendly technologies.

▸ Materials and methods

The study was based on an analysis of Ukraine's legal and regulatory framework, in particular the Law of Ukraine No. 555-IV (2003), which defines the legal and organisational framework for promoting the use of RES, including state support mechanisms, such as "green" tariffs, tax benefits and compensation programmes. The key element of the analysis was the Decree of the Cabinet of Ministers of Ukraine No. 1163-p (2024), which provides for a gradual increase in the share of RES in the energy balance of the agro-industrial complex, development of infrastructure for bioenergy generation and creation of conditions for the integration of the latest technologies into production processes. The study also examines the Decree of the Cabinet of Ministers of Ukraine No. 761-p (2024), which focuses on expanding the use of solar and wind energy in agriculture and identifies key measures to stimulate investment in renewable energy projects, including the provision of grants and low-interest loans.

The analysis of the economic benefits of implementing measures aimed at developing RES in the agricultural sector of Ukraine was carried out on the basis of statistical data published by the State Statistics Committee of Ukraine (n.d.) for the period 2018-2024. Financial investments in renewable energy projects, the dynamics of energy efficiency indicators, and changes in the use of these sources in the activities of agricultural enterprises were considered. In addition, the analysis involved information provided by the Ministry of Agrarian Policy and Food of Ukraine (2024), which includes detailed data on the distribution of state funding allocated to support the implementation of energy efficient technologies, as well as the results of an assessment of the economic benefits of such initiatives.

Statistical studies have revealed significant changes in the energy costs of agricultural enterprises, their impact on production costs and profitability. The data analysis also made it possible to assess the effectiveness of regulatory instruments aimed at stimulating the development of renewable energy, in particular, the relationship between the amount of public funding for such projects and energy efficiency in agriculture. Special economic research methods were used in the study. Statistical analysis (in particular, trend and comparative methods) was used to process data on the share of RES in the overall energy balance of agricultural enterprises, the dynamics of investment in the sector, and changes in energy costs. The empirical material was processed, including calculations, graphing and aggregation of indicators, using the Microsoft Excel spreadsheet processor, which ensured the results were clearly and accurately presented. The trend analysis tracked changes in key economic indicators (production cost, level of energy independence) in the period 2018-2024. Comparative analysis was used to compare the economic results of using traditional and RES. The economic and legal method was used to study the regulatory framework governing the development of renewable energy in the agricultural sector. The content analysis method was also applied to study scientific sources and regulatory documents, which allowed for a comprehensive assessment of the economic prospects and challenges of introducing RES in the agricultural sector of Ukraine.

In addition, the study used a case study of a specific agricultural enterprise ("Agro-Kartel" LLC, Chernihiv region) to model the economic effect of switching to biomass as a heat source and estimate the payback period of investments. The choice of this enterprise was made due to its specialisation in greenhouse vegetable production, high energy intensity of production processes, and the availability of facilities that have already been partially adapted to the implementation of energy efficient technologies, while the location of the enterprise in a region with a developed agricultural raw material base for bioenergy and favourable logistical conditions for biomass supply ensured that the results obtained were representative of similar scenarios for average agricultural producers in Ukraine. To take into account spatial differentiation, elements of spatial analysis were applied, in particular, regarding the regional distribution of solar power plants and zonal climate features that affect the efficiency of RES. For the purpose of international comparison, a comparative analysis of macroeconomic effects and models of state policy in the field of RES was carried out on the example of Denmark, Germany, China and the United States. Additionally, the resource potential of biomass was assessed by sources of origin (straw, livestock waste, corn residues), volumes and potential for replacing natural gas. An environmental and economic assessment was also applied, which included an analysis of the impact on CO_2 emissions, the possibility of utilising agricultural waste and reducing the environmental burden on the environment.

To evaluate the economic feasibility of using biomass as an energy source in greenhouse farming, a comparative method of analysing operating costs for two alternatives was applied: the use of natural gas and the use of wood pellets. The calculation of heat demand was carried out using the formula (1):

$$Q = S \cdot q, \tag{1}$$

where Q – total heat demand for the heating season, kWh; S – greenhouse area, m²; q – average heat demand per 1 m², kWh/m².

The volume of natural gas required to cover this need was determined by the following formula (2):

$$V_{gas} = \frac{Q}{H_{gas} \cdot \eta_{gas}}, \tag{2}$$

where V_{gas} – volume of natural gas liquefied, m³; H_{gas} – lower calorific value of natural gas, kWh/m³; η_{gas} – thermal efficiency of the gas boiler, expressed as a fraction.

The cost of heating with natural gas was calculated using the formula (3):

$$C_{gas} = V_{gas} \cdot P_{gas}, \tag{3}$$

where C_{gas} – total gas heating costs, UAH; P_{gas} – price per 1 m³ of natural gas, UAH.

For the alternative variant with biomass, the amount of fuel required was calculated using the formula (4):

$$M_{\text{biomass}} = \frac{Q}{H_{\text{biomass}} \cdot \eta_{\text{biomass}}}, \tag{4}$$

where M_{biomass} – mass of wood pellets, kg; H_{biomass} – lower calorific value of pellets, kWh/kg; η_{biomass} – biomass boiler efficiency, in fractions of a unit.

The cost of biomass heating was determined by the formula (5):

$$C_{\text{biomass}} = M_{\text{biomass}} \cdot P_{\text{biomass}}, \tag{5}$$

where C_{biomass} – total biomass costs, UAH; P_{biomass} – price per 1 kg of pellets, UAH.

The fuel savings were calculated as the difference between the total costs of gas and biomass using the formula (6):

$$\Delta C = C_{\text{gas}} - C_{\text{biomass}}. \tag{6}$$

The payback period for the biomass boiler was estimated using the following formula (7):

$$T = \frac{I_{\text{add.}}}{\Delta C}, \tag{7}$$

where T – payback period, years; $I_{\text{add.}}$ – additional investment in the purchase of a biomass boiler, UAH.

Results

The integration of RES is one of the important areas that determine the further development of Ukraine's agro-industrial complex, as the use of RES contributes to economic growth by increasing production efficiency, reducing production costs and reducing dependence on traditional energy resources. Sources such as biomass, biogas, solar, wind and hydropower can significantly reduce energy costs, which creates conditions for improving the competitive position of Ukrainian agricultural products on both domestic and international markets. In addition, an additional advantage is the positive impact on the environment, as the introduction of RES in production processes helps to reduce greenhouse gas emissions, which is critical for global efforts to combat climate change (Mitov, 2024).

The role of renewable energy in the development of the agricultural sector goes beyond energy efficiency. It includes technological modernisation, rational use of resources, and the formation of sustainable models for the development of the sector. According to IRENA (2025) and the State Agency for Energy Efficiency and Energy Supply of Ukraine (2021), renewable energy should be considered a fundamental element of agricultural reform, combining economic and environmental goals into a single strategic development concept. The use of biogas plants on farms to process organic waste and generate energy has already been implemented in a number of agricultural enterprises in Vinnytsia and Poltava regions. Solar panels are used to provide energy for irrigation systems in the southern regions of Ukraine, in particular in Odesa and Kherson regions, where climatic conditions are conducive to maximising the use of solar energy. In addition, in Cherkasy region, there are farms that use combined RES models, combining solar energy with biogas plants to optimise energy consumption and increase the autonomy of production processes. The practice of using RES shows that RES are already becoming an integral part of the strategic development of Ukraine's agro-industrial complex, providing economic benefits, increasing competitiveness and minimising environmental impact (Usman *et al.*, 2024).

The use of RES is based on the principles of minimising energy dependence and rationalising resource consumption, which, in the face of current challenges, ensures the agricultural sector's high adaptability to global economic and environmental changes. The development of renewable technologies makes it possible not only to solve energy supply problems, but also to create additional economic incentives for attracting investment in agriculture (Ismanzhanov & Tashiev, 2016). Such processes contribute to the formation of a more diversified and sustainable agricultural production, which plays a significant role in ensuring the economic stability of the state. Types of RES in the agricultural sector are presented in Table 1.

Table 1. Types of RES in the agricultural sector

Type of RES	Feature	Examples of application in the agricultural sector
Solar energy	Using solar radiation to generate electricity or heat	Installation of solar panels to power farms, irrigation pumps, and greenhouse heating
Wind energy	Generating electricity using wind turbines	Providing energy to agricultural facilities such as warehouses or lighting systems
Bioenergy	Generating energy from biomass, biogas or biofuels produced by processing organic waste	Use of livestock waste to produce biogas, which is used for heating or powering equipment
Geothermal energy	Utilising the earth's heat for power generation or heating	Geothermal pumps for heating greenhouses or maintaining the temperature on farms
Hydropower	Generating electricity from small hydropower plants that use the movement of water	Use of mini-hydroelectric power plants to meet the energy needs of water farms or mills
Energy from waste	Generating energy by burning or processing agricultural and municipal waste	Use of straw, nut shells or crop residues as fuel to generate heat or electricity

Source: compiled by the authors based on V. Omelchenko (2022)

The use of solar panels is optimal in the southern regions, where the average sunshine hours per year are 2,000-2,200 (Ministry of Agrarian Policy and Food of Ukraine, 2024). However, the installation of such panels requires significant upfront investment, and their performance depends on weather conditions. Bioenergy has a high potential due to the large volumes of agricultural waste, which allows for the production of biogas and biofuels while reducing the environmental burden, but the main drawback of this type of energy is the high cost of infrastructure. Wind energy is feasible in steppe regions (Zaporizhzhia and Donetsk regions) where wind speeds exceed 5 m/s, but its deployment is limited by high costs and space requirements (Humeniuk & Humeniuk, 2023). Energy from waste is effective for heating households, but requires logistics and special equipment. Geothermal and hydropower have limited application due to specific geographical conditions.

A review of the practice of countries such as Denmark, China, Germany, and the United States shows that the achievement of higher economic results in the process of introducing renewable energy into the agricultural sector was made possible by the development of effective governmental regulatory mechanisms aimed at attracting investment in renewable energy. A special role in this was played by the creation of systems that ensure integration between the private sector and scientific institutions. In Germany, in particular, the Energiewende programme (Ethics Commission for Secure Energy Supply, 2011) was a key factor in modernising the energy infrastructure, aimed at a gradual transition to the use of RES, which in turn significantly reduced the dependence of the agricultural sector on fossil fuels, with the federal state of Bavaria seeing a 15% reduction in energy consumption in the agricultural sector between 2021 and 2024. In Lower Saxony, farms that switched to biogas plants reduced energy costs by 20%, which had a positive impact on their profitability (Qawaqzeh *et al.*, 2020).

The Danish experience shows that the implementation of a strategy of investing in the development of biogas plants focused on the needs of the agricultural sector has become a significant economic factor in reducing the costs associated with the disposal of agricultural waste and in ensuring stable access to energy resources for farmers. The effectiveness of this strategy was largely ensured by the introduction of government support programmes, which included a system of subsidies and tax breaks. In particular, in 2012, Denmark introduced a new subsidy scheme that provided fixed subsidies for biogas producers, which helped to increase biogas production for electricity and heat generation, as well as for processing into biomethane, which replaced natural gas. The scheme was valid for new applications until 2018, but the subsidies were granted for a 20-year period, so the bulk of biogas produced in Denmark today is still subsidised. Thanks to such programmes, the share of biomethane in the Danish gas system reached almost 40% in 2024, and by 2030, it is projected that gas consumption in the country will be 100% "green" (IRENA, 2025).

In China, the development of renewable energy in agricultural regions was manifested through the active introduction of solar panels and mini-hydroelectric power plants, which significantly increased the level of energy autonomy of agricultural enterprises. The introduction of RES has reduced farmers' electricity costs by an average of 30%, while productivity has increased by 15% due to stable energy supply. In addition, exports of organic products increased by 12% due to compliance with international environmental standards (Ramasubramanian *et al.*, 2021). Thus, the economic impact of this initiative is undeniable, as the use of RES in the agricultural sector has not only reduced energy costs, but also created the conditions for increased productivity and a more sustainable economic environment.

The practice of the countries under review shows that the integration of public investment, support for innovative technologies and incentives for agricultural businesses are fundamental prerequisites for the successful implementation of RES. In the context of Ukraine, such an integrated approach could become the basis for improving the energy efficiency of the agricultural sector, contributing to the sustainable economic development of the industry and reducing its dependence on fossil energy resources. This, in turn, will help to increase the competitiveness of Ukrainian farmers both in the domestic and international markets (Wang & Zhang, 2023).

Solar energy in Ukraine showed significant progress by 2022, reaching an installed capacity of 6.32 GW of solar power plants (SPPs), accounting for about 6% of the country's total generation (Humeniuk & Humeniuk, 2023). This was made possible by favourable natural conditions, the development of technical infrastructure, and government support, which created attractive conditions for investing in solar energy. However, agricultural enterprises faced a number of challenges in adopting solar technologies, mainly the high cost of equipment and limited access to finance, which made it difficult to integrate RES into the agricultural sector.

As of 24 April 2024, there were 1,369 solar power plants in operation in Ukraine, owned by 931 licensees, accounting for 75% of all renewable energy facilities. The largest number of SPPs is concentrated in six regions: Ivano-Frankivsk (142 plants), Dnipro (134), Vinnytsia (122), Khmelnytsky and Kyiv (107 each), and Mykolaiv (92). Instead, Luhansk and Donetsk regions have only 2 stations each, while Sumy region has 5 stations and Poltava region has 7 stations. Some of the solar power plants are located in the temporarily occupied territories of Kherson, Zaporizhzhia, Donetsk, and Luhansk regions, and they are currently not part of the Integrated Power System of Ukraine (Hubareva, 2023). The dynamics of launching new SPPs (according to licences) in 2018-2024 is shown in Figure 1.

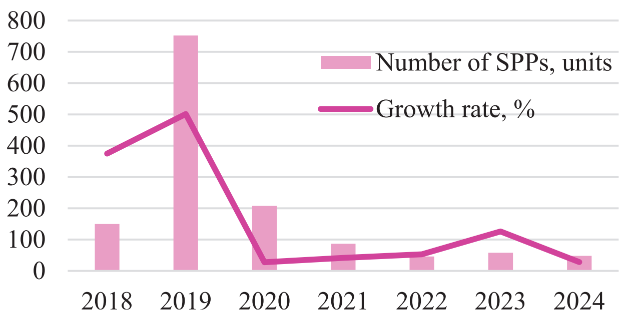

Figure 1. Dynamics of launching new SPPs (according to licences) in 2018-2024
Source: compiled by the authors based on L. Belozerova (2024)

The most active development of solar energy in Ukraine took place in 2019, when the largest number of new plants were commissioned. However, in the following years, the pace of construction slowed down, and after the outbreak of a full-scale war in 2022, licences for new SPPs stopped being issued in Kherson, Zaporizhzhia, Mykolaiv, Kharkiv, Donetsk and Luhansk regions due to hostilities and occupation. By 2020, solar energy was a leader among European countries in terms of installed capacity growth, which demonstrates the significant interest of international investors in this sector. In 2020, approximately USD 1.4 billion was invested in the development of Ukrainian solar energy, and leading companies such as Jinko Solar, Trina Solar, ABB, and SMA Solar Technology were active in the market. The successful implementation of green auction projects, which are being implemented to reduce the cost of electricity and increase competition between investors, confirms the economic efficiency of this approach. For example, in 2019, during the first "green" auction, a quota for the construction of solar power plants with a total capacity of 78 MW was allocated at an average price of 5.5 euro cents per kWh, which was a significant step towards stabilising the industry (Hubareva, 2023). In the agricultural sector, solar panels are used to power irrigation systems, heat greenhouses, and power agricultural equipment, which helps to increase the energy independence of farms and reduce electricity costs. The dynamics of the installed capacity of solar power plants in Ukraine is shown in Figure 2.

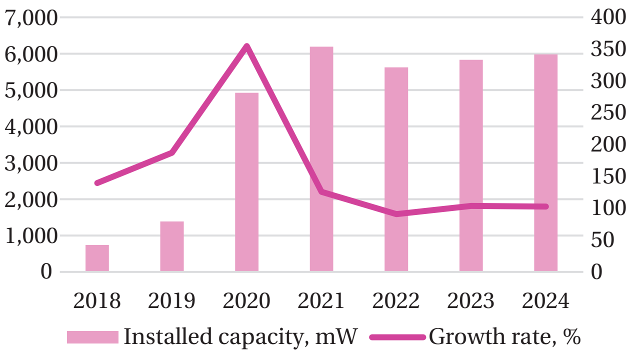

Figure 2. Dynamics of installed capacity of solar power plants in Ukraine, MW
Source: compiled by the authors based on L. Belozerova (2024)

During 2019-2020, the installed capacity of solar power plants in Ukraine increased, with record volumes of SPPs commissioned (up to 6,194 MW in 2021). Starting in 2022, the war caused a decline in installed capacity to 5,623 MW, but the industry gradually recovered (5,983 MW in 2024), indicating that the sector is adapting to new conditions. The active implementation of solar energy contributes to the development of regions, especially rural areas, which is achieved through the creation of new jobs in the construction and operation of solar power plants, which in turn not only reduces unemployment but also stimulates economic activity in remote areas of the country. The use of solar energy also reduces greenhouse gas emissions, with each megawatt of installed solar capacity reducing CO_2 emissions by 1,500-2,000 tonnes annually, which has a positive impact on the environment and contributes to Ukraine's international climate commitments (Mathew *et al.*, 2024). Thus, the development of solar energy is a promising area of energy policy and a significant contribution to the sustainable development of the economy and society. The installed capacity of RES facilities operating under the "green" tariff is shown in Figure 3.

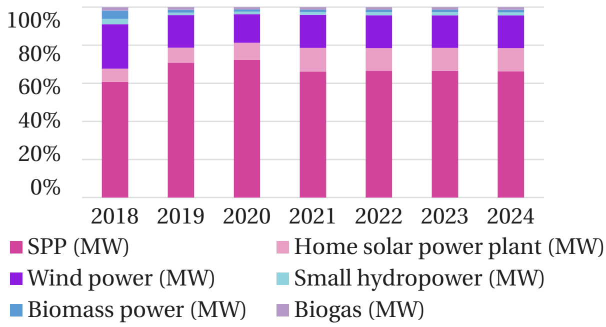

Figure 3. Installed capacity of RES operating under the "green" tariff, MW
Source: compiled by the authors based on L. Belozerova (2024)

As of the end of 2021, the installed capacity of RES in Ukraine was 9,655.9 MW, including solar installations that covered the needs of private households (SPH), or 8,450.8 MW excluding SPH. The largest increase was observed in solar and wind energy, but since the beginning of 2022, the development of these sectors has slowed down, especially in 2022. At the same time, the home solar power plant segment continues to grow as households look for energy-independent solutions. Despite the challenging environment, biogas, bioenergy and micro-hydropower generation are also seeing gradual growth, indicating that the market is adapting to the crisis. From an economic point of view, the use of decentralised solar power plants in the agricultural sector helps to reduce energy costs, which allows farmers and businesses to increase their competitiveness, ensure energy independence and reduce the vulnerability of production to energy market fluctuations. In addition, such innovative solutions help to optimise energy consumption, which is of particular importance for export-oriented agricultural enterprises.

The military aggression of the Russian Federation against Ukraine has caused widespread damage to the country's energy infrastructure, which has had a negative impact on the development of renewable energy (Semenenko *et al.*, 2024). Significant damage to the renewable energy infrastructure caused by the hostilities, including the destruction of substations, grid systems, loss of equipment, and the inability to access power plants in the occupied territories, has significantly affected the industry. For example, as of the end of 2024, about 70% of wind farms and 45-50% of solar power plants were decommissioned, which led to a more than twofold drop in electricity production from alternative sources (Ministry of Agrarian Policy and Food of Ukraine, 2024). Most of these facilities are located in the south of the country, where natural conditions favour the use of solar energy, and the calculation of total losses will only be possible after the de-occupation of these territories is complete.

The introduction of RES in the agricultural sector requires systemic changes at the level of modernisation of power grids to ensure the integration of new capacities, as well as improvement of legislation that would stimulate domestic production of equipment for solar power plants (Andreitsev *et al.*, 2024). Particular attention should be paid to the use of land unsuitable for agricultural use, such as the territories in the exclusion zone of the Chernobyl nuclear power plant (NPP), where the pilot project “Solar Chernobyl” (n.d.) has already been implemented, which generates electricity using areas unsuitable for agricultural use. In addition, initiatives are being implemented to create wind and bioenergy capacities on degraded lands, which will reduce the dependence of the agricultural sector on traditional energy sources.

The national solar energy development policy should focus on attracting foreign investment, introducing innovative technologies and strengthening international cooperation, as the economic benefits of integrating RES into the agricultural sector can lead to increased productivity, improved energy efficiency and reduced production costs, which will open up new horizons for the sustainable development of this strategic sector of Ukraine’s economy. The National Renewable Energy Action Plan until 2030 (Decree of the Cabinet of Ministers of Ukraine No. 761-p, 2024) outlines strategic goals and areas for the development of RES that should significantly change the structure of the country’s energy sector, in particular by integrating modern environmental technologies. According to the plan, the share of RES in gross final energy consumption should reach 27% by 2030, which implies significant growth in three key sectors: in heating and cooling systems, the share should reach 33%, in electricity generation – 29%, and in the transport sector – 17%.

To achieve these goals, 38 large-scale measures are planned to be implemented, including investments in key areas of the industry’s development. USD 12.6 billion is planned to be invested in electricity generation from RES, including USD 1.681 billion for the development of biomass and biogas generation facilities. In addition, USD 6.7 billion is earmarked for the reconstruction of heat supply systems, and the development of biofuels for the transport sector is estimated at USD 450 million for bioethanol production and USD 19 million for biodiesel. A special place in the structure of the National Plan is occupied by bioenergy, which is characterised by high potential for Ukraine due to its agricultural specialisation, favourable climatic conditions and access to significant amounts of biowaste. The use of biomass and biogas not only contributes to the country’s energy independence, but also significantly reduces greenhouse gas emissions by converting organic waste into an energy source (Decree of the Cabinet of Ministers of Ukraine No. 1163-p, 2024; No. 761-p, 2024).

At the same time, the growth rate of electricity production from biomass and biogas remains relatively slow compared to other types of renewable energy. As of the beginning of 2024, the total installed capacity of electricity generation facilities using biomass and biogas reached 319 MW (excluding facilities in the temporarily occupied territories). During this period, 68 biogas plants with a total electrical capacity of 135 MW were operating in Ukraine, as well as 24 biomass power facilities with a total capacity of 178 MW, operating under the “green” tariff mechanism (Hubareva, 2023).

The development of bioenergy is one of the most promising areas for increasing the share of RES in total electricity production, especially in the context of the energy crisis and the need to reduce dependence on imported fossil fuels. As of early 2025, Ukraine has already implemented a number of projects to convert thermal power plants (TPPs) and combined heat and power plants (CHPs) to use biomass, including at the Kamianets-Podilskyi CHP, which runs on wood chips, and at the Burshtyn TPP, which is testing the combustion of agro-pellets. The biomethane industry is also developing, and the first biomethane plants are already in operation, for example, at MHP Eco Energy, which produces biomethane from agricultural waste.

The integration of biomass and biomethane into highly manoeuvrable generating units, cogeneration systems or CHP plants, which are usually fuelled by natural gas, requires investments in equipment upgrades, new boilers and emission treatment systems. The cost of such a retrofit varies from EUR 5 million to EUR 20 million, depending on the capacity of the plant. Despite the high upfront costs, these changes can reduce natural gas consumption and dependence on imported fuel. According to the Bioenergy Association of Ukraine, bioenergy can account for up to 15% of the country’s total energy balance, which is equivalent to replacing up to 3 billion m^3 of gas per year, significantly strengthening the country’s energy security (Belozerova, 2024).

According to the Bioenergy Policy Roadmap until 2050 and Action Plan until 2025 (2020), the main sources of bioenergy resources are agricultural residues, which account for 44% of the total, and energy crops, which account for 32% of this volume. Among agricultural residues, the largest share is occupied by grain straw (33%) and corn processing by-products (35%). Despite the significant potential of these resources, their energy use remains low: the potential of straw is used by less than 1%, and corn and sunflower residues are almost never involved in the bioenergy cycle. As a result, a significant amount of available fuel resources, estimated at USD 3-4 billion, remains untapped, which is a significant loss for a country with a high level of energy dependence. The structure of agricultural residues biomass potential is shown in Figure 4.

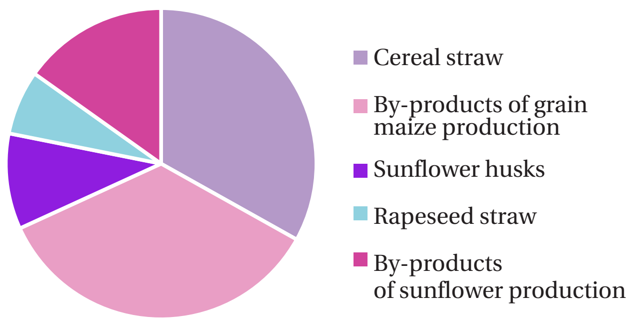

Figure 4. Structure of agricultural residues biomass potential, MW

Source: compiled by the authors based on L. Belozerova (2024)

In particular, straw and husks are efficient sources of thermal energy, and their combustion technologies in the form of fuel, wood or briquettes are already well established in practice. However, the weak infrastructure for collecting and processing such residues, as well as the lack of proper legislative incentives, are the main barriers to realising their energy potential. The efficient use of bio-waste, including agricultural residues, is of strategic importance for achieving Ukraine's energy independence and reducing the cost of imported energy. The potential of bioenergy in Ukraine allows to replace up to 5 billion m^3 of natural gas annually, which can reduce the cost of its imports by more than USD 2 billion. Integration of such resources into the bioenergy system will not only provide the country with additional energy, but also create new economic incentives for the agricultural sector. In particular, farms will be able to generate additional income from the sale of raw materials for biogas plants, and the development of local biowaste processing infrastructure will help reduce the cost of agricultural residues and increase the profitability of agricultural production.

The experience of other countries, such as the United States and European countries, demonstrates the significant potential and effectiveness of integrating bio-waste into the overall energy balance, which allows increasing the share of bioenergy in RES (Aliyev *et al.*, 2024). Given its agricultural resources, Ukraine has the opportunity to adapt successful approaches of other countries to its own conditions. However, the implementation of such initiatives requires large-scale infrastructure modernisation, attraction of foreign and domestic investments, proper state regulation, and close international cooperation (Islam *et al.*, 2024). The experience of integrating bio-waste in the US and European agriculture is shown in Table 2.

Table 2. Experience in integrating bio-waste in the US and European agriculture

Country	Share of bioenergy in total agricultural energy consumption as of the end of 2024	Main sources of biowaste	Economic effect	Government support
USA	12%	Livestock waste, corn residues	Reduce energy costs in the agricultural sector by USD 3 billion per year	Tax benefits, USDA grants for the development of biogas projects
Germany	18%	Farm waste, silage corn	900 biogas plants, 30% reduction in natural gas consumption in agriculture	Fixed tariffs for biogas, subsidies
Denmark	25%	Manure, straw, crop residues	Reduced CO_2 emissions by 2.5 million tonnes per year	State financing of biogas cooperatives
France	10%	Winemaking waste, seed husks, animal residues	Save up to 20% on farm energy costs	Subsidies for the installation of biogas plants, low-interest loans

Source: compiled by the authors based on B. Crotman *et al.* (2024)

The general experience of these countries shows that successful integration of bio-waste into the agricultural sector helps to reduce energy costs, increase environmental efficiency and reduce dependence on fossil fuels. The use of bio-waste as an energy resource is characterised by significant economic viability, especially in the context of rising prices for traditional energy resources such as natural gas and coal. For example, 3 tonnes of corn cobs, which can provide the same amount of energy as 1,000 m^3 of natural gas, cost about UAH 3,000. At the same time, in the European Union, the price for 1,000 m^3 of gas is approximately EUR 1,000. In Ukraine, the equivalent energy value can be achieved for less than EUR 100, highlighting the significant cost difference. A similar cost-effectiveness is also observed in comparison with coal, where 2 tonnes of bio-waste correspond to 1 tonne of coal in terms of energy value, but cost approximately UAH 2,000, while a tonne of coal is estimated to cost between UAH 10,000-15,000 (Yerniyazova *et al.*, 2024). The article presents the calculation of reducing the cost of growing vegetables on the example of using biomass as an alternative energy source for heating greenhouses in "Agro-Kartel" LLC (Chernihiv region). For a greenhouse farm with an area of 1 hectare (10,000 m^2), with a seasonal heat demand of 150 kWh/m^2, the total heat demand was 1,500 kWh. If natural gas was used with an efficiency of 90% and a lower calorific value of 9.5 kWh/m^3, the required fuel volume was about 175.4 thousand m^3. At a price of UAH 8 per m^3, heating costs during the season amounted to approximately UAH 1.4 million. When switching to wood pellets (boiler efficiency – 85%, calorific value – 4.8 kWh/kg), the annual fuel requirement was about 367.6 thousand kg. At a cost of UAH 3/kg, the total cost of biomass did not exceed UAH 1.1 million. A comparison of heating costs is presented in Table 3.

Table 3. Comparison of heating costs

Indicator	Natural gas	Biomass
Fuel demand	175,439 m^3	367,647 kg
Cost of fuel	UAH 1,403,512	UAH 1,102,941
Capital expenditure on equipment	UAH 200,000	UAH 500,000
Total costs (first year)	UAH 1,603,512	UAH 1,602,941
Total costs (subsequent years)	UAH 1,403,512	UAH 1,102,941
Annual fuel savings	–	UAH 300,571
Payback period	–	1 year

Source: compiled by the authors based on L. Belozerova (2024)

Thus, switching to biomass for heating a 1-hectare greenhouse in Chernihiv region can reduce annual fuel costs by UAH 300,571. The additional investment in equipment pays for itself in about one year. After that, the company receives net savings on fuel, which helps to reduce the cost of its products and increase its competitiveness in the market. Ukraine has a significant agricultural potential, which creates the preconditions for energy self-sufficiency through the large-scale use of biofuels. One of the promising areas that can contribute to solving the problem of energy supply at both the community and private household levels is the processing of agricultural residues, such as straw, into pellets. The creation and development of straw processing facilities can significantly reduce heating costs and solve the problem of energy supply in settlements without access to the gas supply system.

The introduction of RES in the Ukrainian agricultural industry is a key and promising area for creating conditions that will ensure the sustainable development of this sector, as evidenced by the results of numerous studies. In particular, an analysis of international experience shows that successful integration of RES into agriculture is possible through a combination of systemic state support, introduction of advanced technologies and active participation of the private sector. In this context, the achievements of developed economies that have managed to ensure a significant share of RES in the overall energy balance through effective investment attraction, research and innovation are illustrative (Nosratabadi *et al.*, 2019). Ukraine, with its considerable agricultural, land and natural potential, has all the prerequisites for the active development of renewable energy in the agricultural sector. Solar energy is developing particularly rapidly, as it is proving effective in reducing energy dependence and stimulating economic activity in rural areas. The introduction of such initiatives helps to increase the level of energy autonomy of farms, reduces energy costs and stimulates the development of related industries.

Despite the significant challenges caused by military aggression, Ukraine retains opportunities to restore and modernise its energy sector, including the agricultural sector. The integration of RES into this sector will help reduce the environmental impact of traditional energy technologies, while opening up new prospects for job creation, local economic development and international competitiveness of agricultural products. Enhancing the country's energy security through the development of RES is one of the key aspects of the sustainable development strategy, which is particularly relevant in the context of rising global energy prices and the need to reduce greenhouse gas emissions. The prospects for the use of RES, in particular biogas, solar and wind energy, are directly linked to the development of international cooperation, available funding and the introduction of modern technologies into production.

Despite the significant potential of Ukraine's agricultural sector, the current state of energy modernisation in the industry is characterised by a number of challenges. The main barriers include insufficient funding for renewable energy projects, as well as a limited level of awareness among agricultural producers about the benefits of using renewable energy. Low access to credit resources and lack of adequate information support slow down the pace of adaptation of the agricultural sector to modern energy sustainability requirements. At the same time, the implementation of effective government policies aimed at stimulating investment and educational initiatives can significantly improve the situation, increasing the level of energy autonomy of farms and contributing to their profitability. Challenges and threats to the introduction of RES in the agricultural sector of Ukraine are presented in Table 4.

Table 4. Challenges, threats and ways to overcome barriers to the introduction of RES in the agricultural sector of Ukraine

Challenges	Threats	Recommended ways to overcome
Military operations and destruction of energy infrastructure	Destruction of energy networks, shortage of equipment, risk of investment loss	A state programme to rebuild power grids with grants and international assistance; compensation mechanisms for agricultural enterprises investing in renewable energy
Lack of financial resources in the agricultural sector	High initial investment, lack of affordable financing for small farms	Introduction of state preferential loans and subsidies for agricultural producers implementing RES; simplification of the tax burden for RES projects
Dependence on imported equipment	Logistical difficulties due to the war, currency risks, higher import prices	Establish a state programme to stimulate domestic production of solar panels and wind turbines; simplify customs clearance for imports of critical components
Shortage of personnel due to mobilisation and migration	Decrease in the number of specialists in the field of renewable energy, lack of skilled workers	Introduce educational programmes and grants for retraining agricultural sector workers in the field of renewable energy; attract foreign specialists and partnership programmes
Limited network infrastructure in rural areas	High cost of connecting SPPs to the grid, overloading of existing power lines	Create a mechanism of state co-financing for the construction of local power grids for agricultural enterprises
High risks of seasonality and instability of generation	Instability of solar energy in winter, dependence on weather conditions	Introduce compensation mechanisms and stimulate the development of energy storage systems in the agricultural sector; support combined solutions (RES + biogas)
Competition for land resources	The use of fertile land for solar power plants may reduce the area for growing crops	Provide state guarantees for the use of degraded and unproductive land for RES; introduce tax benefits for companies that place SPPs on land unsuitable for agricultural activities
Problems with utilisation of used equipment	Lack of a system for recycling solar panels, environmental risks	Introduction of a national programme for the recycling of renewable energy components; obligation of producers to ensure waste recycling

Source: compiled by the authors based on V. Kovalenko (2024)

Despite the potential of renewable energy in the agricultural sector, there are a number of barriers that need to be addressed systematically. The hostilities have complicated the implementation of RES projects due to the destruction of infrastructure and the rising cost of equipment, which requires the active participation of the state and international partners in financing the restoration and modernisation of the energy system. Financial problems, lack of staff, and difficulties in accessing grid infrastructure have also become challenges that require the expansion of government support programmes, including concessional lending, subsidies for equipment purchases, and tax incentives for agricultural enterprises. Particular attention should be paid to legislative regulation of RES waste disposal and the development of local equipment production. The introduction of a national programme for the recycling of solar panels and batteries will help minimise environmental impact and create new jobs. Effective implementation of RES in the Ukrainian agricultural sector is only possible with a comprehensive approach that includes government support, attracting international investment and improving the legislative framework.

▸ Discussion

The economic potential for the introduction of RES in the agricultural sector identified in this study was consistent with the findings presented in A.Q. Al-Shetwi *et al.* (2024), which proved that the transition to 100% RES is possible if systemic barriers – technical, financial and regulatory – are removed. This study emphasised not only the importance of modernising the energy infrastructure in the agricultural sector, but also the need to create conditions for energy autonomy by reducing dependence on imported energy, an aspect that was particularly important in the context of energy vulnerability caused by military events.

Comparison of the results with the study by A. Dankevych *et al.* (2023) showed similar conclusions about the effectiveness of bioenergy technologies in reducing costs and improving energy efficiency in agricultural production. At the same time, the study focused on a comprehensive analysis of financial models for the implementation of biogas plants and biomass processing systems, taking into account the dynamics of production costs and access to state support. This made it possible to take into account the specifics of the Ukrainian context, in particular, the financing constraints for small agricultural producers. The importance of technological modernisation raised in R.R.C. Bastos *et al.* (2020) correlated with the analytical block of the study, which outlined the technological potential of agricultural waste processing for biofuel production. However, in contrast to the global focus of the aforementioned source, the present study focused on localised examples, taking into account the practical aspects of introducing new boilers, residue processing infrastructure and investment payback periods.

Financial instruments, in particular "green" bonds, were considered by L. Chang *et al.* (2023) as a means of mitigating the risks associated with the introduction of RES. The study reflected this problem through the prism of institutional support and its absence at the level of agricultural microbusiness: the lack of targeted government programmes capable of providing access to such instruments for regional farms was noted. The results were also consistent with the findings of S. Boiko *et al.* (2023), who considered distributed generation as a means of increasing energy reliability in remote regions. The analysis of the Ukrainian agricultural sector confirmed that decentralisation of energy solutions, in particular through the installation of solar power plants in rural areas, does help reduce energy losses, especially in areas with unstable energy supply.

In the study by H. Tazvinga *et al.* (2020) highlighted the importance of taking into account local socio-economic and climatic conditions when adapting international RES experience. The study demonstrated the practical implementation of this thesis in the case of Ukraine: the expediency of placing RES infrastructure on degraded lands, in particular in the Chernobyl NPP area, as well as restrictions on wind energy in densely populated or difficult climatic zones, were substantiated. A summary of the study results in view of the position of R. Przygodzka *et al.* (2024) allowed confirming that state support in Ukraine is crucial, but unlike the Polish example, the Ukrainian model has not yet provided for the systematic integration of small farms into new energy formats due to the uneven distribution of resources and difficulty in accessing subsidies.

The effectiveness of investments in RES as a factor of economic growth in the agricultural sector was confirmed by the findings of E. Getachew *et al.* (2024), according to which a decrease in dependence on traditional energy sources is accompanied by an increase in energy efficiency. This conclusion coincided with the results of calculations of energy savings when using biomass in greenhouse heating presented in the study, which at a practical level demonstrated cost reduction and rapid return on investment. At the same time, not all studies confirm only the positive impact of RES, as E. Saitov (2020) drew attention to the difficulties associated with the development of wind energy in Central Asia and noted that high infrastructure costs and adaptation of technologies to local conditions are significant obstacles that may be relevant for Ukraine. D. Mignogna *et al.* (2024) emphasised the need for a cautious approach to the use of bioenergy, as although it has significant potential to reduce CO^2 emissions, overexploitation of biomass can lead to soil degradation, which is contrary to the principles of sustainable development.

Comparison of the results with the findings presented in existing studies shows that the development of RES in the agricultural sector has a number of common patterns that are manifested in different economic and institutional environments. According to the research of A.Q. Al-Shetwi *et al.* (2024), Poland, thanks to an effective government strategy and sound financial incentives, was able not only to reduce energy costs in the agricultural sector, but also to strengthen its economic sustainability. The same trend was observed in the results presented here, where the introduction of solar panels or biogas plants, subject to adequate financial and credit support, can significantly optimise the energy component of agricultural production costs and increase the competitiveness of farms in domestic and foreign markets, but Ukraine has not yet developed such a consistent and transparent system of regulatory measures that would ensure the rapid scaling of "green" technologies among small and medium-sized rural enterprises.

Comparison with the example of Kazakhstan presented in A. Abdikarimova *et al.* (2023) showed that in this country, the introduction of alternative energy in the agricultural sector faces insufficiently adapted regulatory mechanisms and a lack of clear political will. Similar problems, according to the study, remain relevant for Ukraine as well, as unregulated legislative procedures and limited access to investment for small farms make it difficult to introduce the latest solar or biogas technologies. This situation confirms the thesis that without government support and an optimised regulatory framework, even high-quality technical solutions cannot realise their full potential and influence the overall level of energy autonomy of the agricultural sector (Matviishyn & Harbarynina, 2023).

When analysing the cost-effectiveness of solar energy, it is worth noting that the results presented in this study (in particular, the calculations showing a reduction in the costs of heating and electricity for agricultural enterprises) are consistent with the findings of R.R.C. Bastos *et al.* (2020), who highlighted the significant economic potential of photovoltaic systems for farms. However, the limited access to modern high-performance equipment, especially in crisis regions where active hostilities are still ongoing, remains a significant obstacle. The study results confirmed that military aggression, which caused damage to energy infrastructure and the occupation of certain territories, made it difficult to implement solar power plants in the most favourable locations.

Regarding innovative solutions for small farms, the experience of combining biogas plants and solar panels described by L. Chang *et al.* (2023) logically correlates with the conclusion that it is advisable to decentralise the location of RES facilities and develop combined models. This approach truly ensures a higher level of energy autonomy; however, the implementation of such projects requires not only capital-intensive equipment but also appropriate mechanisms for state and international assistance to offset initial investment costs and promote the dissemination of these solutions at the local level. In this context, automation and intelligent power system management technologies are becoming critically important, as emphasised by D. Mignogna *et al.* (2024). The results obtained in this study fully confirm the high potential of digital optimisation of production processes to improve energy efficiency, but the likelihood of large-scale adoption of such solutions is still low due to significant financial barriers, which are especially noticeable for the segment of small and medium-sized agricultural enterprises.

In general, a comparison of Ukrainian experience with the work of foreign authors leads to the conclusion that strategic planning for the development of the agro-industrial complex, which integrates renewable energy, requires a synergy of economic, environmental and social factors. As summarised by A. Kaya & D.B. Budak (2023) conclude that only close cooperation between the research sector, government institutions and private investors contributes to the full deployment of bioenergy technologies, which is confirmed by the assessment of the prospects for RES development in Ukraine: with proper government regulation, reasonable modernisation of energy grids and available financial resources, farms are able to significantly reduce their dependence on fossil fuels, while improving their economic performance and environmental responsibility. Thus, the results of the discussion show that although the development of RES has significant potential, a variety of aspects need to be taken into account to maintain energy independence in the agricultural sector. To achieve optimal results, it is necessary to ensure a comprehensive approach that includes government support, investment, training and innovation.

▸ Conclusions

A comprehensive analysis of the economic factors that accompany the integration of RES into the agricultural sector has shown that there are significant opportunities for consolidating financial, production and intellectual resources that can become the basis for sustainable growth of the domestic agricultural sector. The examples of solar, wind, and bioenergy use discussed above confirm that diversification of energy sources, combined with the rational use of agricultural residues and biomass potential, can minimise the energy dependence of farms, reduce energy costs by 20-30%, and increase profitability by at least 15% due to lower production costs. At the same time, the systematic use of renewable energy requires multi-level innovations that include not only technological modernisation of equipment but also the development of favourable economic and legal mechanisms. The potential of renewable technologies in agriculture is driven by the existing raw material base: agricultural waste alone in Ukraine amounts to more than 100 million tonnes annually, which can replace up to 5 billion m^3 of natural gas per year (about 15% of total annual consumption). The transformation of such waste into highly profitable fuel in the form of biogas or pellets not only reduces the costs associated with the purchase of traditional energy sources, but also improves the environmental performance of farms by reducing greenhouse gas emissions. Each megawatt of installed solar capacity reduces CO_2 emissions by 1,500-2,000 tonnes annually, which is important in meeting the country's climate commitments.

The use of RES in agricultural production processes has a number of key benefits: it increases the level of energy independence, improves the financial stability of agricultural enterprises, opens up opportunities for developing new markets, and creates the preconditions for increasing Ukraine's scientific and technological attractiveness in global value chains. At the same time, the economic efficiency of such projects directly depends on the relevant government policy, which should include both financial and credit instruments (grants, soft loans) and legislative norms that encourage the localisation of energy equipment production, acceleration of permitting procedures, and development of public-private partnerships. The prospective development of the energy potential of the agricultural sector in Ukraine requires expanded compensation programmes, improved green auctions and support for long-term lending, which is especially important in the context of the post-war restoration of energy and logistics infrastructure, with coordination between different sectoral agencies interested in developing a comprehensive strategy that reconciles economic priorities with environmental safety playing a crucial role. The limitation of this study is its focus exclusively on the main areas of renewable energy implementation in the agricultural sector, without taking into account demographic, socio-cultural factors and the role of digital technologies.

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Економічні аспекти впровадження відновлюваних джерел енергії в агропромисловому комплексі

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▸ **Анотація.** Метою дослідження було виявлення економічних викликів впровадження відновлюваних джерел енергії в агропромисловому комплексі України та обґрунтування шляхів їх подолання з урахуванням сучасних трансформацій. Методологічну основу становили методи статистичного аналізу (зокрема, трендового й порівняльного), економіко-правовий аналіз, а також контент-аналіз наукових джерел і нормативно-правових документів. У процесі дослідження було проаналізовано сучасні тенденції розвитку сонячної, вітрової та біоенергетики в аграрному секторі. Встановлено, що найбільший економічний ефект забезпечують проєкти, засновані на використанні біомаси, біогазу та сонячної енергії, які дозволяють досягти зниження витрат на енергозабезпечення до 20-25 % у середньому. Виявлено, що найбільші перспективи має біоенергетика завдяки значному обсягу доступної аграрної сировини; обґрунтовано, що щорічний потенціал заміщення імпортного газу біопаливом становить до 5 млрд кубометрів, що еквівалентно зменшенню витрат на понад 2 млрд доларів США. Проаналізовано динаміку впровадження сонячної енергетики в аграрному секторі за період 2018-2024 років, зокрема встановлено, що в умовах збройного конфлікту відбулося зниження частки працюючих сонячних електростанцій до 50-60 % через пошкодження інфраструктури, однак у західних і центральних регіонах зберігається тенденція до зростання встановлених потужностей. Виявлено, що ефективність впровадження відновлювальних джерел енергії залежить від рівня державної підтримки, наявності цільових інструментів, таких як «зелені» тарифи, кредити з низькою відсотковою ставкою, а також прозорих регуляторних механізмів. Практичне значення дослідження полягає у наданні рекомендацій для посилення підтримки впровадження відновлюваних джерел енергії, що сприятиме енергоефективності аграрного сектору, підвищенню прибутковості фермерських господарств та конкурентоспроможності їхньої продукції

▸ **Ключові слова:** інноваційні технології; сталий розвиток; конкурентоспроможність; екологічна стабільність; державна підтримка; інвестиційні стимули