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Nurlan Bizhanov[1], Bakhtiyar Zharlykassov[2], Duman Utebayev[3], Almagul Kassymova[4], Oxana Telegina[5]

Development and research of a generating complex for agricultural facilities using renewable energy sources

Abstract: The study was conducted to determine the possibilities and advantages of introducing a generating complex based on renewable energy sources to increase the sustainability and energy efficiency of agricultural facilities. For this purpose, a model of a generating complex using renewable energy sources to meet the energy needs of agricultural facilities has been evaluated. The impact of the integration of the Bergey Excel 10 wind turbine, the NIBE F1155 geothermal installation, and the JA Solar JAM72S20-405/PR solar panels with the SolarEdge SE40K inverter on the energy systems of agricultural facilities was considered. The integration of solar panels and low-power wind turbines significantly reduced energy costs, achieving savings from 5,500 kWh to 180,000 kWh per year

✉ Corresponding Author: Bakhtiyar Zharlykassov; e-mail: bakhtiyarzharlykassov@gmail.com

[1] Department of Electric Power Industry, Akhmet Baitursynuly Kostanay Regional University, Kazakhstan; ORCID iD: 0000-0003-0044-6398; e-mail: nurlanbizhanov@outlook.com

[2] Department of Software, Akhmet Baitursynuly Kostanay Regional University, Kazakhstan; ORCID iD: 0000-0003-4547-6697; e-mail: bakhtiyarzharlykassov@gmail.com

[3] Department of Electric Power Industry, Akhmet Baitursynuly Kostanay Regional University, Kazakhstan; ORCID iD: 0009-0009-6129-8465; e-mail: utebayev063@hotmail.com

[4] Department of Physics, Mathematics and Digital Technology, Akhmet Baitursynuly Kostanay Regional University, Kazakhstan; ORCID iD: 0000-0002-1905-7707; e-mail: kassymova_a@outlook.com

[5] Department of Physics, Mathematics and Digital Technology, Akhmet Baitursynuly Kostanay Regional University, Kazakhstan; ORCID iD: 0009-0000-0666-9723; e-mail: omtelegina@outlook.com

compared to conventional sources. During the evaluation of the effectiveness of the complex, it was revealed that the payback period for investments in such technologies makes them economically feasible. In addition, the findings showed that the productivity of agricultural facilities has increased due to improved working conditions and lower energy costs. An analysis of the environmental impact of the generating complex showed a reduction in the level of polluting CO_2 emissions by 10–25 tonnes per year, which had a positive impact on the health of local ecosystems. The study also revealed that the introduction of renewable energy sources can be an incentive to create new jobs in the agricultural sector, which contributes to the economic development of the region.

Keywords: solar panels, wind turbines, environmental sustainability, alternative fuels, savings

Introduction

In the context of global climate change and the depletion of conventional energy resources, the agricultural sector faces the need to find sustainable and cost-effective solutions to meet its energy needs. The use of renewable energy sources is a promising way to optimize energy processes in agriculture. The integration of technologies such as solar panels, wind turbines, and the use of biomass can significantly reduce energy costs and minimize carbon emissions (Cen et al. 2021). In this context, an important step is to evaluate models of generating complexes that can ensure the efficient use of renewable energy sources. The present study is aimed at analyzing the possibilities of introducing such complexes in agricultural production, assessing their economic feasibility, and the impact on environmental sustainability and on the energy independence of the agricultural sector.

The problem of introducing renewable energy sources in the agricultural sector remains relevant due to the need to increase sustainability and energy independence. Dhonde et al. (2022) and Delapedra-Silva et al. (2022) focused on the economic advantages of using renewable energy sources, such as solar panels, for agricultural needs. Dhonde et al. (2022) emphasized the reduction of electricity costs, which makes the use of solar energy economically feasible and reduces dependence on conventional sources. Delapedra-Silva et al. (2022) also pointed out the importance of investment payback periods, emphasising that although initial investments can be significant, the long-term benefits of reducing energy costs make such projects attractive.

Ababneh and Hameed (2022) analyzed the possibilities of using biomass as an alternative fuel, identifying the potential for reducing carbon emissions. They emphasized that the use of biomass not only improved the ecological situation but could also become an important source of income for farmers. Scolaro and Kittner (2022) argued that the introduction of low-power wind turbines could significantly increase the energy independence of agricultural facilities. In their study, they also emphasized the importance of combining wind and solar energy to achieve optimal results. Kebede et al. (2022) and Khezri et al. (2022) came to a common conclusion about the high efficiency of the integration of several renewable energy sources in agriculture.

Kebede et al. (2022) emphasized that combining different technologies allows for maximum productivity and contributes to successful projects with a stable energy supply. In turn, Khezri et al. (2022) noted that the use of generating complexes improves working conditions, which increases productivity, considering the impact of such complexes on employee motivation and the general atmosphere on farms.

Newton et al. (2021) identified a positive impact on the health of local ecosystems due to a decrease in pollution levels. They described cases where the introduction of renewable energy sources has contributed to the restoration of biodiversity in agricultural regions. Mohsin et al. (2022) linked the introduction of renewable energy sources with the creation of new jobs in the agricultural sector. They emphasized that the development of green technologies could contribute to the growth of the economic complex and improve social conditions in rural areas. Rahman et al. (2022) emphasized the need for further study and implementation of renewable energy sources to ensure the sustainability of agriculture in the face of global challenges. They argued that only an integrated approach to this problem would allow for effective coping with future challenges.

Notwithstanding the considerable advancements achieved by prior research, critical gaps persist, highlighting the significance of this work. A significant gap is the effect of renewable energy adoption on the socio-economic development of rural areas, where renewable energy systems might possibly foster economic diversity, job creation, and local resilience. Although much attention has been directed at technological and environmental advantages, the wider socio-economic implications remain little examined. Furthermore, there is a need for more thorough evaluations of the long-term environmental effects of renewable energy systems in agriculture, specifically on biodiversity, soil health, and ecosystem stability. Moreover, the compatibility of diverse renewable energy technologies within certain agricultural settings has not been adequately examined. Comprehending the integration and mutual enhancement of solar, wind, and biomass systems across various agricultural sectors is essential for optimising energy solutions for farms with varied energy requirements. This research aims to bridge these gaps by presenting a comprehensive perspective on the possibilities of renewable energy and providing insights that may enhance both the sustainability and economic health of agricultural enterprises and rural communities.

The purpose of the study was to assess the potential and benefits of using renewable energy sources in agriculture in Kazakhstan to increase its sustainability and energy efficiency. Research objectives:

1. To examine the efficacy of integrating renewable energy sources into Kazakhstan's agricultural sector, emphasising their economic and environmental advantages, especially in rural and semi-rural areas with restricted energy access and elevated energy expenses.
2. To investigate the feasibility of incorporating solar and wind energy systems into the current energy framework of agricultural facilities in Kazakhstan, considering the local climate and geographical factors.
3. To evaluate the influence of renewable energy generation facilities on the productivity and sustainability of agricultural output in Kazakhstan, particularly their contribution to improved energy efficiency, decreasing operational expenses, and promoting long-term environmental sustainability.

1. Materials and methods

This research examines the incorporation of renewable energy technologies in the agriculture industry, emphasizing their economic viability and environmental consequences. The study used a qualitative methodology using secondary sources, including case studies, technical specifications, and reports from established renewable energy systems in agricultural contexts. This study utilizes data on JA Solar JAM72S20-405/PR solar panels, Bergey Excel-10 wind turbines, and NIBE F1155 geothermal heat pumps. These technologies were selected for their capacity to address agricultural energy requirements, particularly in rural areas with diverse climatic circumstances. The performance features, including energy production capacity, cost, and environmental advantages, were evaluated using publicly accessible information and manufacturer specifications.

A thorough examination of current case studies was performed to investigate the integration of renewable energy technology into agricultural systems worldwide. The case studies were obtained from farms and agricultural companies in Denmark, Germany, Portugal, and Kazakhstan. The experiences of these farms were used to evaluate the economic implications of incorporating renewable technology, including cost reductions and the long-term financial viability of implementing solar, wind, and geothermal systems in agricultural environments.

The technical compatibility of renewable energy technologies with existing agricultural infrastructures was assessed by analysing their integration in prior projects. Analyses of the integration of solar panels with wind turbines or geothermal systems were conducted to comprehend how various energy sources might synergize, especially in hybrid systems aimed at providing a stable power supply and diminishing dependence on traditional energy sources.

The research evaluated the economic effect by analysing data on capital expenditures, yearly operating expenses, and savings generated from renewable energy system installations. The financial parameters of these systems were juxtaposed with traditional energy sources, focusing on payback times and long-term cost reduction. The environmental implications of these technologies were evaluated, emphasizing the mitigation of CO_2 emissions. Data on emissions reduction from current renewable energy systems was obtained from technical publications and case studies, and juxtaposed with emissions generated by traditional power production.

The study also included an evaluation of energy efficiency across various renewable energy solutions. Data was extracted from current installations of solar panels, wind turbines, and geothermal heat pumps in agricultural settings to assess their efficacy across diverse climates, especially in areas with elevated solar radiation and wind resources. The emphasis was on evaluating energy-generating capacity and the system's capability to fulfil the energy requirements of agricultural facilities, including greenhouses and livestock operations, amid fluctuating weather conditions.

The study examined the effect of renewable energy integration on agricultural productivity and sustainability, focusing on its influence on farm operations and resilience. The study analyzed how farms using renewable technologies decreased their dependence on external energy sources, leading to improved operational efficiency and energy security. The enduring sustainability of agricultural enterprises was evaluated in terms of how energy independence enabled farms to endure variations in energy costs and market volatility.

This study does not include original field research; rather, it synthesizes existing information from several sources. These sources provide technical specifications, economic analyses, and environmental impact studies of renewable energy systems in agricultural contexts. This method offers a comprehensive analysis of the feasibility and advantages of renewable energy systems in agriculture, focusing on economic returns, environmental sustainability, and energy efficiency.

3. Results

Renewable energy sources are essential for the sustainable advancement of agriculture and the economy, given the depletion of natural resources and the acceleration of climate change. Agriculture, historically reliant on conventional energy, is progressively integrating renewable resources to reduce fossil fuel use and improve sustainability. Solar, wind, biomass, and geothermal energy have considerable promise for agriculture by diminishing carbon emissions and saving resources (Mathur et al. 2022).

Solar energy is economically viable and versatile for agricultural applications, including illumination, heating, and machinery operation (Kravtsova et al. 2024). The studies indicated that solar energy reduces dependence on conventional sources, leading to sustained financial savings. In regions with elevated solar radiation, particularly in the south and southeast, energy expenses decreased by as much as 30%, hence enhancing energy autonomy (Do et al. 2021; Yap et al. 2022). Wind energy further provides advantages for agriculture. Compact wind turbines, appropriate for rural regions with consistent wind, provide dependable energy. The integration of wind turbines with solar panels in hybrid systems decreased operating expenses by 20%, especially in places rich in wind resources (Do et al. 2021; Fu and Niu 2023).

Biomass energy, which transforms organic waste into heat and electricity, is a significant asset for agriculture (Prokopov et al. 1993). Biogas facilities, which transform waste into energy and fertilizers, complete the production cycle and diminish carbon emissions by 15% on farms involved in grain cultivation and animal rearing (Sasikumar et al. 2021). Geothermal energy provides dependable heating and hot water, particularly in regions abundant in geothermal resources. The research indicated that geothermal heat pumps, such as the NIBE F1155, save heating expenses by 20%, maintaining consistent temperatures in severe regions. The amalgamation of geothermal systems with solar and wind energy enhanced energy security and operational efficiency in agricultural enterprises (Table 1).

Every renewable energy source has unique benefits, aiding in decreased reliance on fossil fuels and fostering sustainable agriculture. The research indicated that the use of renewable energy in agriculture lowered operational expenses, yielded ecological advantages, and enhanced

Table 1. Economic assessment of the implementation of the NIBE F1155 geothermal installation with a capacity of 25 kW

Tabela 1. Ocena ekonomiczna wdrożenia instalacji geotermalnej NIBE F1155 o mocy 25 kW

Parameter	Value
Model	NIBE F1155
Power	25 kW
Annual generation of thermal energy	180,000 kWh
Initial costs	60,000 USD
Installation depth	50–80 metres
Pump type	Geothermal heat pump
Annual operating expenses	2,500 USD
Payback period	5–6 years
Long-term savings (10 years)	50,000 USD
Reduction of CO_2 emissions	25 tonnes/year

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

output. Solar and wind energy resulted in substantial cost savings and enhanced operating efficiency. Incorporating solar and wind systems into existing agricultural infrastructure requires meticulous design, especially in modifying older systems (Lubishtani and Lubishtani 2024). An autonomous system integrating solar collectors and panels was one approach. This decreased energy usage from traditional sources by up to 25%, so reducing expenses and the farm's carbon impact. Solar panels also powered water pumps for irrigation and heating, enhancing resilience in rural regions with restricted access to centralized energy (Halko et al. 2021).

Alterations to energy infrastructure, including the installation of inverters to convert direct current to alternating current for agricultural machinery, were determined to enhance energy management. The research emphasized the need for formulating an energy plan that incorporates solar and thermal management systems, further augmented by monitoring systems to optimize energy use. Integrating solar, wind, and geothermal energy sources into a unified system optimizes efficiency and stability. The NIBE F1155 geothermal system, shown in Table 1, delivered consistent heating with a payback time of 5 to 6 years and projected long-term savings of 50,000 USD. This hybrid methodology significantly decreased energy expenses and improved agricultural sustainability, especially in areas with fluctuating weather.

In an era of increasing environmental crises and instability of global fuel markets, renewable energy sources offer a sustainable alternative to conventional fuels. The use of renewable energy provides a number of economic, environmental, and social benefits, including reducing carbon emissions, strengthening energy independence, and creating new jobs (Table 2). Every year, the transition to renewable energy is becoming more and more justified for both the economy and society as a whole, making this transition an essential part of the global sustainable development strategy.

Table 2. Advantages of using renewable energy sources

Tabela 2. Zalety korzystania z odnawialnych źródeł energii

Advantage	Description	Example
Reducing carbon emissions	Reducing CO_2 emissions by using renewable resources instead of fossil fuels	30% reduction in farm emissions
Economic efficiency	Long-term savings due to lower fuel and operating costs	Cost reduction by 25% in 5 years
Energy independence	Provision of autonomous power supply, especially in remote regions	Increase energy independence by 50%
Social development	Job creation and improvement of working conditions in rural areas	Creation of 15 jobs on the farm
Improving ecosystem quality	Reduction of pollution and improvement of soil and water conditions as a result of the abandonment of hydrocarbons	Ecosystem improvement by 20%

Source: compiled by the authors based on (Do et al. 2021).

From an economic perspective, renewable energy sources provide enduring advantages, with operational expenses much lower than those of traditional energy sources. Despite the significant initial expenditures for systems like solar panels, wind power facilities, or biogas installations, the long-term benefits are tremendous. The research indicated that subsequent to the initial expenditure, farms might realize a decrease in operational expenses of up to 30%, mostly attributable to decreased maintenance and fuel costs related to renewable energy. Moreover, technological improvements and heightened investment have made renewable energy systems more affordable, enabling agricultural firms to diminish their reliance on fossil fuels and alleviate the risks associated with volatile oil and gas prices.

Renewable energy sources further provide environmental advantages. In contrast to coal and oil, which cause considerable air and water pollution, renewable sources produce low emissions, therefore enhancing air and water quality. Biogas facilities that process organic waste create clean energy and assist in waste management by mitigating methane emissions (Myronycheva et al. 2017). The researchers indicated that biogas utilisation resulted in a 15% decrease in methane emissions, highlighting its efficacy in mitigating greenhouse gases. The use of renewable energy technology aids in the conservation of biodiversity by obviating ecologically detrimental activities like fossil fuel extraction and deforestation.

The beneficial effects of renewable energy on public health include a decrease in pollution, resulting in fewer respiratory ailments among populations. Farms using renewable energy sources saw a reduction in health-related expenses and a 10–20% decrease in hospital admissions for respiratory issues. Moreover, renewable energy fosters energy autonomy, especially in isolated regions. This autonomy is essential during periods of global fuel market volatility, guaranteeing that farms continue to function and thrive, even under adverse conditions. Thus, renewable energy sources represent not only a way to combat climate change but also an effective tool for increasing economic sustainability and social stability. Expanding the use of renewable energy becomes the key to a secure future for generations to come, helping to preserve natural resources and improve living conditions for the entire population (Temirbaeva et al. 2024).

The design of a renewable energy generation facility entails the selection of appropriate technologies for the integration of renewable energy into current agricultural energy systems (Akhtar et al. 2021). The research evaluated the integration of several renewable sources, solar panels, wind turbines, and geothermal systems, into a cohesive system that optimizes efficiency and guarantees a reliable energy supply.

The autonomous system integrates JA Solar JAM72S20-405/PR solar panels with the Thermo Systems TS 200 solar collector to provide power and thermal energy for agricultural enterprises. The solar panels, characterized by high efficiency and extended longevity, are optimized for optimal sunlight absorption according to local climate and topography. The system incorporates a SolarEdge SE40K inverter to convert the direct power produced by the panels into alternating current for agricultural applications. The incorporation of a Tesla Powerwall 2 battery, with a 13.5 kWh capacity, guarantees an uninterrupted power supply during times of diminished solar activity. The Victron SmartSolar MPPT 150/60 solar controller enhances the system's reliability and efficiency by optimising energy flow and ensuring constant performance.

The Thermo Systems TS 200 solar collector complements the panels by providing thermal energy for indoor heating or water heating. This model is characterized by high heating capacity and energy efficiency, which makes it particularly suitable for agricultural facilities. The collector is integrated into the system via a heat exchanger, which allows for rational utilization of the heat produced.

The Bergey Excel 10 wind turbine complements solar panels, providing energy generation at low levels of solar activity. The Bergey Excel 10 belongs to horizontal-axial turbines, and therefore, has a greater ability to capture energy than vertical-axial installations, and can operate at lower wind speeds, and therefore, is optimal for regions with steady winds, especially Almaty, Atyrau, Mangystau, and Karaganda regions, where winds are stable and strong. Vertical-axis turbines are more compact and easier to maintain, but they are effective mainly in variable wind conditions, for example, in the Turkestan, Karaganda, Atyrau, Jambyl, and North Kazakhstan regions. The wind turbine is also connected to the battery system, which allows storing energy and using it in the absence of wind.

The projected complex also includes NIBE F1155 geothermal installations using heat pumps to extract heat from underground sources, providing heating and a hot water supply. These systems are efficient in regions with geothermal resources, have low operating costs, and a long service life. Wind turbines in the complex serve as an additional source of energy, especially in areas with constant wind currents. They efficiently generate electricity during periods of low solar activity, ensuring an uninterrupted power supply to the equipment at any time of the day. In combination with solar panels and energy accumulators, wind turbines maintain a stable energy supply.

The energy storage system is an important part of the generating complex, as it allows storing excess energy for use during peak periods (Dai et al. 2025; Shram and Kachan 2023). Lithium-ion batteries or deep-cycle batteries with high capacity and durability are used for this purpose. Batteries also help smooth out power fluctuations, ensuring an even distribution of energy throughout the day and preventing system overloads. In some cases, hydrogen storage technology can be used, which is especially useful in remote areas where long-term energy storage is needed.

Renewable energy integration schemes include management and control systems that automatically regulate energy distribution and storage. Modern complexes use intelligent networks and controllers that control the generation and consumption of energy depending on the needs of the facility and the availability of energy sources. This allows optimal use of each source, reduces the load on the equipment, and prevents excess energy.

A well-designed renewable energy complex ensures high efficiency, flexibility, and reliability of energy supply. The use of such systems in agriculture allows not only reducing energy costs, but also increasing independence from centralized networks, contributing to sustainable and environmentally sound production. Renewable energy sources are increasingly being used in agriculture around the world, due to their sustainability, economic benefits, and environmental benefits (Climate Action Plan (2050) 2016).

The experience of farmers in other countries includes many successful examples of how they have effectively implemented renewable energy sources, reduced costs, and increased energy independence. These projects serve as a useful guideline for Kazakhstan, which has significant potential for the development of renewable energy sources. In Denmark, the Nordic Folkecenter for Renewable Energy uses combined solar and wind energy systems to meet electricity and heating needs. Installed solar panels and wind turbines provide year-round energy supported by battery systems. This allowed the farm to achieve almost complete autonomy from centralized power grids. The Danish experience demonstrates the potential of combined installations that can be adapted for Kazakhstan, especially in its windy regions such as the Kostanay and Aktobe regions.

The Alpental Energy farm in Germany successfully uses biogas plants that process livestock waste into energy. This not only reduces methane emissions, which corresponds to the strategic climate goals of German legislation (Federal Climate Change Act… 2021), but also covers a significant part of energy costs. Kazakhstan has also begun to introduce emission regulations, although they are not yet as strict as in Europe. The availability of appropriate laws and penalties can stimulate the development of biogas technologies and help to reduce the negative impact on the environment. Through the use of organic waste, the farm not only provides itself with energy, but also receives fertilizers as a by-product. This method has potential for large agricultural enterprises in Kazakhstan, especially in the southern regions, where animal husbandry is widespread.

The Olivais do Sul farm in Portugal has a solar panel system for irrigation and lighting. The high level of solar radiation allows the household to almost completely meet its electricity needs. The Portuguese experience can be useful for Kazakhstan, which has significant solar resources, especially in the south of the country. Solar panels can be effectively used for the irrigation of agricultural crops in Atyrau and Mangistau regions, where the climate and intense sun contribute to increasing the efficiency of solar generation.

Renewable energy sources are also being introduced in Kazakhstan. For example, the agrofirm EkoAlma in the Almaty region uses solar panels to operate an irrigation system. This allows the farm to reduce energy costs, especially in the summer months, when irrigation needs increase. Such examples confirm the prospects of renewable energy in Kazakhstan's agriculture.

The potential of renewable energy in Kazakhstan is high due to the availability of solar, wind, and biomass resources. Using successful foreign examples and local renewable energy implementations can become an important component of the sustainable development of Kazakhstan's agriculture, ensuring energy independence and improving environmental performance.

The economic assessment of the implementation of a renewable energy generating complex requires a detailed analysis of the initial costs, operating costs, and long-term savings (Linchenko et al. 2022). Given the increased attention to sustainable development and the increasing availability of technologies, renewable energy sources are increasingly being considered as a profitable alternative to conventional fuels. Consideration of the economic feasibility of such projects includes an analysis of capital investments, operating costs, and possible financial benefits, which allows an objective assessment of the potential of their application in agriculture and other industries.

Solar panels are effectively used in agricultural facilities, providing energy supply during the day (Ismanzhanov and Tashiev 2016; Smyk and Arkhypova 2023). It is important to note that solar panels can power pumps, which, in turn, circulate the coolant through solar collectors. This allows providing an additional heat source for heating rooms or heating water, improving energy efficiency in the summer. The use of the SolarEdge SE40K inverter helps to maximize the output power of the solar system, and allows it to be integrated with other energy sources (Table 3).

Table 3 provides a comprehensive assessment of the economic feasibility of using JA Solar Panels in conjunction with the SolarEdge SE40K Inverter against the use of traditional grid power. The initial expenditure for the solar installation, amounting to 60,000 USD, is considerable. Nevertheless, the table highlights that this investment yields significant long-term savings, projected at 30,000 USD over the course of 10 years. This comparison underscores a significant advantage of renewable energy systems: while the initial capital investment is more than that of traditional energy infrastructure, the long-term operational costs for renewable energy are much reduced. The solar panels incur yearly running charges of just 2,000 USD, whereas traditional systems often entail much higher operational costs, estimated at 4,000 USD per year.

The six-year payback time for solar panels signifies that, after this duration, the farm will commence reaping the benefits of savings from decreased energy expenses. This statistic is essential as it delineates the breakeven point at which the system begins to provide a return on investment. Moreover, the energy cost per kWh from solar energy is far lower than that from traditional energy sources, making it a more cost-effective option over time. From an environmental standpoint, the implementation of solar energy leads to a decrease of 25 tonnes of CO_2 emissions annually, thus reinforcing the case for transitioning to renewable sources, not only for economic benefits but also for advancing sustainability objectives.

Wind is a variable source of energy; however, the installation of such a wind turbine allows for effective use of the natural resource available in rural areas. Wind energy can cover electricity

Table 3. Economic assessment of the introduction of JA Solar JAM72S20-405/PR solar panels with SolarEdge SE40K inverter

Tabela 3. Ocena ekonomiczna wprowadzenia paneli słonecznych Ja Solar Jam72s20-405/Pr z falownikiem Solaredge Se40k

Parameter	Value	Conventional Energy Sources
Panel model	JA Solar JAM72S20-405/PR	–
Number of panels	10	–
Area of one panel	2 m^2	–
Total area of the complex	20 m^2	–
Single panel power	0.405 kW	–
Total capacity of the complex	4.05 kW	–
Annual electricity generation by one panel	550 kW/h	–
Total annual generation	5,500 kW/h	–
Initial costs (USD)	60,000	30,000
Annual operating expenses (USD)	2,000	4,000
Energy cost per kWh (USD)	0.011	0.15
Payback period	6 years	–
Long-term savings (10 years)	30,000 USD	–
Reduction of CO_2 emissions	25 tonnes/year	0 tonnes

Source: compiled by the authors based on Mik et al. 2021.

needs during periods when solar activity is low and solar panels do not generate enough energy. In addition to providing energy for the basic needs of an agricultural facility, energy from a wind turbine can be used to power various systems such as ventilation, lighting, or water supply systems (Table 4).

Table 4 juxtaposes the cost ramifications of implementing a Bergey Excel 10 Wind Turbine against traditional grid electricity. The initial expenditure for the wind turbine is around 50,000 USD, which is lower than that for solar panels, although it remains substantial in comparison to traditional energy infrastructure costs. The yearly operational expenditures of the wind turbine are much cheaper at 500 USD, in contrast to the 4,000 USD often linked to traditional energy use. This price tag exemplifies a key benefit of renewable energy: reduced ongoing expenses, which may lead to significant savings over time. The payback time of 8–9 years for the wind turbine exceeds that of solar panels, indicating that farmers must endure a longer wait before realizing profits. Nonetheless, this payback time is within a justifiable range, given the long-term savings that will accrue post-breakeven. The projected long-term savings from the wind turbine amount to 15,000 USD over a decade, demonstrating its efficiency over time despite a protracted initial payback period. Similar to solar energy, wind turbines have considerable environmental advantages. The annual decrease of 10 tonnes of CO_2 underscores its beneficial effect on reducing the farm's carbon footprint. Wind energy, particularly in regions

Table 4. Economic assessment of the implementation of the Bergey Excel 10 wind turbine with a capacity of 10 kW

Tabela 4. Ocena ekonomiczna wdrożenia turbiny wiatrowej Bergey Excel 10 o mocy 10 kW

Parameter	Value	Conventional energy sources
Type of complex	Bergey Excel 10 wind turbine	–
Number of wind turbines	1	–
Wind turbine height	18–30 m	–
Power	10 kW	
Annual electricity generation	16,000–25,000 kWh	–
Initial costs (USD)	50,000	30,000
Annual operating expenses (USD)	500	4,000
Energy cost per kWh (USD)	0.020–0.031	0.15
Payback period	8–9 years old	–
Long-term savings (10 years)	15,000 USD	–
Reduction of CO_2 emissions	10 tonnes/year	0 tonnes

Source: compiled by the authors based on Akheel et al. (2024).

with stable wind patterns, serves as a feasible, clean energy source that offers economic benefits and contributes to environmental sustainability goals.

Several governments and international organisations offer support programmes and subsidies that reduce the financial burden on investors and make the introduction of renewable energy more attractive from an economic standpoint. For example, in Germany, there is a programme "2023 Amendment of the Renewable Energy Sources Act" (2023), which provides subsidies and guarantees tariffs for electricity from renewable energy sources (2023 Amendment of the Renewable Energy Sources Act… 2023). Kazakhstan has a programme to support renewable energy through a fixed tariff mechanism, which contributes to increased investment in solar and wind installations (UNDP Kazakhstan 2023).

Operating costs for renewable energy-generating complexes are usually lower compared to conventional energy sources. Such complexes do not require regular fuel costs, since sunlight, wind, or biomass are practically free resources. For example, solar panels and wind turbines require only minimal maintenance. Biogas plants using agricultural waste, in addition for generating energy, allow for the saving on the disposal of organic waste (Paton et al. 2005). The main expenses in the operation of the generating complex are related to repairs, periodic maintenance, and the replacement of battery system elements. The durability of the equipment allows for reducing the frequency of repairs, which additionally decreases operating costs.

In the long term, taking into account the absence of fuel costs and savings on conventional energy sources, such installations become economically profitable. Many agricultural enterprises using solar panels and wind turbines achieve full payback within 4–6 years, depending on the type of installation and the region (Jeločnik and Subić 2021). For example, solar panels can begin to bring net savings after several years of operation, especially in regions with high levels of solar radiation.

The economic feasibility of introducing a renewable energy-based generating complex is becoming increasingly evident against the backdrop of rising fossil fuel prices and climate change, which requires a transition to sustainable technologies. Modern farms and enterprises can use such installations to reduce their costs and increase environmental sustainability, while maintaining energy independence.

This research established a model that delineates a systematic method for choosing and integrating renewable energy technology into agricultural systems based on farm-specific criteria. The process starts with an estimate of energy consumption at the farm level and climate profile, which act as fundamental criteria for assessing technical feasibility (Fig. 1). This cycle is followed by a decision node for identifying the most appropriate renewable energy sources (e.g., solar panels for areas with strong insolation, biomass for waste-abundant farms, and wind for regularly windy locales).

The model points out the importance of interoperability with current energy infrastructure, including the requirement for inverters, controllers, or hybridisation techniques. The approach facilitates data-driven decision-making by evaluating initial investment, local resource availability, and long-term energy requirements. The concluding phases of the model underscore the economic returns and ecological advantages, consistent with the paper's focus on cost efficiency, energy independence, and reduction of carbon emissions. This systematic approach substantiates the article's conclusion that technology integration must be personalized, flexible, and contingent upon regional capabilities and agricultural typologies.

The introduction of renewable energy in agriculture has a high potential to improve environmental sustainability and economic efficiency (Chernets et al. 2008). However, despite the obvious advantages, there are a number of obstacles on the way to this transition, hindering the widespread use of renewable energy on farms. Among the main problems are high initial investments, complex technical requirements, lack of infrastructure, and limited knowledge in the field of renewable energy operation. Nevertheless, these obstacles can be overcome based on government support, the use of innovative solutions, and the education of rural entrepreneurs.

A primary technical obstacle to the use of renewable energy in agriculture is the substantial initial investment needed for systems like solar panels, wind turbines, and biomass facilities. Small and medium-sized farms sometimes have difficulties in financing the initial expenses associated with these technologies. The expenses associated with acquiring, installing, and integrating renewable energy systems into existing infrastructure may be exorbitant, particularly for farms that operate with narrow profit margins. Government incentives, including subsidies, grants, and tax exemptions, may substantially mitigate this cost. Moreover, private sector funding alternatives, such as low-interest loans or leasing arrangements, might assist farmers in managing initial expenses. By alleviating the cost impediment, these solutions may enhance the accessibility of renewable energy technology for farms of diverse scales. Crowdfunding or

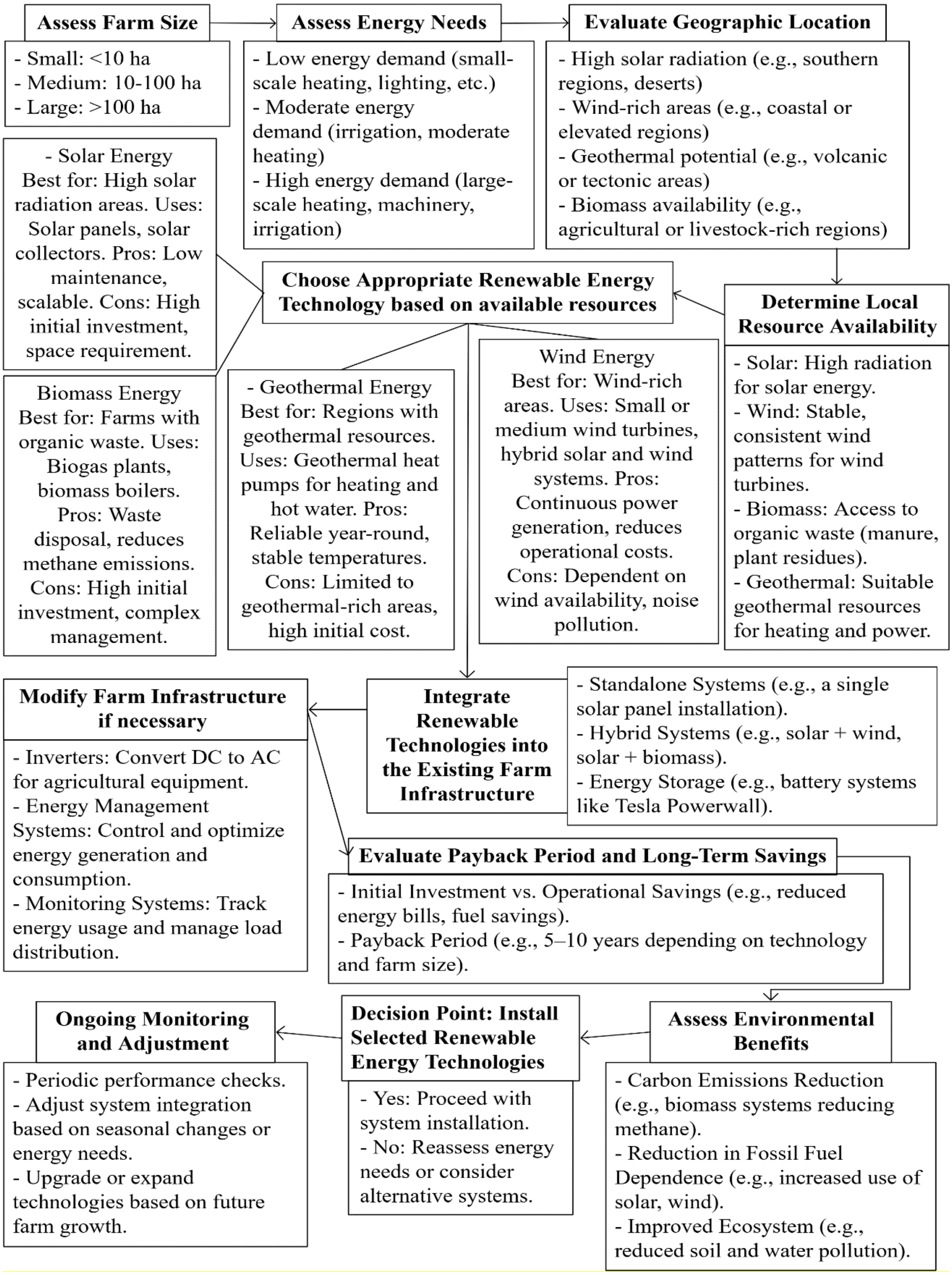

Fig. 1. Model for integrating renewable energy technologies into agricultural systems

Rys. 1. Model integracji technologii energii odnawialnej z systemami rolniczymi community-based finance models are an alternative strategy that may assist rural communities in securing cash for renewable energy initiatives, enabling them to distribute costs and advantages.

The technological intricacy of renewable energy systems poses another considerable hurdle. Implementing and managing hybrid systems that combine several renewable sources, such as solar, wind, and biomass, necessitates specialized expertise and technical proficiency. A significant number of farmers lack the requisite competence to install, operate, and repair these devices. Moreover, overseeing the integration of renewable energy systems with current agricultural infrastructure, such as energy storage, inverters, and energy management systems, may be challenging. A viable answer to this difficulty is the implementation of training and capacity-building initiatives. Equipping farmers and technicians with the requisite skills to operate and maintain these technologies helps reduce the chance of operational failure. Additionally, creating technical support centres in remote regions may provide continuous assistance and maintenance services, ensuring the sustained functionality and efficiency of systems over time. Such an initiative would substantially alleviate the load on farmers and empower them to handle renewable energy technology more efficiently.

Numerous rural regions lack the infrastructure necessary for the integration of renewable energy systems (Prokopov et al. 1989). This encompasses both the physical infrastructure, including electric grids and energy storage systems, and the logistical infrastructure necessary for the installation and maintenance of renewable energy equipment. Many isolated farms, for example, lack access to reliable power networks or the requisite infrastructure to incorporate solar or wind energy. A hybrid system integrating solar and wind energy may serve as a viable alternative for many rural farms, particularly when augmented with energy storage technologies such as batteries. These systems retain surplus energy produced during peak generating periods for use during times of diminished energy output. Moreover, the establishment of microgrids, decentralized energy systems intended to function autonomously or in tandem with the main grid, can provide a dependable option for rural agriculture. Governments and private sector enterprises must prioritize investments in renewable energy infrastructure in rural regions to enable the seamless integration of these technologies.

A significant obstacle to broad adoption is the inadequate understanding and awareness of renewable energy technology among farmers (Shebanin et al. 2025). A significant number of farm workers lack awareness of the potential advantages of renewable energy or are reluctant to invest in unfamiliar technology. This deficiency in understanding may hinder farmers from making educated choices about energy solutions that might enhance their operations. Governments, NGOs, and business organisations should initiate awareness campaigns to address this issue. These efforts should concentrate on informing farmers about the economic savings, environmental advantages, and long-term sustainability provided by renewable energy systems. Demonstration projects and pilot farms exemplify the actual use of renewable energy, illustrating how these technologies enhance agricultural output and decrease expenses. Furthermore, establishing peer networks for farmers to exchange experiences and learn from one another's triumphs and mistakes in renewable energy may enhance confidence and promote adoption.

The intermittency and unpredictability of renewable energy sources, particularly sun and wind, provide substantial challenges. Solar energy generation relies on sunshine, which may be variable owing to meteorological conditions, diurnal cycles, and seasonal changes (Ismanzhanov et al. 2012). Likewise, wind energy is contingent upon wind patterns, which may fluctuate by place and season. This intermittency presents issues in maintaining a consistently stable power source. A potential answer to this issue is the use of hybrid renewable energy systems. Integrating solar, wind, and biomass systems enables farms to diversify their energy sources, assuring a more reliable energy supply (Anguelov and Kavaldzhieva 2021). Moreover, energy storage technologies, including batteries, may save surplus energy generated at peak production times for use when renewable power is insufficient. Such an arrangement guarantees that farms have a consistent energy source, even during intervals of less sunshine or wind.

The introduction of renewable energy sources in agriculture is a promising area that can lead to significant improvements in energy independence and environmental sustainability (Buzaubayeva et al. 2023). Attracting international funds to finance projects in the field of renewable energy can help to remove the obstacles hindering their implementation. This will create conditions conducive to the further development of agricultural energy based on renewable energy sources.

4. Discussion

The results of this study corroborate the conclusions of other experts, affirming that renewable energy sources provide economic and environmental advantages for the agriculture industry. Consistent with the findings of Bogdanov et al. (2021), this research underscores the pivotal significance of renewable energy-producing complexes in augmenting the energy autonomy of farms, diminishing dependency on traditional energy sources, and promoting sustainability in agricultural operations. A combination of solar, wind, and biomass energy systems may actually yield a steadier energy supply and diminish energy expenditures, a finding corroborated by Avgoustaki and Xydis (2021). These studies underscore the increasing significance of minimising energy expenses, particularly considering volatile energy prices, and the contribution of renewable energy to enhancing the competitiveness and profitability of agricultural enterprises.

The study findings complement those of Nguyen et al. (2021), indicating that biomass serves as an efficient means to mitigate carbon emissions while enhancing sustainable agricultural output. This research validates the capacity of biomass to convert organic waste into energy, establishing both an alternative energy source and a sustainable waste management system. Nonetheless, similar to Dong et al. (2021), the study recognizes that inadequate management of biomass resources may negatively impact ecosystem health, resulting in soil degradation and diminished biodiversity. This underscores the need to formulate integrated strategies for biomass management to optimize its advantages while mitigating adverse environmental effects.

The findings of this research about the payback time for investments in renewable energy technologies correspond with those of Rahmat et al. (2022), who observed that the payback period for solar and wind systems generally ranges from 4 to 6 years. This research indicates that farmers may get financial benefits from lower energy expenses, allowing them to reinvest savings into various operational facets; nevertheless, Rahmat et al. (2022) highlighted that this is contingent upon geographical circumstances, system types, and project scales. Notwithstanding the initial substantial investment, the declining costs of renewable technologies and the rising prices of conventional energy might further reduce the payback time, making these technologies more appealing for long-term investment.

The research conducted by Qadir et al. (2021) reinforces the idea that reallocating savings to various sectors of the farm, such as research and development, employee training, and technological enhancements, can markedly enhance overall farm efficiency and competitiveness. This research emphasizes that investments in renewable energy systems may transform agricultural operations by enhancing energy efficiency and fostering further innovation possibilities. This research identifies financial barriers as a primary challenge obstructing the widespread adoption of renewable technologies, a concern echoed by Pathak et al. (2022), who discovered that substantial initial investment costs pose a significant obstacle for small- and medium-sized enterprises (SMEs) in agriculture.

Furthermore, the research underscores the significance of governmental assistance and financial mechanisms, which are essential for surmounting the financial obstacles encountered by small-scale farmers in the adoption of renewable technology. This conclusion aligns with Rashed and Shah (2021), who recognised subsidies, tax incentives, and low-interest loans as viable strategies to alleviate the financial strain on farmers. Promoting government investment in renewable energy initiatives will certainly expedite the shift to sustainable agriculture methods, especially in rural regions.

The findings of Mahalik et al. (2021) indirectly confirmed the important role of education in the successful implementation of renewable energy technologies in the agricultural sector. They not only provide farmers with the necessary knowledge about available technologies and methods of their application but also help them develop the skills necessary for the operation and maintenance of equipment. In addition, such programs can contribute to the creation of networks and communities among farmers, which will allow for the exchange of experiences and best practices in the field of sustainable development.

Thus, the level of awareness among farmers is an important factor in the successful implementation of renewable energy technologies. Educational programs not only inform about the benefits of renewable energy sources but also develop the skills necessary for the effective operation of these technologies. As a result, the creation of a sustainable system for educating and informing farmers about renewable energy sources can increase interest in these technologies. A sustainable learning system refers to the availability of educational resources for all farmers, including free courses and seminars, and the integration of practical knowledge and technologies that contribute to the sustainable development of the country and ecosystems. Such a system can not only inform about the advantages of renewable energy sources but also provide support in their implementation, which, in turn, contributes to the wider adoption of renewable energy sources in the agricultural sector.

The development and application of a renewable energy-based generating complex can significantly improve the energy efficiency and sustainability of agricultural facilities. The future of agriculture depends on the ability to adapt to new realities and apply innovative solutions that will make it more sustainable and competitive.

A significant contribution of this research is its instructional component. It robustly corroborates the findings of Elahi et al. (2022), who highlighted the significance of awareness programmes in enhancing farmers' comprehension of renewable energy technology. The research finds that educational initiatives are crucial in promoting the adoption of renewable energy solutions, therefore enhancing farmers' readiness to invest in these technologies. By imparting essential facts about cost efficiencies, ecological advantages, and feasible execution, these programs might motivate a greater number of farmers to make educated choices about the adoption of renewable energy systems.

The outcomes of this study highlight the need for cohesive policy frameworks that amalgamate financial assistance, education, and technical competence to facilitate farmers' shift to renewable energy. Future research should investigate how collaboration between the government and the private sector might improve investment accessibility for farmers, especially in developing nations where the initial prices of renewable technology remain a substantial barrier. Moreover, it might concentrate on longitudinal assessments of farms that have adopted renewable energy systems to comprehend the enduring effects on agricultural production, sustainability, and profitability.

Conclusions

This research illustrates the considerable potential of incorporating renewable energy technologies, such as solar panels, wind turbines, and geothermal heat pumps, into agricultural practices. The study underscores the economic advantages of adopting renewable energy, namely regarding energy cost reductions and long-term financial viability, by an extensive examination of current case studies and secondary sources. Renewable energy technologies, such as the JA Solar JAM72S20-405/PR panels and Bergey Excel 10 wind turbines, provide a cost-efficient substitute for traditional energy sources, characterized by reduced operating expenses and payback times of 6 to 9 years. The integration of these systems fosters energy independence, hence augmenting the resilience of agricultural facilities against external variations in energy costs.

From an environmental standpoint, the use of renewable energy sources markedly decreases CO_2 emissions, fostering more sustainable agriculture practices. The research indicated that solar and wind systems may significantly decrease greenhouse gas emissions, facilitating the agriculture sector's adherence to global sustainability objectives. The findings emphasize the need for integrating solar and wind energy with energy storage systems to improve energy stability, particularly in areas with fluctuating weather patterns.

This study demonstrates that incorporating renewable energy systems into current agricultural energy infrastructures enhances the productivity and sustainability of agricultural operations. The implementation of renewable energy enhances energy efficiency, reduces reliance on traditional power networks, and bolsters the economic sustainability of agricultural operations. The amalgamation of hybrid energy systems, including solar, wind, and geothermal energy, significantly improves power supply stability and reduces the dangers associated with dependence on a single energy source.

The results indicate that the use of renewable energy systems in agriculture enhances energy efficiency and fosters sustainability, hence making farms more economically resilient and ecologically accountable. The research highlights the imperative for specific policy assistance, including financial incentives and technical training, to promote the integration of renewable energy technologies in agriculture, especially in areas with significant energy requirements and potential for renewable resource production.

A limitation of the study was the lack of long-term data on the functioning of generating complexes in real-world operating conditions, which makes it difficult to assess their sustainability and effectiveness over time. It is necessary to investigate the impact of the introduction of generating complexes on the socio-economic development of the regions in which they are implemented, including an analysis of changes in farmers' incomes and the creation of new jobs.

The Authors have no conflicts of interest to declare.

References

2023 Amendment of the Renewable Energy Sources Act (EEG 2023) 2023. [Online:] https://www.iea.org/policies/19488-2023-amendment-of-the-renewable-energy-sources-act-eeg-2023 [Accessed: 2025-09-21].

Ababneh, H. and Hameed, B.H. 2022. Electrofuels as emerging new green alternative fuel: A review of recent literature. *Energy Conversion and Management* 254, DOI: 10.1016/j.enconman.2022.115213.

Akheel et al. 2024 – Akheel, M.M., Sankar, B., Boopathi, K. Reddy Prasad, D.M., Prabhu Shankar, N. and Rajkumar, N. 2024. Optimizing efficiency and analyzing performance: Enhanced airfoil cross-sections for horizontal axis small wind turbines. *Wind Engineering* 49(1), pp. 162–180, DOI: 10.1177/0309524X241259946.

Akhtar et al. 2021 – Akhtar, I., Kirmani, S. and Jameel, M. 2021. Reliability assessment of power system considering the impact of renewable energy sources integration into grid with advanced intelligent strategies. *IEEE Access* 9, pp. 32485–32497, DOI: 10.1109/ACCESS.2021.3060892.

Anguelov, K. and Kavaldzhieva, K. 2021. Methodology for determining the socio-economic factors in the performance of Cost-Benefit Analysis for the production of electricity from biomass. [In:] *2021 17th Conference on Electrical Machines, Drives and Power Systems, ELMA 2021 – Proceedings*. Sofia: Institute of Electrical and Electronics Engineers, DOI: 10.1109/ELMA52514.2021.9502978.

Avgoustaki, D.D. and Xydis, G. 2021. Energy cost reduction by shifting electricity demand in indoor vertical farms with artificial lighting. *Biosystems Engineering* 211, pp. 219–229, DOI: 10.1016/j.biosystemseng.2021.09.006.

Bogdanov et al. 2021 – Bogdanov, D., Gulagi, A., Fasihi, M. and Breyer, C. 2021. Full energy sector transition towards 100% renewable energy supply: Integrating power, heat, transport and industry sectors including desalination. *Applied Energy* 283, DOI: 10.1016/j.apenergy.2020.116273.

Buzaubayeva et al. 2023 – Buzaubayeva, P., Gulzhan, A., Baimagambetova, Z. and Kenges, G. 2023. Financial technologies to support agricultural innovations in Kazakhstan: Prospects for digital development. *Futurity of Social Sciences* 1(2), pp. 30–44, DOI: 10.57125/FS.2023.06.20.03.

Cen et al. 2021 – Cen, S., Li, K., Liu, Q. and Jiang, Y. 2021. Solar energy-based hydrogen production and post-firing in a biomass fueled gas turbine for power generation enhancement and carbon dioxide emission reduction. *Energy Conversion and Management* 233, DOI: 10.1016/j.enconman.2021.113941.

Chernets et al. 2008 – Chernets, O.V., Korzhyk, V.M., Marynsky, G.S., Petrov, S.V. and Zhovtyansky, V.A. 2008. Electric arc steam plasma conversion of medicine waste and carbon containing materials. *GD 2008 - 17th International Conference on Gas Discharges and Their Applications* 465–468. [Online:] https://ieeexplore.ieee.org/document/5379362 [Accessed: 2025-10-05].

Climate Action Plan 2050. 2016. [Online:] https://unfccc.int/files/focus/application/pdf/161114_climate_action_plan_2050.pdf [Accessed: 2025-09-21].

Dai et al. 2025 – Dai, Z.C., Tan, M., Yang, Y., Liu, X., Wang, R. and Su, Y.X. 2025. Massive Coordination of Distributed Energy Resources in VPP: A Mean Field RL-Based Bi-Level Optimization Approach. *IEEE TRANSACTIONS ON CYBERNETICS*, DOI: 10.1109/TCYB.2024.3525121.

Delapedra-Silva et al. 2022 – Delapedra-Silva, V., Ferreira, P., Cunha, J. and Kimura, H. 2022. Methods for financial assessment of renewable energy projects: A review. *Processes* 10(2), DOI: 10.3390/pr10020184.

Dhonde et al. 2022 – Dhonde, M., Sahu, K. and Murty, V.V.S. 2022. The application of solar-driven technologies for the sustainable development of agriculture farming: A comprehensive review. *Reviews in Environmental Science and Bio/Technology* 21(2), pp. 139–167, DOI: 10.1007/s11157-022-09611-6.

Do et al. 2021 – Do Thi, H.T., Pasztor, T., Fozer, D., Manenti, F. and Toth, A.J. 2021. Comparison of desalination technologies using renewable energy sources with life cycle, PESTLE, and multi-criteria decision analyses. *Water* 13(21), DOI: 10.3390/w13213023.

Dong et al. 2021 – Dong, H., Xue, M., Xiao, Y. and Liu, Y. 2021. Do carbon emissions impact the health of residents? Considering China's industrialization and urbanization. *Science of the Total Environment* 758, DOI: 10.1016/j.scitotenv.2020.143688.

Elahi et al. 2022 – Elahi, E., Khalid, Z. and Zhang, Z. 2022. Understanding farmers' intention and willingness to install renewable energy technology: A solution to reduce the environmental emissions of agriculture. *Applied Energy* 309, DOI: 10.1016/j.apenergy.2021.118459.

Federal Climate Change Act (Bundes-Klimaschutzgesetz) 2021. [Online:] https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Gesetze/ksg_aendg_en_bf.pdf [Accessed: 2025-09-21].

Fu, X. and Niu, H. 2023. Key technologies and applications of agricultural energy internet for agricultural planting and fisheries industry. *Information Processing in Agriculture* 10(3), pp. 416–437, DOI: 10.1016/j.inpa.2022.10.004.

Halko et al. 2021 – Halko, S., Suprun, O. and Miroshnyk, O. 2021. Influence of temperature on energy performance indicators of hybrid solar panels using cylindrical cogeneration photovoltaic modules. [In:] *2021 IEEE 2nd KhPI Week on Advanced Technology, KhPI Week 2021 – Conference Proceedings*, pp. 132–136. Kharkiv: Institute of Electrical and Electronics Engineers, DOI: 10.1109/KhPIWeek53812.2021.9569975

Ismanzhanov et al. 2012 – Ismanzhanov, A.I., Murzakulov, N.A. and Azimzhanov, O.A. 2012. Investigation on heat exchange in interlayer space of multilayer greenhouses. *Applied Solar Energy* 48(2), pp. 118–120, DOI: 10.3103/S0003701X12020107.

Ismanzhanov, A.I. and Tashiev, N.M. 2016. Development and research of the technology for powdering agricultural products using solar energy. *Applied Solar Energy* 52(4), pp. 256–258, DOI: 10.3103/S0003701X16040101.

Jeločnik, M. and Subić, J. 2021. Economic effects of the wind-turbine and solar panels application in vegetables' production at the family farms. [In:] *IX International Scientific-Practical Conference: Innovative Aspects of the Development Service and Tourism*, pp. 61–75. Stavropol: Sequoia.

Kebede et al. 2022 – Kebede, A.A., Kalogiannis, T., Van Mierlo, J. and Berecibar, M. 2022. A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration. *Renewable and Sustainable Energy Reviews* 159, DOI: 10.1016/j.rser.2022.112213.

Kherzri et al. 2022 – Khezri, M., Heshmati, A. and Khodaei, M. 2022. Environmental implications of economic complexity and its role in determining how renewable energies affect CO_2 emissions. *Applied Energy* 306, DOI: 10.1016/j.apenergy.2021.117948.

Kravtsova et al. 2024 – Kravtsova, D., Ziuhan, U. and Fraimovych, A. 2024. Solar panels' energy efficiency optimisation using mathematical methods with computerisation of calculations. *Journal of Kryvyi Rih National University* 22(2), pp. 68–72, DOI: 10.31721/2306-5451-2024-2-22-68-72

Linchenko et al. 2022 – Linchenko, V., Zhuk, D., Lysenko, N., Stepenko, S. and Zhuk, I. 2022. Green energy: Problems of environmental protection. *Ecological Safety and Balanced Use of Resources*, 13(2), pp. 58–68, DOI: 10.31471/2415-3184-2022-2(26)-58-68.

Lubishtani, M. and Lubishtani, F.B. 2024. Using geodetic data to optimize the distribution of solar and wind energy installations. *Machinery & Energetics* 15(2), pp. 69–80, DOI: 10.31548/machinery/2.2024.69.

Luca, B. 2022. *Energy assessment of a geothermal heat pump system in a residential context*. Torino: Politecnico di Torino.

Mahalik et al. 2021 – Mahalik, M.K., Mallick, H. and Padhan, H. 2021. Do educational levels influence the environmental quality? The role of renewable and non-renewable energy demand in selected BRICS countries with a new policy perspective. *Renewable Energy* 164, pp. 419–432, DOI: 10.1016/j.renene.2020.09.090.

Mathur et al. 2022 – Mathur, S., Waswani, H., Singh, D. and Ranjan, R. 2022. Alternative fuels for agriculture sustainability: Carbon footprint and economic feasibility. *AgriEngineering* 4(4), pp. 993–1015, DOI: 10.3390/agriengineering4040063.

Mik et al. 2021 – Mik, K., Zawadzki, P., Tarłowski, J., Bugaj, M., Grygiel, P. and Bykuć, S. 2021. Multifaceted analyses of four different prototype lightweight photovoltaic modules of novel structure. *Energies* 14(8), DOI: 10.3390/en14082239.

Mohsin et al. 2022 – Mohsin, M., Taghizadeh-Hesary, F., Iqbal, N. and Saydaliev, H.B. 2022. The role of technological progress and renewable energy deployment in green economic growth. *Renewable Energy* 190, pp. 777–787, DOI: 10.1016/j.renene.2022.03.076.

Myronycheva et al. 2017 – Myronycheva, O., Bandura, I., Bisko, N., Gryganskyi, A.P. and Karlsson, O. 2017. Assessment of the growth and fruiting of 19 oyster mushroom strains for indoor cultivation on lignocellulosic wastes. *BioResources* 12(3), pp. 4606–4626, DOI: 10.15376/biores.12.3.4606-4626.

Newton et al. 2021 – Newton, A.C., Evans, P.M., Watson, S.C.L., Ridding, L.E., Brand, B., McCracken, M., Gosal, A.S. and Bullock, J.M. 2021. Ecological restoration of agricultural land can improve its contribution to economic development. *PloS One* 16(3), e0247850, DOI: 10.1371/journal.pone.0247850.

Nguyen et al. 2021 – Nguyen, X.P., Hoang, A.T., Ölçer, A.I., Engel, D., Pham, V.V. and Nayak, S.K. 2021. Biomass-derived 2.5-dimethylfuran as a promising alternative fuel: An application review on the compression and spark ignition engine. *Fuel Processing Technology* 214, DOI: 10.1016/j.fuproc.2020.106687.

Pathak et al. 2022 – Pathak, S.K., Sharma, V., Chougule, S.S. and Goel, V. 2022. Prioritization of barriers to the development of renewable energy technologies in India using integrated Modified Delphi and AHP method. *Sustainable Energy Technologies and Assessments* 50, DOI: 10.1016/j.seta.2021.101818.

Paton et al. 2005 – Paton, B.E., Chernets, A.V., Marinsky, G.S., Korzhik, V.N. and Petrov, V.S. 2005. Prospects of using plasma technologies for disposal and recycling of medical and other hazardous waste. Part 2. *Problemy Spetsial'noj Electrometallugii* (4), pp. 46–54.

Prokopov et al. 1989 – Prokopov, V.G., Shvets, Y.I., Fialko, N.M., Meranova, N.O., Korzhik, V.N. and Borisov, Y.S. 1989. Mathematical-modeling of the convective heat-transfer processes during formation of the gas-thermal coating layer. *Dopovidi Akademii Nauk Ukrainskoi RSR, Seriya A-Fiziko-Matematichni ta Technichni Nauki* 6, pp. 71–76.

Prokopov et al. 1993 – Prokopov, V.G., Fialko, N.M., Sherenkovskaya, G.P., Yurchuk, V.L., Borisov, Y.S., Murashov, A.P. and Korzhik, V.N. 1993. Effect of coating porosity on the process of heat-transfer with gas-thermal deposition. *Powder Metallurgy and Metal Ceramics* 32(2), pp. 118–121, DOI: 10.1007/BF00560034.

Qadir et al. 2021 – Qadir, S.A., Al-Motairi, H., Tahir, F. and Al-Fagih, L. 2021. Incentives and strategies for financing the renewable energy transition: A review. *Energy Reports* 7, pp. 3590–3606, DOI: 10.1016/j.egyr.2021.06.041.

Rahman et al. 2022 – Rahman, M.M., Khan, I., Field, D.L., Techato, K. and Alameh, K. 2022. Powering agriculture: Present status, future potential, and challenges of renewable energy applications. *Renewable Energy* 188, pp. 731–749, DOI: 10.1016/j.renene.2022.02.065.

Rahmat et al. 2022 – Rahmat, M.A.A., Abd Hamid, A.S., Lu, Y., Ishak, M.A.A., Suheel, S.Z., Fazlizan, A. and Ibrahim, A. 2022. An analysis of renewable energy technology integration investments in Malaysia using HOMER pro. *Sustainability* 14(20), DOI: 10.3390/su142013684.

Rashed, A.H. and Shah, A. 2021. The role of private sector in the implementation of sustainable development goals. *Environment, Development and Sustainability* 23(3), pp. 2931–2948, DOI: 10.1007/s10668-020-00718-w.

Sasikumar et al. 2021 – Sasikumar, C., Sundaresan, R., Nagaraja, M. and Rajaganapathy, C. 2021. A review on energy generation from manure biomass. *Materials Today: Proceedings* 45, pp. 2408–2412, DOI: 10.1016/j.matpr.2020.10.832.

Scolaro, M. and Kittner, N. 2022. Optimizing hybrid offshore wind farms for cost-competitive hydrogen production in Germany. *International Journal of Hydrogen Energy* 47(10), pp. 6478–6493, DOI: 10.1016/j.ijhydene.2021.12.062.

Shebanin et al. 2025 – Shebanin, V., Kormyshkin, A., Ruzhniak, M., Reshetilov, G., and Kormyshkina, I. 2025. Formation of complex community restoration management models in the context of sustainable agricultural development. *Scientific Horizons* 28(2), pp. 116–128, DOI: 10.48077/scihor2.2025.116.

Shram, O. and Kachan, Yu. 2023. Determination of appropriate energy storage devices in the power grids of industrial enterprises. *Journal of Kryvyi Rih National University* 21(2), pp. 52–59, DOI: 10.31721/2306-5451-2023-1-57-52-59.

Smyk, I. and Arkhypova, L. 2023. Analysis of influence of meteorological conditions on the efficiency of solar panels in Ivano-Frankivsk Region. *Ecological Safety and Balanced Use of Resources* 14(1), pp. 99–107, DOI: 10.31471/2415-3184-2023-1(27)-99-107.

Temirbaeva et al. 2024 – Temirbaeva, N., Sadykov, M., Osmonov, Zh., Osmonov, Y. and Karasartov, U. 2024. Renewable energy sources in Kyrgyzstan and energy supply to rural consumers. *Machinery & Energetics* 15(3), pp. 22–32, DOI: 10.31548/machinery/3.2024.22.

Tomaszewska et al. 2021 – Tomaszewska, B., Akkurt, G.G., Kaczmarczyk, M., Bujakowski, W., Keles, N., Jarma, Y.A., Baba, A., Bryjak, M. and Kabay, N. 2021. Utilization of renewable energy sources in desalination of geothermal water for agriculture. *Desalination* 513, DOI: 10.1016/j.desal.2021.115151.

UNDP Kazakhstan 2023. Financial support programs for entrepreneurs implementing energy efficiency and renewable energy projects. [Online:] https://www.undp.org/kazakhstan/news/financial-support-programs-entrepreneurs-implementing-energy-efficiency-and-renewable-energy-projects [Accessed: 2025-09-21].

Yap et al. 2022 – Yap, K.Y., Chin, H.H. and Klemeš, J.J. 2022. Solar energy-powered battery electric vehicle charging stations: Current development and future prospect review. *Renewable and Sustainable Energy Reviews* 169, DOI: 10.1016/j.rser.2022.112862.

Nurlan Bizhanov, Bakhtiyar Zharlykassov, Duman Utebayev, Almagul Kassymova, Oxana Telegina

Opracowanie i badania kompleksu wytwórczego dla obiektów rolniczych wykorzystującego odnawialne źródła energii

Streszczenie

Badanie przeprowadzono w celu określenia możliwości i zalet wprowadzenia kompleksu wytwórczego opartego na odnawialnych źródłach energii w celu zwiększenia zrównoważonego rozwoju i efektywności energetycznej obiektów rolniczych. Zbadano wykorzystanie odnawialnych źródeł energii w rolnictwie. W tym celu oceniono model kompleksu wytwórczego wykorzystującego odnawialne źródła energii dla zaspokojenia potrzeb energetycznych obiektów rolniczych. Rozważono wpływ integracji turbiny wiatrowej Bergey Excel 10, instalacji geotermalnej NIBE F1155 oraz paneli słonecznych JA Solar JAM72S20-405/PR z falownikiem SolarEdge SE40K na systemy energetyczne obiektów rolniczych. Integracja paneli słonecznych i turbin wiatrowych małej mocy znacznie obniżyła koszty energii, pozwalając na oszczędności od 5500 kWh do 180 000 kWh rocznie w porównaniu z konwencjonalnymi źródłami. Analiza wykazała, że wykorzystanie biomasy jako alternatywnego paliwa do ogrzewania i obsługi sprzętu rolniczego może nie tylko zmniejszyć emisję dwutlenku węgla, lecz także zapewnić bardziej zrównoważony system energetyczny. Podczas oceny efektywności kompleksu okazało się, że okres zwrotu inwestycji w takie technologie czyni je ekonomicznie wykonalnymi. Ponadto ustalenia wykazały, że produktywność obiektów rolniczych wzrosła dzięki poprawie warunków pracy i niższym kosztom energii. Uzyskane dane potwierdzają, że wykorzystanie odnawialnych źródeł energii w sektorze rolnym przyczynia się nie tylko do zwiększenia niezależności energetycznej, lecz także do poprawy ogólnej równowagi środowiskowej. Analiza wpływu kompleksu wytwórczego na środowisko wykazała zmniejszenie poziomu emisji zanieczyszczającego CO_2 o 10–25 ton rocznie, co miało pozytywny wpływ na zdrowie lokalnych ekosystemów. Badanie wykazało również, że wprowadzenie odnawialnych źródeł energii może być zachętą do tworzenia nowych miejsc pracy w sektorze rolniczym, co przyczynia się do rozwoju gospodarczego regionu.

Słowa kluczowe: panele słoneczne, turbiny wiatrowe, zrównoważony rozwój środowiska, paliwa alternatywne, oszczędności