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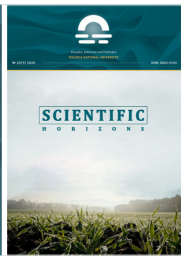

The impact of renewable energy implementation on agricultural sustainability in the context of climate change

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Abstract. This study was aimed at exploring the potential of renewable energy sources (RES) in enhancing the resilience of agriculture to climate change, with a focus on the applicability of these technologies in the context of Kazakhstan. The study was based on qualitative and quantitative analysis of the current state of the sector, comparative analysis of renewable energy technologies, examination of practical cases, and assessment of the applicability in the Republic of Kazakhstan. As a result of the study, it was found that RES, such as solar, wind, and biogas energy, had significant potential for increasing the resilience of agriculture in the context of climate change. It was established that these technologies effectively reduced the dependence of the agricultural sector on fossil fuels, which was particularly valuable for remote regions.

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It was emphasised that a 2 kW system could generate 6-10 kWh per day in sunny regions such as Turkestan or Almaty regions, where insolation reached 1,500-1,800 kWh/m^2 per year, and 1-10 kW turbines could generate 2-20 kWh per day in windy areas such as Kostanay and Akmola, where wind speeds reached 5-7 m/s. The study also revealed that in Kazakhstan, from 2020 to 2024, electricity generation from RES increased from 3.24 billion kWh to 7.581 billion kWh. It was noted that such energy sources contributed to climate adaptation by ensuring reliable energy supply for irrigation in arid zones or heating during unstable seasons, while also reducing greenhouse gas emissions, thereby lowering the environmental burden on the agricultural sector. For Kazakhstan, this opened up prospects for increasing yields due to stable access to energy, reducing dependence on fuel imports, and improving environmental performance, especially considering that from 2020 to 2024, the cost of RES decreased from USD 0.057 to USD 0.04 for solar energy and from USD 0.039 to USD 0.03 for wind energy, while coal and gas ranged from USD 0.04-0.25 with a peak in 2022. Thus, RES addressed current problems and also created a foundation for the long-term sustainable development of agriculture, which was especially important in the context of climate risks

Keywords: solar energy; wind turbines; biogas plants; energy supply to remote areas; social and environmental benefits; economic efficiency

INTRODUCTION

Agriculture worldwide faced growing challenges related to global processes such as climate change, depletion of traditional energy resources, and the need to ensure food security for the planet's rapidly growing population. Dependence on fossil fuels, including oil, gas, and diesel, made the agricultural sector vulnerable to economic factors such as price fluctuations and increased its contribution to environmental problems, which required the search for sustainable alternatives. For countries with developed agriculture, such as Kazakhstan, these issues gained particular importance since the agri-sector played a key role in the economy, ensuring employment, exports, and stability of the food market. Renewable energy sources (RES) in this context represented a promising strategic solution, capable of reducing the environmental footprint of the sector, improving the efficiency of natural resource use, and strengthening its ability to adapt to future challenges (Iurchenko *et al.*, 2024). The potential of RES to transform agriculture was especially important in the context of the global transition to a green economy, which made the study timely and relevant, while also underlining the importance of this topic for the sustainable development of the agricultural sector.

One of the key aspects in agriculture was the study of the possibilities of using RES to reduce dependence on fossil fuels and increase the resilience of agricultural production. In the work of S. Sydykov *et al.* (2023), the prospects for using renewable energy installations in the agricultural sector were considered, highlighting the accessibility and environmental advantages, but at the same time paying insufficient attention to the practical aspects of implementation, such as adapting technologies to various climatic conditions, which limited the practical value of the results obtained. The study by M. Laljebaev *et al.* (2022) noted the potential of wind energy, focusing on the prospect of turbine installation and scaling in the windy regions of Kazakhstan, but overlooked economic barriers and the issue of payback for small farms. In the study by D. Esenzhol *et al.* (2023), the role of biogas units in waste processing and energy production was analysed, emphasising the ability to create a closed-loop system in production, but without addressing the challenges associated with training farmers and ensuring stable system operation under limited resources, which restricted the applicability of the findings.

Another important area was the analysis of the social and economic effects of implementing RES in agriculture, which made it possible to assess the impact on the lives of farmers and the development of rural areas. In the work of A.T. Omarova *et al.* (2022), the economic benefits of solar systems in agriculture were analysed, highlighting the capacity to save fuel costs, but without considering the long-term consequences of such systems for small farms, including equipment wear and the need for component replacement. In the study by D. Streimikiene *et al.* (2021), the factors influencing the integration of RES in agriculture were examined, focusing on social aspects and the prospects of this direction, but at the same time paying insufficient attention to workforce qualification and the availability of training for local residents. The study by C.A. Pizarro-Loaiza *et al.* (2021) noted the potential of biogas technologies for improving living conditions in rural areas, particularly highlighting the role in providing heat and energy, but failed to address logistical and infrastructure challenges necessary for scaling such systems.

An additional aspect requiring attention was the provision of energy supply to remote rural areas using RES, which was particularly relevant for regions with limited access to centralised grids and traditional fuel types. In the study by G. Augustyn *et al.* (2021), the potential for using solar panels for autonomous farm power supply was explored, emphasising the independence from external power sources, but without paying due attention to seasonal fluctuations in solar activity and the impact on the stability of energy supply in rural regions. In the work of N. Ganjei *et al.* (2022), a hybrid solar-wind power station was designed for use in isolated rural areas, focusing on its adaptability to local farm conditions, but giving insufficient consideration to issues of transportation and installation of equipment in hard-to-reach locations. The study by Y. Chen *et al.* (2023) analysed the efficiency of a solar and biogas-based system for heating farms and communities, highlighting the advantages of such energy sources in the ability to use local resources, but overlooking the issue of limited technical support availability for such systems. Thus, this study proposed a broader approach, combining aspects of energy accessibility and social impact while considering the interconnection and practical applicability, which made its conclusions more comprehensive and oriented towards the real conditions typical for Kazakhstan.

The aim of this study was to examine the potential of RES – solar, wind, and biogas energy – in increasing the resilience of agriculture to climate change, reducing dependence on traditional energy sources, and improving energy supply to rural areas, with an emphasis on the applicability under the conditions of Kazakhstan. The research objectives included: identifying the economic, environmental, technical, and social benefits of RES for the agricultural sector to determine how these technologies could help reduce costs and improve farmers' living conditions; analysing the use of RES in various countries such as India, Germany, and Kenya, as well as adapting the collected data to the specific features of Kazakhstan, including its climatic diversity and agricultural needs; assessing the prospects of scaling RES in the agri-sector and the impact on food security in the long term.

MATERIALS AND METHODS

The methodology of this study, conducted at Astana International University, was based on qualitative and quantitative analysis, which allowed for a comprehensive examination of how solar, wind, and biogas energy could reduce the agricultural sector's dependence on traditional energy sources, improve energy supply in remote areas, and enhance resilience to climate challenges. The main focus was placed on data collection, systematisation, and interpretation, taking into account global trends and the specific context of Kazakhstan as a region with diverse climatic and economic conditions. During the study, an analysis was carried out of existing publications by international organisations dedicated to the use of RES in agriculture, such as reports by the International Renewable Energy Agency (n.d.), the Food and Agriculture Organization (n.d.a), and the World Bank (2025), which provided data on the cost of RES, the environmental effects, and the impact on food security. For the Kazakhstani context, national reports were examined, including key documents such as the Concept for the Development of the Agro-Industrial Complex of the Republic of Kazakhstan for 2021-2030 (2021), which defined strategic directions for the development of agriculture and energy in the agrarian sector. In addition, materials on climate change were considered, such as a publication by M. Syzdykova (2024), which covered the impact of temperature and precipitation on the agricultural sector. This analysis made it possible to identify key trends and determine gaps in current knowledge that required further examination.

The study also included a comparative analysis of three types of RES – solar, wind, and biogas energy – in terms of the applicability to agriculture. The technical characteristics were examined, such as principles of operation, resource requirements, and integration potential into agricultural processes (e.g., irrigation, product processing, heating). The comparison was carried out based on qualitative criteria (reliability, autonomy) and generalised economic indicators (cost reduction, payback period) to understand how each technology could meet the needs of farmers in the context of climate change. To support the theoretical findings, practical case studies of RES implementation in agriculture were analysed. Cases from various regions and countries, such as India, Germany, and Kenya, were considered in terms of implementation conditions, achieved results, and lessons that could be adapted for other countries, including Kazakhstan. Special attention was paid to how these technologies addressed problems similar to those in Kazakhstan – droughts in the south, power supply interruptions in the north, and waste management in livestock regions. This stage enabled the linking of general principles with real outcomes, providing a practical basis for projections.

A separate stage was dedicated to assessing the applicability of RES in Kazakhstan, taking into account its geographical, climatic, and socio-economic characteristics. Data on solar activity, wind potential, and volumes of organic waste were used to determine which technologies were best suited for different regions. In particular, solar activity data included information on the number of sunshine hours and radiation levels taken from a report by the Eurasian Research Institute (Akhmetkaliyeva, 2025). Information on wind potential was based on assessments from the same source. Data on organic waste volumes were obtained from materials by the Bureau of National Statistics Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (n.d.), which presented statistical indicators of waste generation, including organic waste. The current problems of the agricultural sector were analysed, and modelling was carried out on how RES could address these challenges. This analysis was based on generalised assessments of costs and benefits, as well as potential social effects such as job creation and improved living conditions. Based on the conducted analysis, the findings were synthesised to form projections and prospects for Kazakhstan. The forecasting included an assessment of RES scaling in agriculture over the coming decades, the impact on food security, and the role of international cooperation. The forecasts were built considering global trends such as declining technology costs and growing investments in green energy, as well as adapting to the conditions of Kazakhstan, including its climatic diversity and economic priorities.

RESULTS

Agriculture required significant energy resources to carry out daily tasks, from fieldwork to product processing. The main types of energy were electricity, diesel fuel, and natural gas, which were used in a wide range of processes. Processes such as irrigation depended on pumps powered by electricity or diesel to deliver water to fields, which was especially important in arid areas where crop cultivation was impossible without artificial irrigation. Greenhouses that provided year-round harvests of vegetables and herbs consumed energy for heating and lighting, most often relying on gas or electricity. Agricultural machinery such as tractors, combines, and trucks operated primarily on diesel fuel, which made up a significant portion of farmers' operating expenses. Finally, product processing, such as grain drying, milk cooling, or oil production, required stable power supply to operate the equipment. In Kazakhstan, energy consumption in the agricultural sector reflected the country's geographical diversity: in the south, in regions such as Almaty Region, a significant share of energy was used for orchard and field irrigation, while in the north, in grain belt regions such as Kostanay Region, the focus was on fuel for machinery used in vast wheat fields.

The high dependence of agriculture on fossil fuels created a range of vulnerabilities that became increasingly evident amid global instability. Rising oil and gas prices directly increased farmers' costs, reducing the incomes and competitiveness in the market. This issue was particularly acute in countries dependent on imported energy resources, such as Kazakhstan, where any disruption in supply could halt key processes, such as sowing or harvesting, especially in steppe regions like Akmola and Kostanay, where agriculture relied heavily on machinery. Moreover, in remote rural areas such as the mountainous zones of Almaty Region or the desert territories of Kyzylorda Region, energy supply was often unstable due to outdated infrastructure or its complete absence. Power or fuel outages led to machinery downtime, spoilage of perishable products, and a general decline in productivity. Such dependence on traditional energy sources made the agricultural sector fragile in the face of external shocks – whether economic crises or geopolitical constraints – highlighting the need for alternative solutions. Climate change further complicated matters by increasing the vulnerability of agriculture and hindering long-term planning. Droughts, which became more frequent and severe, limited access to water needed for irrigation – a critical issue for regions with low precipitation such as Turkestan and Mangystau. Conversely, floods destroyed crops, washed away fertile topsoil, and damaged infrastructure, disrupting supply chains and harming farmers' economies, as observed in flood-prone areas of East Kazakhstan Region. Changes in temperature patterns shifted traditional growing seasons, increased pest and disease activity, and worsened conditions for conventional crops such as wheat or barley, resulting in reduced yields and rising food prices.

Remote rural areas in many regions around the world faced chronic energy supply issues, which significantly limited the economic development and quality of life (Karlilar Pata *et al.*, 2025). The main challenge lay in the shortcomings of existing infrastructure: centralised energy grids were focused on cities and large settlements, leaving remote areas either without electricity or with unstable access. The length of power lines required to reach such zones demanded significant investment, and the maintenance was complicated by equipment wear, rugged terrain, and harsh climatic conditions. According to the International Energy Agency (2023a), as of 2023 around 9% of the world's population (approximately 685 million people) lacked access to electricity, primarily in rural areas. In Kazakhstan, this issue was evident in vast steppe and mountain territories such as parts of Almaty, East Kazakhstan, and Kyzylorda regions, which often remained beyond the reach of reliable energy grid coverage. According to the Ministry of Energy of the Republic of Kazakhstan, the electrification level of rural areas in Almaty Region reached 87% (as of 2023), but in mountainous districts such as Alakol or Raiymbek, outages occurred up to 12-15 times a year, lasting from 4 to 24 hours due to snowstorms and line breakages (Draft Law of the Republic of Kazakhstan, 2025). In East Kazakhstan Region, around 25% of the rural population (approximately 180,000 people) lived in remote villages where in 2023 power outages lasted up to 25 hours per month in winter due to network wear (the average equipment age was 40-50 years). In Kyzylorda Region, rural electrification was at 72%, and in remote Aral villages, outages lasted 3-5 days annually due to sandstorms and the absence of backup sources. The worn-out infrastructure built during the Soviet era led to frequent blackouts – in some villages, outages lasted from several hours to days, especially in winter when snowstorms damaged the lines (Samruk-Energy, 2025). Connecting small farms to centralised systems was economically unfeasible: the cost of laying lines (around 2-3 million tenge per kilometre) and energy losses over long distances made this option unaffordable for local budgets. Reliance on diesel generators as an alternative was also problematic, as deliveries were unreliable due to poor roads and weather. As a result, farmers faced equipment downtime, product spoilage, and limitations in using modern technologies, which reduced the competitiveness and worsened living conditions. These issues highlighted the need for alternative solutions for autonomous and sustainable energy supply where traditional infrastructure was ineffective.

At the same time, according to reports and updates from the Ministry of Energy of the Republic of Kazakhstan (n.d.), the implementation of RES already demonstrated potential in these regions. For example, in Almaty Region in 2023, 15 solar systems with a capacity of 2-5 kW were installed in mountainous districts (e.g., Yenbekshikazakh), generating 6-10 kWh per day and supplying energy to 70 farms due to high insolation. In East Kazakhstan Region, a biogas plant with a capacity of 8 kW had operated in Ulan District since 2022, processing 400 tonnes of manure annually and producing 2-4 kWh per day, covering the needs of a farm with 15 head of cattle and reducing emissions by 250-300 tonnes of CO_2-equivalent annually. In Kyzylorda Region, in Kazaly District, wind turbines with a capacity of 3 kW had been tested since 2021, generating 5-12 kWh per day at wind speeds of 5-6 m/s, supplying energy to pumps for farms up to 5 hectares. RES became an increasingly significant solution for overcoming the energy and environmental challenges faced by modern agriculture (Bialkovska *et al.*, 2025). These sources of energy offered an alternative to traditional energy sources, reducing dependence on fossil fuels and contributing to the resilience of the agricultural sector under climate change. Among the key types of RES were solar, wind, and biogas energy, each of which had unique characteristics and application potential in agriculture (Table 1).

Table 1*. Advantages of renewable energy sources in electricity production in agriculture*

Category	Advantage	Solar energy	Wind energy	Biogas energy
Economic	Reducing operating costs	No fuel costs: diesel expenses reduced by up to 100% Payback period of 5-7 years at a panel cost of USD 0.6/W	Payback of turbines (1-10 kW) in 5-10 years with 30% cost reduction over 10 years	Waste management: reduces manure management costs by 50-70%
	Cost stability	Protection against fuel price increases, such as diesel, which often fluctuates in remote areas	Independence from unstable gas prices subject to market changes	Local energy production from waste, eliminating fuel delivery costs
Ecological	Reducing CO_2 emissions	Diesel replacement: emissions reduced by 1.5-2 tonnes of CO_2/year per 5 kW system (2.7 tonnes of CO_2/year from diesel)	No emissions: reduction of carbon footprint by 0. 9-1 t CO_2/kW installed capacity/year	Methane capture: e.g., 250-400 t CO_2-eq/year reduction from a farm with 20 cattle
	Reducing pollution	No exhaust gases, protecting soil and air from diesel pollution	Clean operation: elimination of 20-30 t ash/year compared to coal plants	Waste treatment that prevents pollution of water bodies and soil from manure
Technical	Autonomy and reliability	Generation of 6-10 kWh/day (2 kW system) with 5-10 kWh batteries	Generation of 2-20 kWh/day (1-10 kW turbine), stability in 5-7 m/s wind	2-5 kWh/day from an 8-10 kW unit, stable regardless of weather
	Flexibility and scalability	Easy adaptation from small farms to large settlements	Installation options from small turbines to large parks	Suitable for different scales, from small farms to enterprises
	Ease of maintenance	Panel cleaning 2-4 times/year, service life 20-25 years, battery replacement every 5-10 years	Inspection every 2-3 years, turbine life 20-30 years	Waste loading daily, repair every 5-7 years, service life 15-20 years
Social	Improving living conditions	Electricity access in homes, schools, and hospitals in remote areas	Providing light and heat in isolated communities	Possibility to produce energy and heat for rural settlements
	Job creation	Up to 500-700 jobs/GW (installation, maintenance)	Up to 300-500 locations/GW.	Up to 50-100 places/MW
	Availability of technology for farmers	Mastered within 2-4 weeks	Preparation in 2-3 weeks	Basic training in 1 month

Source: *developed by the authors based on Food and Agriculture Organization (2021), International Energy Agency (2022), International Renewable Energy Agency (2023a), World Bank (2025), Korem (n.d.)*

Solar energy was based on converting sunlight into electricity using photovoltaic panels, making it one of the most accessible and versatile renewable energy technologies. Its operating principle was simple: solar panels captured photons and converted photons into electric current, which was then used directly or stored in batteries for later use. The availability of solar energy depended on geographical location and climatic conditions, but even in regions with moderate insolation, it remained effective due to modern technologies (Moore *et al.*, 2022). In agriculture, solar panels were widely used: the solar panels powered irrigation pumps, providing water to fields without the cost of diesel fuel, which was especially valuable in arid areas. Solar energy was also used to light farms and greenhouses, extending daylight hours and improving growing conditions. Moreover, small-scale solar systems could support product processing operations such as fruit drying or milk cooling, reducing farmers' energy costs. This energy source was particularly promising for countries with high solar activity levels, where various regions could effectively use solar panels for agricultural needs (Agbor *et al.*, 2023).

Wind energy, in turn, utilised the kinetic energy of wind, converting it into electricity using turbines, and represented another powerful tool for agriculture. Its main feature was its dependence on wind strength and consistency, requiring careful selection of installation sites (Shorabeh *et al.*, 2022). Wind turbines came in various sizes: from large wind farms capable of supplying whole regions to small units suitable for individual farms. This scalability made the technology flexible and suitable for both large agricultural enterprises and smallholdings. In rural areas, wind energy was especially valuable thanks to open spaces with fewer obstacles, increasing turbine efficiency. For Kazakhstan, with its steppe expanses and strong winds in the north and west, wind energy could have become an important addition to the energy supply in rural areas, particularly where solar activity was lower. Applications included powering electrical systems for irrigation, mills, or lighting, as well as charging batteries for autonomous use. Wind as a resource was free and inexhaustible, reducing operational costs after initial investments.

Another promising area was biogas energy, based on the anaerobic decomposition of organic waste such as manure, plant residues, and food waste, releasing biogas, which was then used to generate electricity or heat. This process was carried out in special biogas plants, where microorganisms digested biomass to produce methane – the main component of biogas. In agriculture, this technology was particularly valuable as farms generated the raw material for energy production, creating a closed loop: livestock or crop waste turned into fuel, and the by-product (organic fertilisers) was returned to fields to improve soil quality (Singh & Kalamdhad, 2022). Biogas could power generators for electricity, heat greenhouses, or be used for household needs on farms. In the context of the Republic of Kazakhstan, where livestock farming was developed in regions such as Akmola and East Kazakhstan, biogas plants could not only provide energy for farms but also improve the environmental sustainability by minimising waste and improving land fertility. The advantage of biogas energy lay in its independence from weather conditions, unlike solar and wind energy, and in its environmental benefits, as it reduced methane emissions and solved the waste disposal problem.

The economic efficiency of RES became increasingly apparent against the background of rising fossil fuel prices and the development of renewable energy technologies. Although initial installation costs for solar panels, wind turbines, or biogas systems could be high, long-term operational expenses were significantly lower than those of conventional energy sources (Karlilar Pata & Pata, 2025). One example was diesel fuel for agricultural machinery or pumps, which required regular purchasing and was subject to price volatility. In contrast, solar panels, once installed, used free sunlight and had a lifespan of 20-25 years with minimal maintenance. Similarly, wind turbines, despite initial investment, paid for the turbines' operation within 5-10 years in regions with sufficient wind activity. Biogas plants were especially cost-effective for farms, due to using existing waste, converting it into energy without additional fuel costs. Research by the International Renewable Energy Agency (2024a) showed that in 2024, the cost of electricity from RES (Fig. 1) was on average 20-40% lower than from coal or gas plants (Fig. 2).

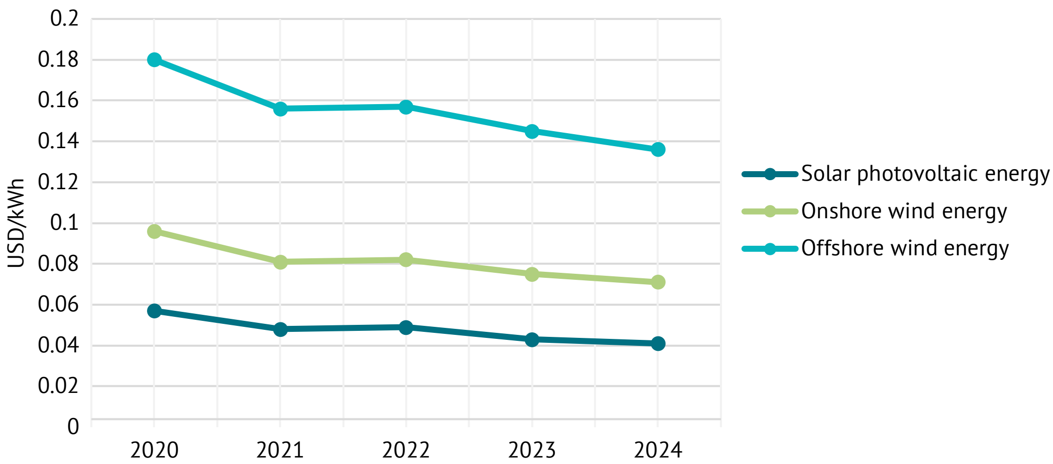

Figure 1*. Dynamics of the cost of electricity production from renewable energy sources*
Source: *developed by the authors based on International Renewable Energy Agency (2024a)*

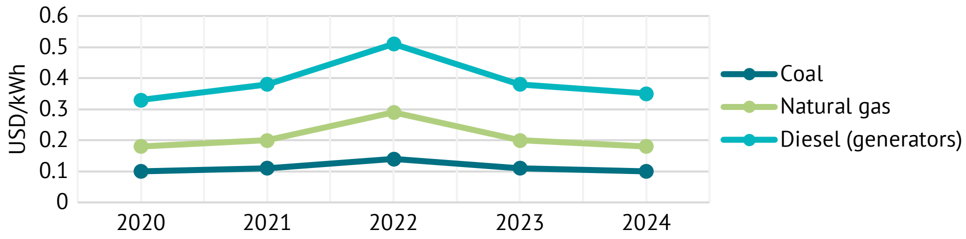

***Figure 2**. Dynamics of the cost of electricity production from traditional energy sources (average indicators)*
***Source:** developed by the authors based on International Energy Agency (2023b)*

Thus, during the period from 2020 to 2024, the cost of RES fell from USD 0.057 to USD 0.04 for solar energy and from USD 0.039 to USD 0.03 for wind energy, whereas coal and gas ranged from USD 0.04 to 0.25, peaking in 2022. Accordingly, in 2024, electricity production from RES was already 20-40% cheaper than from average coal and gas plants, as well as diesel generators. It should also be noted that diversifying energy supply through RES allowed agriculture to reduce risks associated with fossil fuel market instability. Oil and gas prices were influenced by multiple factors: from international sanctions and conflicts to changes in global trade. Such fluctuations created uncertainty for farmers, who found it difficult to plan fuel budgets for machinery or heating. RES, in contrast, provided stability: solar and wind energy were not subject to market prices, and biogas was produced locally from waste, eliminating the need for imports. This was especially important for countries dependent on external supplies, such as Kazakhstan, where a significant share of fuel was imported. The use of RES enabled the creation of autonomous energy supply systems, reducing vulnerability to supply disruptions and increasing cost predictability. Moreover, combining different types of RES – for example, solar panels and biogas plants – improved reliability, due to compensating for each other's weather- or season-related limitations.

Real-world examples demonstrated how RES already reduced agriculture's dependence on traditional energy sources across the globe (Aliyev *et al.*, 2024; Syzdykova, 2024). In India, where more than 60% of the population was employed in agriculture, a programme to install solar irrigation pumps reached millions of farmers. By 2023, over 300,000 such pumps replaced diesel counterparts, cutting annual fuel costs by USD 500-700 per farm and increasing yields due to stable water supply (Ministry of New and Renewable Energy of India, 2024). In Germany, farms actively used biogas plants: by 2022, more than 9,000 farms produced biogas from manure and plant waste, covering the own needs and selling energy surpluses to the grid, generating an additional income of EUR 4 billion (Concept for the Development of the Agro-Industrial Complex of the Republic of Kazakhstan for 2021-2030 2021; Statista, 2025). In Kenya, small-scale wind and solar systems became a lifeline for remote farms: a project in the Turkana region enabled local communities to abandon costly diesel fuel, reducing milk and fish processing costs by 40% (International Renewable Energy Agency, 2021). These cases highlighted the practical benefits of RES and the adaptability to various conditions.

Climate change posed a serious threat to agriculture by increasing the frequency and intensity of extreme weather events such as droughts, floods, and temperature anomalies. These factors disrupted production cycles, reduced yields, and jeopardised food security. RES became an important tool for increasing the agricultural sector's resilience, providing reliable energy supply, reducing environmental harm, and supporting key processes such as irrigation (Shahini *et al.*, 2025). Extreme weather events such as hurricanes, floods, or prolonged droughts often disrupted centralised power supply, leaving farmers without electricity and fuel at critical times. RES offered a decentralised solution that increased farm resilience to such crises (Tanchyk *et al.*, 2024; Akhmetkaliyeva, 2025). It was important to emphasise that agriculture not only suffered from climate change but also significantly contributed to global greenhouse gas emissions, exacerbating the climate crisis. According to the Food and Agriculture Organization (2024; n.d.b), the agricultural sector was responsible for 10-12% of all anthropogenic emissions, including carbon dioxide (CO_2) from fossil fuel combustion, methane (CH_4) from livestock, and nitrous oxide (N_2O) from fertiliser application. These emissions created a vicious cycle: agriculture accelerated climate change, and climate shifts, in turn, reduced its productivity. The transition to RES – solar, wind, and biogas – offered a real way to break this cycle by significantly reducing the industry's carbon footprint. Agriculture generated greenhouse gases through numerous processes. For instance, the use of diesel tractors, generators, and irrigation pumps emitted millions of tonnes of CO_2 annually. According to the International Energy Agency (2024), diesel combustion in agricultural machinery alone produced around 500 million tonnes of CO_2 per year globally. Livestock contributed even more: manure decomposition and ruminant digestion (cows, sheep) released methane, which was 25 times more potent than CO_2 in terms of greenhouse effect. The Food and Agriculture Organization (n.d.b) estimated that in 2022, livestock farming produced about 3.1 billion tonnes of CO_2 equivalent, of which 44% was methane. The use of nitrogen fertilisers in fields, especially in grain production, released nitrous oxide, whose global warming potential was 298 times higher than that of CO_2. Collectively, these sources made the agricultural sector one of the main polluters, and without changes, this share would increase with rising demand for food. RES could radically reduce these figures by replacing dirty technologies with clean ones and converting waste into useful resources.

One of the most effective ways to reduce emissions was the replacement of diesel systems with solar ones. Diesel pumps used for irrigation consumed millions of litres of fuel annually: on average, one 5 kW pump burned around 1,000 litres of diesel per year, emitting 2.7 tonnes of CO_2 (given that 1 litre of diesel emitted 2.68 kg of CO_2) (Environmental Protection Agency, 2025; Bureau of National Statistics Agency for Strategic Planning and Reforms of the Republic of Kazakhstan, n.d.). Solar pumps completely eliminated these emissions by operating on free solar energy. According to the International Renewable Energy Agency (2016), switching to medium-power solar pumps reduced emissions by 1.5-2 tonnes of CO_2 per unit per year. Solar panels also powered greenhouses and refrigeration units, replacing gas and coal systems. In Kazakhstan, irrigation played a key role in the southern regions, so replacing diesel pumps with solar ones could prevent a large amount of CO_2 emissions annually, reducing the carbon footprint. Wind energy also contributed to decarbonisation, especially for large agricultural enterprises with higher energy demand. Unlike fossil fuels, wind turbines did not produce emissions during operation, and the carbon footprint was limited to the production and transport stage (about 10-20 g CO_2 per kWh over the life cycle, compared to 800-1,000 g for coal). A 10 kW turbine installed on a farm could generate 20,000-30,000 kWh annually in windy regions, replacing diesel generators and reducing emissions by 15-20 tonnes of CO_2 per year. Biogas plants, in turn, had a unique dual effect: such plants not only replaced fossil fuels but also prevented methane emissions from organic waste. Manure decomposition in open lagoons released about 1 kg of CH_4 per tonne of waste per day, equivalent to 25 kg of CO_2 in greenhouse terms. Biogas systems captured this methane, burning it to produce energy and converting it into CO_2, which was 25 times less harmful.

Droughts also became one of the most destructive consequences of climate change threatening agriculture by limiting access to irrigation water. According to the World Meteorological Organization (2024), the frequency of droughts increased by 29% since 2000, and the duration and intensity continued to rise, reducing water availability for irrigation and land productivity. This was particularly critical for countries with hot climates or dependence on irrigated farming, where crop cultivation became impossible without artificial watering. Solar pumps became an effective solution, ensuring reliable water supply even in the most arid regions. These devices used solar energy to power water pumps that delivered water from wells, rivers, or reservoirs to fields, requiring no fuel, making this solution cost-effective in the long run. Unlike diesel pumps, solar systems operated silently, did not pollute the air, and could be equipped with batteries for night-time use. The mobility and ease of installation made solar systems ideal for remote farms with limited fuel access. From a technical perspective, solar pumps offered several advantages that enhanced the effectiveness in combating droughts. These pumps operated silently, unlike noisy diesel engines, improving working conditions for farmers and avoiding disturbance to livestock. The absence of exhaust gases prevented air and soil pollution, which was especially important near bodies of water used for irrigation. Another major advantage of such systems was mobility, as small solar pumps were easy to relocate from one plot to another, and installation took only a few hours and required no complex infrastructure.

RES also offered an effective solution for improving energy supply in remote rural areas where traditional infrastructure was either absent or unreliable. Decentralised systems based on solar, wind, and biogas energy allowed farmers and residents in such regions to become independent from centralised grids, eliminating issues related to high connection costs and supply disruptions (Sadovoy *et al.*, 2025). These technologies were adapted for local use, required minimal infrastructure, and could be scaled depending on needs – from a small farm to an entire village. Solar installations were among the most accessible and easiest solutions to implement in remote areas. Photovoltaic panels converted sunlight into electricity that could be used to power pumps, lighting, refrigeration, or household appliances. A 2 kW system, for example, could generate 6-10 kWh per day in sunny regions of Kazakhstan such as Turkestan or Almaty, where average insolation reached 1,500-1,800 kWh/m² per year. Equipped with batteries (5-10 kWh capacity), such systems provided energy even at night or on cloudy days, which was critical for uninterrupted farm operations. Unlike diesel generators, solar panels required no fuel, and maintenance was limited to periodic cleaning and battery replacement every 5-10 years. Thus, installing 1,000 such systems could supply up to 5,000 households or farms, eliminating the need for costly power lines. Wind turbines, in turn, complemented solar systems, especially in high-wind regions such as the steppe zones of northern Kazakhstan (Kostanay, Akmola regions), where average wind speeds reached 5-7 m/s. Small turbines with a capacity of 1-10 kW could generate 2-20 kWh per day, sufficient to power equipment, lighting, or charge batteries. The advantage was that wind was often available when solar energy was limited – for example, in winter or during storms. Combining solar and wind systems (hybrid systems) increased reliability, covering up to 80-90% of a farm's energy needs even in variable weather conditions. Biogas plants were particularly relevant for rural areas with developed livestock farming, such as East Kazakhstan or Akmola regions of Kazakhstan, where millions of tonnes of manure were generated annually. These plants converted organic waste into biogas (methane), which was used to produce electricity and heat. A small 10 kW station could process 1-2 tonnes of manure per day, producing 20-30 kWh of electricity and up to 50 kWh of heat – enough for a farm with 50-100 head of livestock. The by-product – biofertilizer – improved soil and boosted yields. Given that livestock farming produced about 10 million tonnes of manure per year, installing 500 biogas plants could generate up to 5 million kWh of electricity annually, powering thousands of farms and reducing heating and lighting costs. The electricity generation indicators of RES in Kazakhstan from 2020 to 2024 are presented in Figure 3.

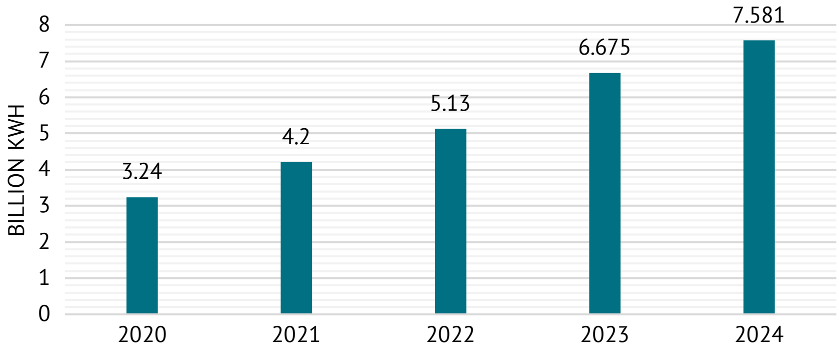

Figure 3. *Dynamics of renewable energy production in Kazakhstan (2020-2024)*
Source: *developed by the authors based on the sources RES power generation in Kazakhstan increased by 15% over the year (2022), United Nations Development Programme (2022), The share of RES in electricity generation in the Republic of Kazakhstan amounted to 5.92% by the end of 2023 (2024), Share of green electricity in Kazakhstan for 2024 amounted to 6.43% (2025)*

In 2020, electricity generation from RES facilities in Kazakhstan amounted to 3.24 billion kWh. The share of RES in total electricity production reached 3%. The installed capacity of RES facilities by the end of the year was approximately 1,970 MW. The main contribution was made by wind and solar power plants. In 2021, electricity generation from RES increased to 4.2 billion kWh, accounting for around 4% of total electricity production. Installed capacity reached 2,010 MW, due to the commissioning of new facilities, including wind farms in Zhambyl Region and solar farms in Almaty Region. Generation growth amounted to approximately 30% compared to the previous year. In 2022, electricity generation from RES grew to 5.13 billion kWh, with a share of 4.5% of the total volume. Installed capacity rose to 2,405 MW owing to new projects such as solar plants in the south and wind farms in the northern regions. The generation increase was about 22% compared to 2021. In 2023, RES electricity generation reached 6,675.5 million kWh (6.675 billion kWh), with a share of 5.92% of total production. Installed capacity rose to 2,868.6 MW, of which wind farms provided 1,394.6 MW, solar – 1,202.61 MW, small HPPs – 269.605 MW, and bio-power plants – 1.77 MW. The increase in generation compared to 2022 was 30%. Finally, in 2024, RES electricity generation amounted to 7,581.33 million kWh, which was significantly more than in the same period of 2023. Installed capacity in 2024 amounted to 3,032.12 MW, and growth continued through new projects.

It should be emphasised that the scaling potential of RES in agriculture was immense, given the declining cost of technologies and rising demand for sustainable solutions. According to the International Renewable Energy Agency (2019; 2023b; 2024b), in 2020 RES covered only about 5% of the global agricultural sector's energy needs, but by 2050 this figure could reach 30-40% with active policy and investment. Solar energy led this process: the cost of photovoltaic panels fell by 85% from 2010 to 2024 (from USD 4 to USD 0.6 per watt), and the efficiency improved due to new materials such as perovskites. By 2035, according to BloombergNEF (2025), solar systems were projected to become the cheapest energy source in 80% of the world's countries, making these systems accessible even for small farms. Wind energy also gained momentum: small turbines (1-10 kW) became popular in rural areas, and the cost dropped by 30% over the last 10 years. Biogas plants, although requiring initial investment, paid off in 3-5 years due to fuel savings and excess energy sales. On a global scale, the International Renewable Energy Agency predicted that by 2040 up to 50 million farms could use RES, generating up to 1,500 terawatt-hours of energy annually – equivalent to India's current consumption. In Kazakhstan, RES scaling could have started with the southern regions (solar irrigation pumps), steppe zones in the north (wind turbines for grain farms), and livestock areas (biogas). If by 2035, 10% of Kazakh farms transitioned to RES, this would provide up to 500 MW of capacity, covering the needs of 50-70 thousand farms. Scaling up RES in agriculture directly impacted food security and global sustainability by addressing key 21st-century challenges. According to the Food and Agriculture Organization (2018), by 2050, global food production would need to increase by 50% to meet the needs of 10 billion people, but climate change already reduced yields: since 2000, droughts and heatwaves had lowered global wheat and maize harvests by 5-10%. RES mitigated these risks by ensuring stable energy supply for irrigation, processing, and storage.

The implementation of RES potential in agriculture was impossible without international cooperation and technology exchange, especially for countries with limited resources. For the Republic of Kazakhstan, international cooperation played a key role in accelerating the transition to RES, especially through partnerships with leaders in this field, such as the European Union and India. The EU, as a global leader in wind energy, possessed advanced technologies and experience: in 2022, wind installations supplied 17% of the region's electricity (WindEurope, 2023), and companies like Vestas (n.d.) and Siemens (n.d.) developed efficient turbines for agricultural needs. Cooperation with the EU could have provided Kazakhstan access to these technologies, adapted for the steppe regions in the north. India, in turn, was an expert in solar pump usage: its PM-KUSUM programme had installed 300,000 such systems by 2023, increasing irrigated land by 1.5 million hectares (Ministry of New and Renewable Energy of India, n.d.). Partnership with these countries could have attracted investments through grants, loans, and foreign direct investment, accelerating RES deployment several times compared to the current pace, while scale effects and competition among suppliers reduced equipment costs. This would have made RES more affordable for Kazakh farmers and strengthened the country's position in global climate initiatives by demonstrating commitment to emission reduction.

RES also brought significant social benefits, among which were job creation and technology accessibility for farmers, contributing to stronger rural communities and the economic stability. The deployment of RES stimulated employment, covering a wide range of activities – from equipment manufacturing, installation, and configuration to routine maintenance and user training. This process created jobs for local residents, including technicians, installers, and system operators, which was especially valuable in rural areas where employment opportunities were often limited to traditional sectors such as livestock or crop production. In the Republic of Kazakhstan, RES development could have provided jobs for thousands of people involved in solar panel manufacturing, wind turbine assembly, or biogas plant management, helping reduce unemployment and retain population in rural areas. Employment in this sector did not require high qualifications at all stages: while design and complex repairs were handled by specialists, installation, basic maintenance, and training were accessible to people with minimal preparation, expanding the pool of potential workers. Moreover, RES development supported the local economy, as part of the equipment could be produced locally, and services for its installation and operation remained within the region, boosting economic activity and improving living standards.

An equally important social benefit was the accessibility of RES technologies for farmers, making such technologies a practical solution even for small holdings. These systems were designed to be easy to learn and operate, allowing farmers to quickly adapt to the use without the need for deep technical knowledge or lengthy training. Solar panels, for example, required only basic understanding for installation and connection, and the management was intuitive even for beginners. Wind turbines, despite more complex design, came with simple instructions, making these turbines suitable for independent use after minimal training. Biogas plants running on farm waste were also accessible to operate: farmers could learn to load raw material and keep the system functional in a short period, relying on basic skills. In Kazakhstan, this was especially relevant, as the rural population often had practical experience with machinery, easing the transition to RES. Such accessibility increased farmers' independence, enabling farmers to implement technologies without external experts, thereby reducing costs and accelerating integration. As a result, farmers gained the opportunity to improve the efficiency of the farms – whether irrigating fields with solar pumps or heating premises using biogas – enhancing the confidence in the future.

DISCUSSION

In the course of this work, it was established that the introduction of RES has a significant impact on the resilience of agriculture in the context of climate change, opening new opportunities for adaptation and development of the sector. These findings highlight that the transition to RES can transform traditional approaches to energy supply in the agricultural sector, making it less dependent on external factors and more flexible in responding to global challenges. The significance of this discovery lies in the fact that RES address current issues such as fuel supply instability or vulnerability to climate shifts, while also laying the foundation for long-term stability, allowing agriculture to evolve under growing environmental and resource constraints. This approach may become key for countries seeking to maintain the food security and competitiveness in the global market, especially where natural conditions and infrastructural specifics require innovative solutions. However, the results also indicate the need for further research into how these technologies can be scaled to make the benefits accessible to a wide range of farmers, including small farms, which often face resource and knowledge constraints. The study by A. Bathaei and D. Štreimikienė (2023) also highlighted the role of RES in enhancing agricultural resilience with an emphasis on the adaptability to climate change, which confirms the findings of this work, although focusing more on theoretical aspects, whereas this study includes practical examples and the regional context of Kazakhstan. In the study by M. Rahman *et al.* (2022), the impact of RES on the resilience of agricultural systems was examined with an emphasis on improving production and process efficiency, which aligns with the results of this research, but with less focus on the social and environmental benefits, which are more thoroughly analysed here. The study by A.S. Pascaris *et al.* (2021) analysed the integration of RES into agricultural enterprises, emphasising the strategic importance, which echoes the conclusions of this study, although this research covers the potential for scaling and adaptation to the specific conditions of remote regions more broadly.

This work also established that the introduction of RES in agriculture has a profound impact on its economic and environmental dimensions, highlighting the potential as a tool for sustainable development. From an economic perspective, the results show that the transition to RES can reduce farmers' dependence on fossil fuels, stabilise costs, and improve the profitability of farms through the use of free natural resources and the minimisation of operational expenses. This means that the agricultural sector can become more resilient to market fluctuations and external economic shocks, which is especially important for countries with developed agriculture, such as Kazakhstan, where the stability of agricultural production directly affects the national economy. In addition, it was noted that environmentally, RES contributes to reducing the carbon footprint of the sector by lowering greenhouse gas emissions and easing the burden on the environment, which in the long term slows the degradation of natural resources necessary for agriculture. These findings underline the dual benefit of RES, as these energy sources not only improve the financial resilience of farmers but also contribute to global efforts to combat climate change, creating a more balanced production model. The study by Y. Majeed *et al.* (2023) highlighted the economic benefits of RES for agriculture with a focus on cost reduction and efficiency improvement, which aligns with the conclusions of this research, although the mentioned study concentrates more on general economic aspects, whereas this research additionally analysed the applicability under the conditions of Kazakhstan. The study by D. Maradin *et al.* (2021) conducted an analysis of the economic efficiency of wind installations, focusing on the long-term profitability, which resonates with the findings of this study, although the current study more extensively addressed environmental and regional aspects adapted to the steppe conditions of Kazakhstan. The study by A. Alengebawy *et al.* (2024) emphasised the environmental effects of biogas systems and the role in waste processing, which supports the results of this work, but places less emphasis on the economic and social benefits, which in this study were considered an important part of agricultural sustainability.

An important result of this research was the study of the impact of RES implementation on electricity availability for remote rural areas, noting that RES can significantly improve and have a notable impact on the social aspects of life in farming communities. Regarding electricity accessibility, it was noted that solar panels, wind turbines, and biogas units provide autonomous solutions, enabling stable energy supply where traditional grids are either absent or unstable, which is especially important for isolated regions. This means that farmers gain the ability to support key production processes without dependence on costly fuel delivery or vulnerable infrastructure, which increases the independence and productivity (Nakashydze *et al.*, 2021). At the same time, from a social perspective, the results emphasise that RES contribute to improving living conditions, creating jobs, and simplifying access to technologies, which strengthens rural communities and reduces social inequality. These findings indicate that the implementation of RES can become a catalyst not only for energy but also for social transformation, allowing remote areas to integrate into modern economic processes and improve the quality of life of the population. This, in turn, opens up opportunities for reducing the gap between urban and rural areas, increasing the resilience of local communities, and supporting the development amid global changes, which is especially relevant for countries with extensive rural regions, such as the Republic of Kazakhstan. The study by C. Roldán-Porta *et al.* (2023) focused on optimising solar and biogas-based systems for sustainable energy supply in farms, highlighting the autonomy, which aligns with the conclusions of this study, but places greater emphasis on technical optimisation, without considering the social effects and regional specifics of Kazakhstan. The study by N. Lefore *et al.* (2021) analysed the social and economic benefits of solar systems, emphasising the accessibility for farmers and small enterprises, which confirms the findings of this research, although focusing more on economic aspects, whereas this study covers the impact on quality of life and community resilience. The study by O. Saidmamatov *et al.* (2021) examined the use of biogas systems for rural areas with an emphasis on the potential for isolated regions, which confirms the conclusions of this work, but pays less attention to the integration of different types of RES. The study by R.F. Tagne *et al.* (2021) analysed the social effects of biogas installations in agriculture, highlighting the role in improving daily life and efficiency, which supports the conclusions of this study, but without analysing the accessibility of technologies and the impact on employment adapted to the conditions of Kazakhstan.

In general, the results of this research, combined with the findings of the mentioned works, underline the importance of RES for agriculture, demonstrating the capacity to support the sector under modern challenges. This reveals the potential of RES as a tool capable of improving various aspects of the agricultural sector, including its resilience, efficiency, and social well-being, which makes RES a vital direction for rural development. The results also confirm that RES can play a key role in adapting agriculture to global changes, offering solutions that resonate across various contexts, especially for regions with significant agricultural potential, where RES can become the foundation for strengthening the sector and its future progress.

CONCLUSIONS

As a result of this work, it was established that the introduction of renewable energy sources (RES), such as solar, wind, and biogas energy, possesses significant potential for transforming agriculture, making it more sustainable under climate change conditions. The study revealed that these technologies are capable of reducing the agricultural sector's dependence on traditional energy sources such as oil, gas, and diesel fuel, improving energy supply in remote rural areas, and strengthening agriculture's capacity to withstand climate challenges such as droughts, floods, and unstable temperatures.

It was noted that in Kazakhstan, RES production increased from 3.24 billion kWh in 2020 to 7.581 billion kWh in 2024, demonstrating the growing contribution. The study also emphasised that decentralised systems, such as solar panels, wind turbines, and biogas plants, provide autonomy, allowing farmers to maintain the operation of irrigation systems, lighting, refrigeration units, and other equipment without reliance on external sources. In addition, the transition to RES reduces the environmental impact of the agricultural sector by cutting greenhouse gas emissions, as the agricultural sector globally produces 10-12% of anthropogenic emissions, including 500 million tonnes of CO_2 from diesel and 3.1 billion tonnes of CO_2-equivalent from livestock farming in 2022, which contributes to slowing climate change. As a result of analysing the experience of other countries such as India, Germany, and Kenya, it was noted that RES not only enhance the resilience of agriculture but also contribute to significant economic and environmental progress. The social and technical aspects of RES also highlighted the value, as the introduction of these technologies can stimulate job creation, and the use is characterised by ease of learning and operation, making these technologies accessible even to small farms without specialised training. Thus, globally, RES strengthens food security by increasing yields through stable energy supply and reducing costs, which opens up prospects for strengthening Kazakhstan's position in the grain and livestock markets, making production more competitive and sustainable, especially considering the decrease in the cost of RES-based electricity production from USD 0.057 to USD 0.04 for solar energy and from USD 0.039 to USD 0.03 for wind energy from 2010 to 2024.

It should be noted that this work has certain limitations in the form of predominantly considering the use of RES in the context of Kazakhstan, which may reduce the generalisability of the conclusions for other regions with different climatic and economic conditions. For further research in this field, a promising direction is the study of the economic feasibility of RES for small and medium-sized farms in various climatic conditions, which will allow for the adaptation of technologies to diverse natural and economic realities and expand the applicability on a global scale.

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CONFLICT OF INTEREST

None.

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Вплив впровадження відновлюваних джерел енергії на стійкість сільського господарства в умовах зміни клімату

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Анотація. Метою цього дослідження було вивчення потенціалу відновлюваних джерел енергії (ВДЕ) у підвищенні стійкості сільського господарства до зміни клімату, з акцентом на застосовності цих технологій в контексті Казахстану. Дослідження базувалося на якісному та кількісному аналізі поточного стану сектору, порівняльному аналізі технологій відновлюваної енергетики, розгляді практичних випадків та оцінці застосовності в Республіці Казахстан. В результаті дослідження було виявлено, що ВДЕ, такі як сонячна, вітрова та біогазова енергія, мають значний потенціал для підвищення стійкості сільського господарства в контексті зміни клімату. Було встановлено, що ці технології ефективно зменшили залежність сільськогосподарського сектору від викопного палива, що було особливо цінним для віддалених регіонів. Було наголошено, що система потужністю 2 кВт може генерувати 6-10 кВт·год на день у сонячних регіонах, таких як Туркестанська або Алматинська області, де інсоляція сягає 1500-1800 кВт·год/м² на рік, а турбіни потужністю 1-10 кВт можуть генерувати 2-20 кВт·год на день у вітряних районах, таких як Костанай та Акмола, де швидкість вітру сягає 5-7 м/с. Дослідження також показало, що в Казахстані з 2020 по 2024 рік виробництво електроенергії з ВДЕ зросло з 3,24 млрд кВт·год до 7,581 млрд кВт·год. Було зазначено, що такі джерела енергії сприяють адаптації до зміни клімату, забезпечуючи надійне енергопостачання для зрошення в посушливих зонах або опалення в нестабільні сезони, а також зменшуючи викиди парникових газів, тим самим знижуючи екологічне навантаження на сільськогосподарський сектор. Для Казахстану це відкрило перспективи збільшення врожайності завдяки стабільному доступу до енергії, зменшенню залежності від імпорту палива та покращенню екологічних показників, особливо враховуючи, що з 2020 по 2024 рік вартість ВДЕ знизилася з 0,057 до 0,04 доларів США для сонячної енергії та з 0,039 до 0,03 доларів США для вітрової енергії, тоді як вугілля та газ коливалися в межах 0,04-0,25 доларів США з піком у 2022 році. Таким чином, ВДЕ вирішували поточні проблеми, а також створювали основу для довгострокового сталого розвитку сільського господарства, що було особливо важливим в контексті кліматичних ризиків

Ключові слова: сонячна енергетика; вітрові турбіни; біогазові установки; енергопостачання віддалених територій; соціальні та екологічні вигоди; економічна ефективність