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Assessment of wind energy potential of Kazakhstan and enhancing wind turbine efficiency

ABSTRACT: The study examined Kazakhstan's wind energy potential and made recommendations to improve wind turbine efficiency for remote power supply. The study includes Wind Atlas data analysis, Weibull distribution wind model modeling, and technical, economic, and socio-economic assessment. The study found that Kazakhstan has vast wind energy potential, making wind power a possible solution for autonomous power supply in distant locations, where 90% of households are not connected to power grids. According to the Wind Atlas data and the Weibull distribution model, 80% of the country's territory has average annual wind speeds of 3–5 m/s, suitable for small wind turbines (15–100 kW), while the Almaty and Kyzylorda regions have speeds above 8 m/s, which provides sufficient specific wind energy density for large wind farms with an installed capacity factor of 40–50%. WindPro and the Climate Forecast System version 2 (CFSv2) database (2014–2024) confirmed that optimizing turbine placement following SP RK 4.04-112-2014 can minimize wake effect. Wind turbine efficiency increases with local adaptation, including lightweight composite materials and control technologies, according to the study. The study also underlined the potential

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for hybrid wind-solar systems with storage to adjust for seasonal changes and stabilize energy supply in energy-deficient locations. One socio-economic hurdle is the lack of human resources and local turbine production, which raises logistics costs. The government plans to boost wind energy development, but subsidies, training programs, and localization of production are needed for sustainable growth, according to the report.

Keywords: renewable energy sources, wind power plants, wake effect, power supply to remote areas, theoretical capacity, specific density, distribution model

Introduction

Wind energy plays a pivotal role in the global transition to sustainable energy, contributing significantly to reducing environmental impact and advancing the shift toward cleaner energy sources. In Kazakhstan, a country marked by vast territories and diverse climatic conditions, wind energy presents substantial opportunities for modernizing the energy sector. Wind energy presents a promising solution, especially in remote and rural areas where access to traditional energy sources is limited or unreliable. The introduction of autonomous and hybrid wind power systems can provide a stable, decentralized energy supply, thus improving the quality of life for local communities, fostering economic development, and reducing dependence on traditional fuels. This approach supports the country's energy sustainability and aligns with global environmental goals, providing a means to promote environmental protection and tackle the challenges posed by climate change.

Studies of the wind energy potential of Kazakhstan analyze wind resources and the development of technologies for efficient use in different climatic and geographical conditions of the country. Bulatov and Neshina (2020) investigated the prospects for the development of wind energy, analyzing the wind potential based on weather station data and proposing strategic directions for the development of the industry, including recommendations for expanding the network of wind power plants (WPPs) and attracting investment to scale up projects in regions with high wind potential. Manaridis and Efimova (2021) emphasized the efficiency of wind turbines designed to operate in low-speed wind flows, with an emphasis on the design of simplified control systems, such as basic speed controllers. Kasym (2023) conducted a detailed analysis of the wind potential of the Akmola region to determine the optimal areas for the location of wind farms, which contributes to the informed selection of sites for the construction of wind farms in regions with moderate wind speeds.

Juan et al. (2021) conducted numerical modeling of wind energy potential in densely populated urban areas using computational fluid dynamics (CFD) to analyze wind flows and suggest optimal turbine layouts that maximize energy efficiency in complex urban environments. Rezaeiha et al. (2020) developed a methodology for preliminary assessment of the wind energy potential of rooftop wind turbines in cities, with a focus on aerodynamic calculations, including modeling turbulence and interaction of wind flows with urban infrastructure, which optimized the placement of turbines on buildings. Shorabeh et al. (2022) presented an approach to site selection for wind farms that uses geographic information systems (GIS) in combination with economic criteria, such as land value, to systematically assess the suitability of areas for wind farm construction.

Couto and Estanqueiro (2021) studied the local complementarity of wind and solar energy at wind farms, developing a methodology that uses temporal and spatial data to optimize hybrid systems, ensuring increased stability of energy supply through the synergistic use of wind and solar resources. Barthelmie and Pryor (2021) analyzed the potential of wind energy to mitigate climate change, with a focus on global environmental benefits, including quantifying greenhouse gas emissions reductions and modeling the long-term impact of wind turbines on the carbon balance. Roga et al. (2022) provided a comprehensive overview of modern wind energy technologies, including innovations in turbine design, such as improved aerodynamic blade profiles and control systems, as well as an analysis of the challenges associated with their implementation in different environments.

Notably, the above-mentioned works, while contributing to the analysis of wind energy potential and technologies, are often limited by a narrow geographical or climatic focus, insufficient consideration of socio-economic factors such as human resource shortages or infrastructure barriers, and the use of outdated data or generalized approaches, which reduces their applicability to the unique conditions of Kazakhstan. Some of the studies cited focus on technical aspects such as turbine optimization or site selection, but do not integrate integrated solutions that consider local environmental and economic challenges. This highlights the need for more tailored and detailed studies to effectively develop wind power in regions with developing infrastructure.

The study aimed to conduct a comprehensive assessment of the wind energy potential of Kazakhstan to determine the possibilities of its use in creating sustainable autonomous energy supply systems for remote regions. To achieve this goal, the following objectives were set:

- to analyze the factors affecting the efficiency of WPPs;
- to study ways to increase the efficiency of WPPs;
- to assess the feasibility of building small WPPs in regions with different wind characteristics;
- to analyze socio-economic factors to formulate strategies for integrating wind power into decentralized energy systems.

1. Materials and methods

The methodology for the study of Kazakhstan’s wind energy potential included a comprehensive approach combining the collection and analysis of meteorological data, mathematical modeling, a feasibility study, and analysis of socio-economic factors.

The main source of data for the assessment of Kazakhstan's wind energy potential was the Wind Atlas of Kazakhstan, developed in 2009 as part of the United Nations Development Programme (UNDP) project "Kazakhstan – Wind Energy Market Development Initiative" (2011). This document provided detailed data on average annual wind speeds, their seasonal and daily variations, prevailing wind flow directions, and specific wind energy potential density (measured in W/m^2) at altitudes from 10 to 100 m for 15 key regions of the country, including Northern, Southern, and Eastern Kazakhstan. For an in-depth analysis of wind resources in the Almaty region, the Weibull Distribution Model (1) was applied, which provided an accurate assessment of wind energy potential for any selected region of Kazakhstan:

$$f\left(v\right)=\frac{dF}{dv}=\frac{k}{c}\cdot\left(\frac{v}{c}\right)^{k-1}\cdot exp\left(-\left(\frac{v}{c}\right)^{k}\right) \qquad (1)$$

where:

v – wind speed,
k – shape parameters, varying between 0.8–2.5,
C – the scaling factor.

The vertical wind speed distribution was numerically estimated using a function (2):

$$V_0=V\cdot\left(\frac{h}{H}\right)^{\alpha} \qquad (2)$$

where:

h – height from the wind wheel hub,
H and V – height and wind speed at the height of the wind vane,
α – soil roughness coefficient (values of 0.15 – for hilly plains, 0.2 – for populated areas).

Based on the analysis of the wind flow characteristics, it is possible to zonate the territory according to the values of the specific density of wind energy potential at an altitude of 80–100 m, which corresponds to the location of the rotor blades of modern wind turbines.

Using the data on wind speed characteristics and their temporal distribution, the assessment of wind energy resources in a particular region was performed using equation (3):

$$WPD=0.613\int_{v}^{v_{max}}v^3f\left(v\right)dv \qquad (3)$$

where:

WPD – wind power density measured [W/m^2],
v – wind speed,

v_{max} – maximum wind speed considered in the calculation,
$f(v)$ – graded wind speed frequency, 0.613 – factor for air density (approximately 1.225 kg/m^3 at sea level and 15°C), and conversion factors.

The WPD for the year was determined as follows (4):

$$WPD = 0.613 \cdot T \cdot 10^{-3} \int_{v}^{v_{max}} v^3 f(v)\,dv \tag{4}$$

where:

WPD – expressed [kWh/m^2],
T – number of hours per year.

Thus, this statistical model described the variability of wind speeds, including the frequency distribution and probability of certain speed regimes, which provided a more accurate assessment of wind power potential. The meteorological data for these calculations were collected using a specialized MeteoObject tool built into the WindPro professional software (2025), which is widely used for wind farm design. The data were based on the CFSv2 reanalysis (2025) developed by the USA National Center for Atmospheric Research (NCAR) (2025) and covered the observation period from 2014 to 2024. Wind speed measurements were made at a height of 10 m above ground level, which corresponds to the standard height of meteorological masts for small wind turbines (15–100 kW) used in decentralized rural energy supply systems. To estimate the specific WPD and zoning of the territory by wind energy potential, calculations were carried out at heights of 80–100 m, where the blades of modern wind turbines with a horizontal axis of rotation are located, using the power output equation, which incorporated air density, blade coverage area, and the cubic dependence of power on wind speed.

The study also analyzed optimal wind turbine placement schemes at wind farms, incorporating the minimization of the wake effect based on the recommendations of building codes, such as the SP RK 4.04-112-2014 (2014).

The power generated by wind turbines with a horizontal axis of rotation was calculated using the mathematical expression (5):

$$E = S \cdot T \cdot \eta \cdot 0.613 \int_{v}^{v_{max}} v^3 f(v)\,dv \tag{5}$$

where:

S – area covered by the turbine blades,
η – efficiency of the wind turbine.

The technical and economic assessment included an analysis of the capital costs of wind farm construction and operational characteristics, such as the energy storage capacity factor.

The socio-economic analysis examined the barriers to wind energy development. The research materials included statistical data from official sources, such as the Ministry of Energy of Kazakhstan (2025), which was used to estimate the electricity demand and priority regions for wind farms. Demographic data, including the number of farms, obtained from the reports of the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan (2024), were used to identify areas for the deployment of small wind turbines, optimizing their location to meet the needs of rural areas and minimize infrastructure costs. The data published by the Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan was also used to assess the energy deficit in the regions (2025). Global trends in wind energy and staffing issues were analyzed based on reports by the International Renewable Energy Agency (IRENA) (2024) and the International Energy Agency (IEA) (2024), including forecasts of the shortage of specialists. These materials and methods provided the theoretical basis for developing recommendations for optimizing wind energy systems in the decentralized regions of Kazakhstan.

2. Results

Renewable energy sources (RES) have become a critical component of the global energy system, playing a significant role in promoting sustainable development and reducing greenhouse gas emissions. According to the International Renewable Energy Agency (IRENA) (2024), RES accounted for approximately 29% of global electricity production, with total energy generation from renewable sources reaching around 8.4 TWh. Increased investments, technological advancements, and stronger government support in regions like Europe, Asia, and North America largely drive this growth.

Among the various renewable energy technologies, wind power, along with solar power, has emerged as one of the leading sources due to its scalability and decreasing production costs. Wind power currently contributes to around 26% of total RES generation and continues to grow rapidly. In particular, China and the United States have seen significant increases in wind energy capacity, with China's wind power capacity growing by 66% in 2023, and states like Texas and Iowa in the US being major contributors to wind energy production. As of 2024, the global installed wind power capacity reached 1,136 GW.

Despite this growth, the wind energy industry faces several challenges, including the need to optimize grid integration, improve plant efficiency, and minimize environmental impacts. For countries with substantial wind energy potential, such as Kazakhstan, these challenges present valuable opportunities to implement advanced solutions that can enhance the contribution of renewable energy to the national energy mix (Krechko and Mikhaylov 2025).

It is worth emphasizing that energy conversion efficiency determines the performance of RES, among which wind power stands out with an efficiency of 35–50%, reaching close to the theoretical maximum (59% according to Betz's law) in modern turbines such as the Vestas V236-15.0 MW, thanks to aerodynamic optimization and intelligent control systems. Hydropower is most efficient with an efficiency of 80–90% but is limited by geographical conditions, while solar power (efficiency of 15–22%) is more versatile but less efficient. Wind power is particularly efficient in regions with winds above 6 m/s, outperforming biomass (20–40%) and geothermal (10–20%) in terms of efficiency and flexibility. Technological progress in wind turbines ensures their competitiveness, making wind power a key area for sustainable energy (Akbarova et al. 2024; Ismanzhanov and Tashiev 2016). It is also worth noting that the cost of building wind power projects has significantly decreased from 2015 to 2025, making them competitive with traditional energy sources. According to IRENA (2024), onshore wind farms cost USD 1.1–1.5 million per 1 MW, which is 110–150 million USD for a 100 MW wind farm, including turbines and infrastructure, while offshore projects cost 2.53.5 million USD per 1 MW. Wind power has reduced in price by 50% since 2010 due to the scaling up of turbine production. In Kazakhstan, where vast land is available, wind farms can be economically viable, although solar projects (USD 0.8–1.2 million per MW) are often chosen due to lower capital costs and ease of installation.

An important factor is that in Kazakhstan, with its vast territory and low population density in rural areas, providing electricity to remote regions remains a significant challenge. Of the ~266,000 farms registered in the country, about 90% (approximately ~239,000 farms) do not have access to the centralized power grid (Bureau of National Statistics… 2024). Maintaining nearly 360,000 km of power grids connecting these areas involves high operating costs and electricity losses of more than 30%, making centralized power supply economically inefficient (Ministry of Energy… 2025; Bureau of National Statistics… 2024; Bureau of National Statistics… 2025). In such conditions, decentralized autonomous wind farms are a promising solution, especially in regions with high wind energy potential. The North and South Kazakhstan regions, where the annual electricity demand in 2022 was about ~3 GWh, are experiencing an energy deficit, which highlights the relevance of introducing local wind energy systems (Ministry of Energy… 2022). These regions have favorable wind conditions, with average wind speeds of 5–7 m/s, which enable the effective use of small and medium-capacity wind turbines to supply farms and small settlements.

Stand-alone wind farms can reduce dependence on expensive diesel generators, which are widely used in remote areas of Kazakhstan, and reduce carbon emissions, supporting the country's sustainability goals (Işık et al. 2025; Niyazbekova et al. 2021). For example, the installation of 10–100 kW wind turbines for individual farms or small 1–5 MW wind farms for rural communities can cover local electricity needs while minimizing energy transportation costs. In the South Kazakhstan region, where agriculture is growing rapidly, such solutions are particularly in demand to supply irrigation systems and processing plants. In Northern Kazakhstan, with its harsh climate, wind turbines can be complemented by energy storage systems to ensure a stable energy supply in winter.

To assess the national wind energy potential, especially in remote and inaccessible regions, the Wind Atlas of Kazakhstan, a specialized mapping and analytical tool, can be used (Fig. 2).

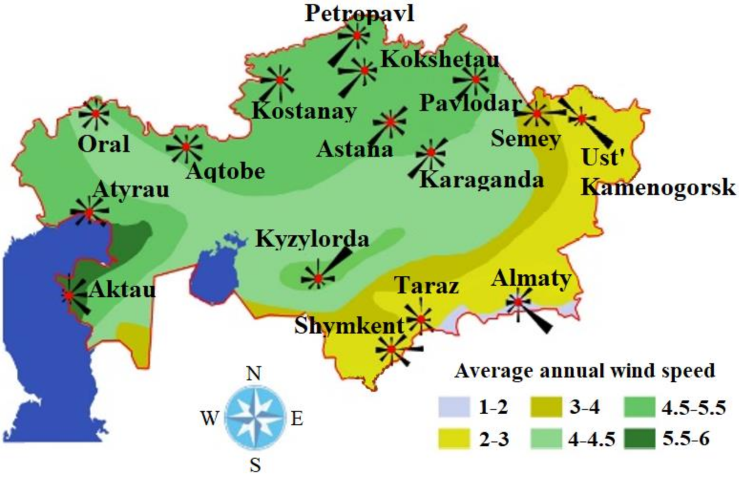

Fig. 1. Atlas of winds of the Republic of Kazakhstan
Source: compiled by the authors

Rys. 1. Atlas wiatrów Republiki Kazachstanu

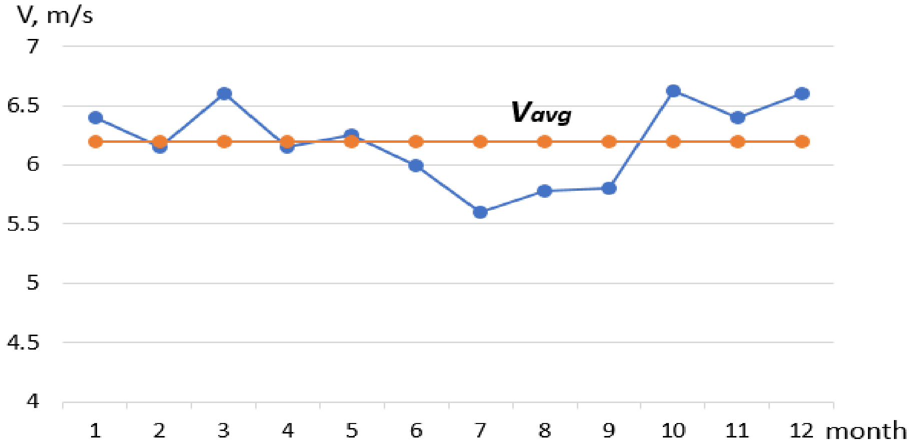

Fig. 2. Annual changes in wind speed
Source: compiled by the authors based on United Nations Development Programme (UNDP) Kazakhstan (2011)

Rys. 2. Roczne zmiany prędkości wiatru

The wind atlas contains detailed data on the wind regime, including average annual wind speeds, directions, seasonal variations, and specific wind power at various heights (usually from 10 to 100 meters). It is used to identify optimal sites for the construction of wind farms, calculate their potential output, and assess the economic viability of projects, especially in conditions of electricity shortages and high transmission losses through centralized grids (up to 30% in Kazakhstan). The application of the Wind Atlas in remote regions of Kazakhstan is particularly important to support decentralized energy supply. To improve the accuracy of the data, the Atlas uses modern methods such as temperature and wind sensing and mathematical modeling to incorporate the impact of terrain and orographic features on the wind regime, making it an indispensable tool for planning sustainable energy supply in rural and remote areas of Kazakhstan.

Notably, average values do not fully reflect local and temporary fluctuations in wind conditions, which significantly affect the efficiency of wind farms. Wind speed and direction vary under the influence of seasonal changes (Fig. 3), terrain features, height above the surface, and microclimatic factors such as the heating effects of steppe plains or mountain-valley winds in regions such as the Junggar Gate.

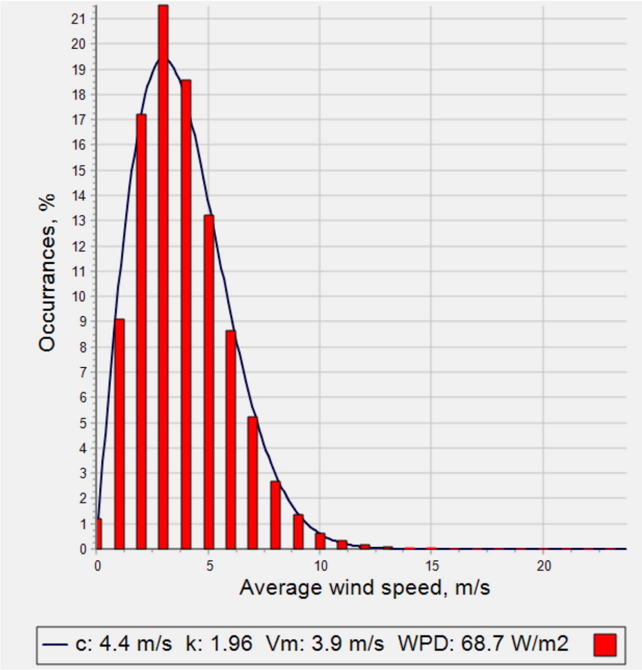

Fig. 3. Weibull distribution model for the Enbekshikazakh region (latitude 43.615756, longitude 78.388376)
Source: compiled by the authors

Rys. 3. Model rozkładu Weibulla dla regionu Enbekshikazakh (szerokość geograficzna 43,615756, długość geograficzna 78,388376)

Figure 2 presents the annual variations in wind speed over the course of 12 months, showing monthly fluctuations in wind speed (blue line) around an average value (orange line, denoted as Vavg) of approximately 6 m/s. The graph highlights that while the average wind speed provides an overall view of the trends, it does not capture the localized and temporary changes in wind conditions, which are crucial for the efficiency of wind farms. These fluctuations, influenced by seasonal variations, geographical factors, and microclimates, can significantly impact wind energy production, as seen in areas with distinctive topographical features such as the Junggar Gate.

An accurate assessment of the wind energy potential and specific wind energy density in a particular region of Kazakhstan plays a key role in determining the most appropriate wind turbine design adapted to local conditions. This information can be used to select turbines that optimally match the speed and climatic characteristics of the wind flow, which directly affects their efficiency and durability. To expand the use of small wind turbines, especially among rural consumers, several factors need to be incorporated: selecting sites with high wind potential, improving the operational efficiency of the installations, and ensuring their autonomy for independent power supply (Brych et al. 2023). The application of a structural-functional approach to wind turbine design allows for a detailed analysis of how the materials and design of individual components, such as blades, the generator, or the control system, affect the overall performance, reliability, and resilience of the turbine to the harsh climatic conditions typical of the steppe and mountainous regions of Kazakhstan. This approach creates more efficient and cost-effective solutions, supporting the national goal of increasing the share of RES.

PB Power and Windlab Systems have conducted detailed calculations of Kazakhstan's wind energy potential based on the Wind Atlas data, with the results shown in Tables 1 and 2.

An analysis of Kazakhstan's wind energy potential shows that approximately 80% of the national territory has an average annual wind speed of 3–5 m/s, which creates favorable conditions for the deployment of wind farms, especially for turbines optimized for moderate wind loads. At the same time, in certain areas, such as the Almaty and Kyzylorda regions, including the Shelek wind corridor and the Zungar Gate, average annual wind speeds exceed 8 m/s, indicating the possibility of constructing wind farms with a high-capacity utilization factor (CUF) reaching 40–50%. These regions are ideal for high-capacity wind turbines capable of generating significant amounts of electricity. However, in practice, the choice of locations for wind farms is often determined not only by wind speed but also by factors such as infrastructure accessibility, proximity to consumers, and wind regime stability (Hadasik et al. 2025; Romankiewicz et al. 2023). Regions with wind speeds of 5–6 m/s, such as Northern Kazakhstan, offer an optimal combination of technical efficiency and operational reliability, making them preferable for most projects. As a result, 68% of Kazakhstan's total installed wind power capacity, approximately 1.4 GW as of 2024, is concentrated in the northern regions, including the Akmola and Kostanay regions, where stable wind flows and a developed transport network contribute to the successful implementation of wind energy projects.

The regions selected for the wind characteristics modeling in Kazakhstan were chosen based on their distinct climatic conditions, which significantly influence the wind power potential in these areas. Kazakhstan's vast territory includes various geographical features, such as steppe regions, mountain ranges, and plains, all of which impact wind speeds and patterns. The regions selected represent a mix of lowland areas (which often experience more stable wind conditions) and mountainous zones (which may have higher wind speeds due to orographic effects). In

Table 1. Theoretical wind capacity of the territory of Kazakhstan

Tabela 1. Teoretyczny potencjał wiatrowy terytorium Kazachstanu

Wind speed	Low	Average	High	Very high	Excessive	Total
Wind speed ranges	<6	6–<7	7–<8	8–<9	>9	–
Wind zone area [km^2]	1,795,140	876,900	50,500	1,200	200	2,723,940
Share of the wind zone area [%]	65.902	32.192	1.854	0.044	0.007	100.00
Wind energy density [MW/km^2]	2	4	7	10	14	–
Power [MW]	3,590,400	3,507,600	353,500	12,000	2,800	7,466,300
The average annual number of hours	1,700	2,000	2,628	3,200	4,200	1888,22
Electricity generation [GWh]	6,103,680	7,015,200	929,000	38,400	11,760	14,098,040
Share of the territory used [%]	43.295	49.760	6.590	0.272	0.083	100

Source: compiled by the authors based on United Nations Development Programme (UNDP) (2022).

Table 2. Wind speed distribution across the territory of the Republic of Kazakhstan

Tabela 2. Rozkład prędkości wiatru na terytorium Republiki Kazachstanu

Wind category (wind speed range m/s)		Low (< 6)	Average (6–7)	High (7–8)	Very high (8–9)	Excessive (>9)
Region name	Region area [thousand km^2]	Wind zone area [km^2]				
Akmola	146,200	45,500	85,200	15,500	–	–
Aktobe	300,600	254,400	46,200	–	–	–
Atyrau	118,600	58,100	60,500	–	–	–
Western Kazakhstan	151,300	61,400	89,900	–	–	–
Karaganda	428,000	343,100	84,600	300	–	–
Pavlodar	124,800	37,700	87,100	–	–	–
Almaty	224,000	197,300	20,000	5,300	1,200	200
Zhambyl	144,200	106,200	36,800	1,200	–	–
South Kazakhstan	117,300	102,400	11,700	3,200	–	–
Kostanay	196,000	81,500	114,500	–	–	–
Northern Kazakhstan	98,040	–	82,800	15,200	–	–
Eastern Kazakhstan	283,300	241,300	40,800	1,200	–	–
Mangistau	165,600	73,200	87,700	4,800	–	–
Kyzylorda	226,000	193,100	29,100	3,800	–	–
Total	2,723,940	1,795,200	876,900	50,500	1,200	200

Source: compiled by the authors based on United Nations Development Programme (UNDP) (2022).

Figures 4–6, the wind distribution data for these three regions are presented using the Weibull distribution function. The Weibull distribution is commonly used in wind energy studies to model the variability and frequency of wind speeds. The figures show the probability density function of wind speeds for each region, with the *x*-axis representing wind speed (m/s) and the *y*-axis indicating the probability density. These figures aim to illustrate the wind characteristics specific to each region, highlighting the regions with the most favorable conditions for wind energy generation.

Selecting a wind turbine for use in Kazakhstan requires a comprehensive approach, covering many factors such as power rating, rotor design, installation height, rotation control, and integration options into local or off-grid power systems. Given the vast territory of the country and low population density in rural areas, stand-alone wind power systems with a capacity of 15 to 100 kW are the optimal solution. Such installations are classified as small-scale projects, which simplifies their implementation and provides benefits for investors. The choice of turbine capacity depends on local electricity needs, for example, power irrigation systems, small industrial facilities, or residential buildings in remote regions such as North or South Kazakhstan. Another

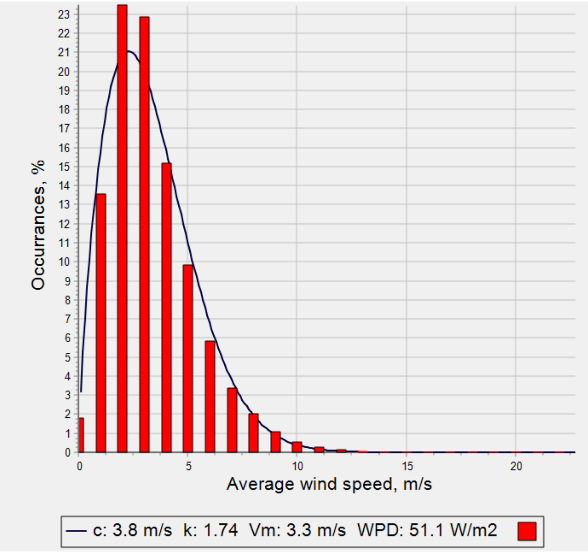

Fig. 4. Weibull distribution model for the Talgar region (latitude 44.219675, longitude 77.132173)
Source: compiled by the authors

Rys. 4. Model rozkładu Weibulla dla regionu Talgar (szerokość geograficzna 44,219675, długość geograficzna 77,132173)

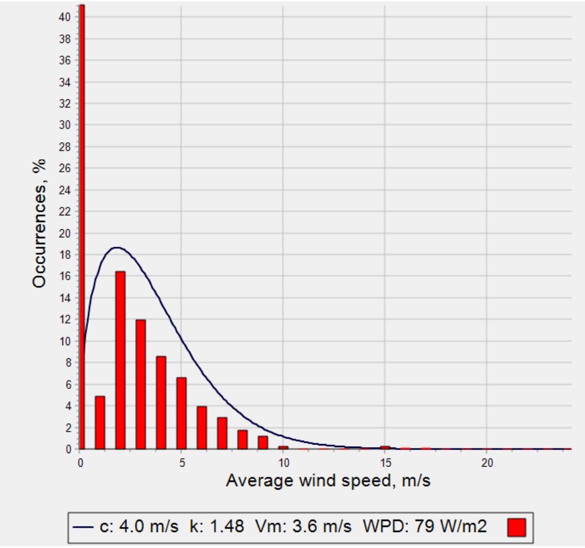

Fig. 5. Weibull distribution model for Zhambyl region (latitude 43.546411, longitude 75.270432)
Source: compiled by the authors

Rys. 5. Model rozkładu Weibulla dla regionu Żambyl (szerokość geograficzna 43,546411, długość geograficzna 75,270432)

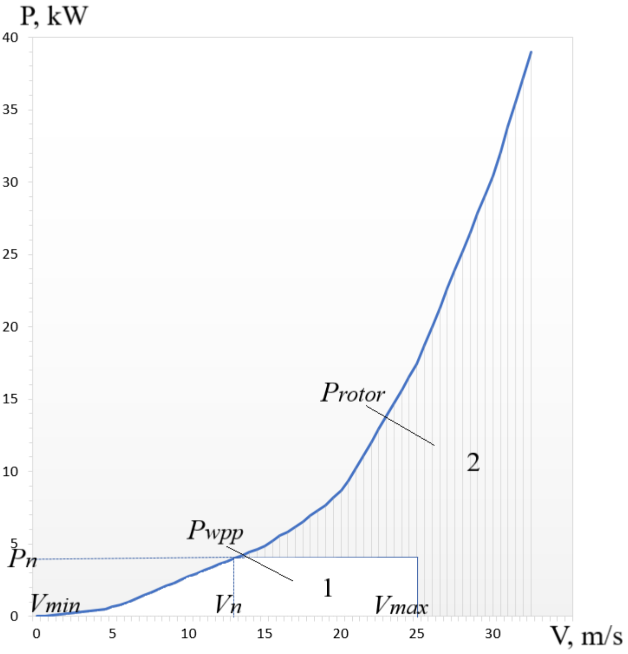

Fig. 6. Dependence of wind farm capacity on wind speed
Source: compiled by the authors

Rys. 6. Zależność mocy elektrowni wiatrowej od prędkości wiatru

important aspect is the choice of installation height, which is typically 10–30 meters for small turbines, to match the wind regime at a level that is affordable for small systems.

Notably, the design of the rotor, i.e., horizontal or vertical axis of rotation, plays a key role in adapting the turbine to wind conditions (Panchenko et al. 2021, 2024). Vertical axis wind turbines (VAWTs) have advantages in regions with low wind speeds (3–5 m/s), which are typical for 80% of Kazakhstan's territory due to their ability to operate efficiently in variable wind directions and their lower dependence on turbulence. Such turbines, such as the Darrieus or Savonius types, are easier to maintain and less sensitive to harsh climatic conditions, making them attractive for rural agriculture. However, horizontal axis wind turbines (HAWT) are often preferred because of their higher efficiency (up to 45–50% compared to 30–35% for VAWT) and lower operating costs, especially in regions with steady wind flows, such as the Almaty or Kyzylorda regions, where wind speeds can exceed 8 m/s. The main disadvantage of HAWTs in low wind conditions is the insufficient rotor speed, which reduces electricity generation. To overcome this problem, innovative solutions are being applied, such as the use of gearboxes to increase generator speed, the use of lightweight composite materials (e.g., carbon fiber) for blades, and the installation of orientation systems such as tail stabilizers or active diffusers, which improve wind flow capture efficiency.

To achieve maximum power generation from wind turbines, it is necessary to increase the efficiency and optimally match the technical characteristics of the equipment with the $f(v)$ function, which reflects the specifics of local wind conditions. When designing WPPs, it is critical to plan the layout of turbines correctly, especially when installing a large number, to avoid the "wake effect" of turbulence caused by rotor rotation, which reduces wind speed and impairs the performance of neighboring plants (Ali et al., 2022; Rubino and Rubino, 2019). According to the construction standards SP RK 4.04-112-2014, the distance between turbines should be at least five to six rotor diameters (typically 400 to 600 m), which minimizes mutual influence and ensures a stable wind inflow (Construction Standards… 2014). In addition, to increase the efficiency of wind farms, it is necessary to optimize the length of cable lines connecting turbines to the power grid to reduce power losses, which reach 30% in remote regions of Kazakhstan, and to guarantee the reliability and sustainability of the plant, especially in the face of energy shortages in the North and South Kazakhstan regions.

The efficiency of a wind farm, expressed through its capacity factor, is determined by the ability of the wind turbine to adapt to the variable wind conditions typical of the steppe regions of Kazakhstan. Figure 7 shows the dependence of turbine performance on wind speed.

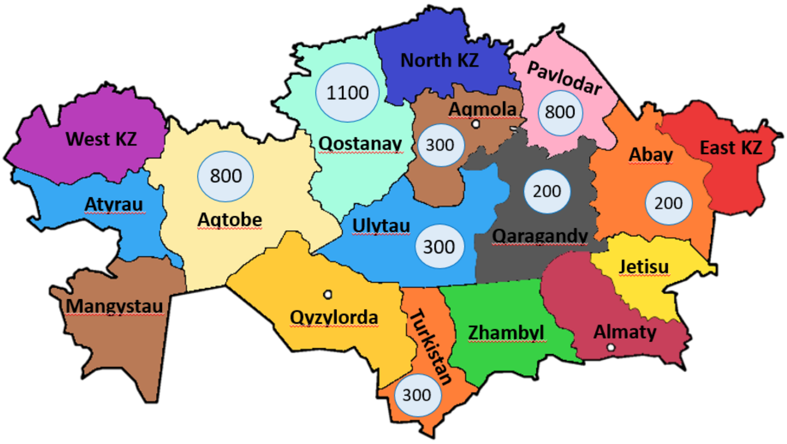

Fig. 7. Small-scale wind farm projects in Kazakhstan planned by 2030
Source: compiled by the authors based on Order of the Minister of Energy of the Republic of Kazakhstan No. 104 "On Approval of the Energy Balance of the Republic of Kazakhstan until 2035" (2023); Concept of Development of the Electric Power Industry of the Republic of Kazakhstan until 2035 (2022)

Rys. 7. Plany dotyczące małych farm wiatrowych w Kazachstanie do 2030 roku

In Figure 7, symbol 1 shows the actual power (P_{wpp}) generated by the wind farm, incorporating operational constraints. This plot is divided into three operating modes: acceleration (from minimum wind speed V_{min} to rated wind speed V_n), where the power gradually increases to the rated value P_n; base (from V_n to maximum speed V_{max}), where the control system stabilizes the power output by maintaining constant torque and speed; and decommissioning (at speeds above V_{max}), where the turbine is stopped to protect against overloads. Symbol 2 (shaded area) shows the theoretical power that the turbine could generate without design constraints, demonstrating the significant wind energy potential of steppe areas where wind speeds can reach high values, e.g., 8 m/s and above. However, as high wind speeds are less common, and medium and low wind speeds (3–5 m/s) prevail over 80% of the territory, turbine optimization should emphasize improving efficiency in these conditions. The development of technologies such as adaptive blade control systems and the use of lightweight materials, as well as strategies to minimize losses under variable wind loads, will increase power generation, improve the sustainability of wind farms, and provide a more reliable energy supply in rural Kazakhstan.

Seasonal and daily fluctuations in the availability of RES, such as solar and wind power, pose significant challenges for off-grid energy installations in remote regions (Marignetti et al. 2023). It should be borne in mind that wind and solar potential are unevenly distributed across the country: for example, the Almaty region has high wind speeds (up to 8 m/s), while southern regions, such as the Kyzylorda region, are characterized by high levels of solar radiation. To solve these problems, it is advisable to introduce hybrid autonomous power supply systems that combine wind and solar installations to ensure stable power generation. Such systems should include efficient energy storage with a coefficient of performance in the range of 0.60–81 to compensate for the instability of generation. When designing a photovoltaic (PV) power plant, energy conversion methods, operating modes, and temporal consumption patterns adapted to local conditions, based on long-term meteorological data such as the Wind Atlas or solar radiation databases, as well as specialized calculations considering the geographical and climatic characteristics of the region, should be considered to ensure reliable and sustainable energy supply to rural areas.

In general, the study of Kazakhstan's wind energy potential confirms significant prospects for the development of wind energy in most of the country. To realize this potential, a comprehensive approach is needed, including increased government support, development of advanced technologies, and consideration of socio-economic factors such as job creation and energy security. While solar power has shown rapid growth in the period from 2019 to 2022, the government of Kazakhstan is currently focusing on wind power, as reflected in its strategic documents. According to the Energy Balance until 2035, 17.5 GW of new energy capacity is planned to be commissioned by 2035, of which 6.5 GW will be from wind and solar generation (United Nations Development… 2022). The Action Plan for the Development of the Electricity Sector until 2035 envisages the construction of five large wind farms with a total capacity of 5 GW (Table 4), as well as the development of small wind farm projects with a capacity of 200 to 1,100 MW in eight regions of the country by 2030 (Fig. 7) (Order of the Minister of Energy… 2023). These initiatives, supported by auctions and international investment, are aimed at diversifying the energy system and increasing the share of renewables to 15% by 2030, contributing to sustainable development and reducing dependence on coal-fired generation.

The successful development of small-scale wind power in Kazakhstan requires the development of a comprehensive legal framework that will facilitate the implementation of small-scale wind power projects. This framework should include financial and administrative

Table 4. Large wind turbines planned for construction by 2028

Tabela 4. Duże turbiny wiatrowe, których budowa jest planowana do 2028 roku

Type of installation	Power	Developer
WPP with a storage system	1 GW	Masdar
WPP with a storage system	1 GW	Total Energies
WPP with a storage system	1 GW	AcwaPowerCompany
WPP + Solar Power Plant (SPP) with storage system	1 GW	HEVEL
WPP with a storage system	1 GW	CPIH

Source: compiled by the authors based on Order of the Minister of Energy of the Republic of Kazakhstan No. 104 "On Approval of the Energy Balance of the Republic of Kazakhstan until 2035" (2023); Concept of Development of the Electric Power Industry of the Republic of Kazakhstan until 2035 (2022).

support mechanisms, such as subsidies, tax incentives, and simplified grid connection procedures, as well as performance and development indicators to encourage investment and innovation (Akhambayev et al. 2025). Given the energy deficit in the southern regions of the country, such as South Kazakhstan, and the significant number of farms without access to centralized power grids, the introduction of off-grid wind turbines with a capacity of 15–100 kW is the most promising solution. These systems, adapted to local wind conditions with wind speeds of 3–5 m/s, can provide a sustainable energy supply for agricultural needs such as irrigation and processing, contributing to the economic development of the regions and reducing dependence on expensive diesel generators.

The load characteristics of remote consumers in Kazakhstan, such as farms, have a significant impact on the efficiency of off-grid power systems. The selection of the optimal system is complex and depends on many factors, including local wind conditions and the energy demand of the area. To optimize the performance of wind turbines, especially in areas with variable wind conditions, various control strategies are employed. These strategies aim to stabilize power output by adjusting rotor speed and maximizing wind energy capture.

For small wind turbines (15–100 kW), commonly used in rural areas, costly mechanisms for controlling blade angles are often replaced by Maximum Power Point Tracking (MPPT) systems. MPPT algorithms continuously monitor wind speeds and adjust the turbine's operation to ensure that it is operating at its most efficient power output. This is particularly effective in low and medium wind conditions (3–5 m/s), which are prevalent in many remote areas of Kazakhstan. By tracking the optimal power point, MPPT increases energy efficiency, ensuring that wind turbines extract the maximum amount of energy from fluctuating wind speeds (Rekioua et al. 2024). At higher wind speeds, such as those typically found in the Almaty region (above 8 m/s), turbines are designed to switch to wind-down mode, which slows or stops the rotor to prevent damage from excessive loads. This dynamic response helps protect the turbines and ensures long-term durability under harsh conditions.

To further enhance the reliability of power supply in remote regions, hybrid systems that combine wind and solar energy with fuel cells are gaining traction. These systems employ Adaptive Neuro-Fuzzy Inference Systems (ANFIS), a type of machine learning algorithm, to optimize power distribution. ANFIS algorithms combine both human-like reasoning and mathematical models to predict and adjust the energy output of the system based on changing conditions. This ensures that power is consistently available, even during periods of variable wind and sunlight, by effectively managing the energy storage and distribution between the wind, solar, and fuel cell components (Cholamuthu et al. 2022).

Moreover, short-term forecasting for wind conditions, supported by machine learning models, helps integrate predictions of fluctuations in wind speed and direction. This forecast data enables better load balancing, preventing system instability as the number of small wind turbines grows. By adjusting the power distribution in real-time based on anticipated wind conditions, these systems can prevent power surges or shortages, ensuring a steady and reliable energy supply in remote locations (Bošnjaković et al. 2022).

Adaptive control systems, which include specialized controllers and innovative technologies, play a crucial role in improving the efficiency of wind turbines. These systems respond to changes in wind patterns by adjusting turbine settings, such as blade pitch or rotational speed, minimizing energy losses, and ensuring a stable power supply in the variable conditions typical of remote regions in Kazakhstan. This adaptability is essential for maintaining reliable and sustainable energy generation in areas with fluctuating weather patterns, ensuring that wind energy can contribute effectively to the decentralized energy grid.

It is also worth highlighting the socio-economic factors that have a significant impact on the development of wind energy in Kazakhstan. The lack of local production of wind turbines and the high cost of transporting them hinder the industry's stable growth, which highlights the need to create domestic production facilities to reduce the cost of logistics and support the sector (Hotra et al. 2024). Another problem is the shortage of qualified personnel: Kazakhstan's electricity sector lacks 20% of specialists, and approximately 3,000 workers have left the industry due to low salaries and lack of attractiveness of the profession (International Energy Agency, 2024; International Renewable… 2023). To address these challenges, it is necessary to raise the prestige of technical professions, improve working conditions, provide competitive salaries, and promote career opportunities in the wind energy sector to attract new personnel and support the sustainable development of the industry.

To account for the potential impacts of climate change on wind energy systems, several strategic interventions should be implemented to ensure the continued efficiency and reliability of wind turbines. First, adaptive wind turbine designs should be prioritized. This includes incorporating advanced materials, such as lightweight composites and corrosion-resistant coatings, to improve the durability of turbines in harsh climatic conditions. Additionally, turbines should be equipped with dynamic blade pitch control systems that adjust the blade angle according to varying wind speeds, optimizing energy capture while preventing damage during high-wind events (Deryaev 2024). This would ensure that turbines can perform efficiently under both low and high wind conditions, which are expected to become more variable with climate change.

In addition to enhancing turbine design, improving forecasting models is crucial. The integration of climate change projections into wind resource models will help predict long-term shifts in wind regimes, allowing for better turbine placement planning and energy generation forecasting. High-resolution climate models and machine learning algorithms can provide more accurate, localized wind predictions, thus improving the integration of wind energy into the national grid. These models can also support short-term forecasting, enabling grid operators to optimize power generation and distribution based on real-time wind data, further stabilizing energy supply in the face of variable generation.

To maximize wind turbine efficiency and support the transition to renewable energy, a combination of technological, policy, and social interventions is necessary (Nenko et al. 2021). On the technological front, hybrid systems that integrate wind and solar power, coupled with energy storage solutions, should be developed to address the intermittency of wind generation. Such systems can provide a continuous power supply during periods of low wind. From a policy perspective, government support through subsidies and incentives for the development of adaptive wind turbine technologies and decentralized energy systems in rural areas is essential. This support should also include investments in research to further develop integrated control systems, such as MPPT and ANFIS, which optimize energy distribution and improve system reliability.

Social interventions should focus on capacity building in the wind energy sector. This includes creating educational programs to train engineers and technicians specialized in wind energy technologies, particularly in remote areas where expertise is often scarce. Engaging local communities in wind energy projects can help raise awareness, ensure smoother implementation, and foster long-term support for renewable energy initiatives.

In conclusion, by combining advanced turbine designs, improved forecasting models, hybrid energy systems, and robust policy support, Kazakhstan can enhance the efficiency of its wind energy systems. These strategies will not only ensure that the country’s wind energy potential is fully realized but also contribute to its broader goals of sustainable development and carbon neutrality.

3. Discussion

Jung and Schindler (2023) confirmed the findings of high wind energy potential in regions with moderate to high wind speeds, but the global analysis in the mentioned study is less detailed in local climatic and geographical features, unlike the present study, which uses the Weibull model and the Wind Atlas to accurately assess different zones and regions. Bianchini et al. (2022) analyzed the limitations of small wind turbines (15,100 kW) in low wind speed conditions, which is consistent with the conclusions of this study, but the study did not consider in detail the adaptation of turbines to the extreme conditions of the steppe zones of

Kazakhstan, which limits the results obtained. Torres-Madroñero et al. (2020) also addressed the problems of energy efficiency of small turbines, but did not include recommendations for control systems suitable for Kazakh conditions. Wilberforce et al. (2023) emphasized the importance of hybrid wind-solar systems for low-speed zones, which complements the analysis of storage integration in this study, but the approach of the mentioned study is less focused on the specifics of Kazakhstan.

The study also revealed that Kazakhstan's wind energy potential allows for the use of both large wind farms in regions with high wind speeds (above 8 m/s) and small turbines for rural areas with wind speeds of 3–5 m/s, requiring a comprehensive approach to turbine selection. This approach incorporates the rated power, type of rotor design (horizontal or vertical axis), installation height (10–30 m for small turbines, 80–100 m for large turbines), control systems, and integration into autonomous or local networks with storage. In comparison with the results of Charabi and Abdul-Wahab (2020), which analyzed the performance of turbines to minimize energy costs, this study offers a more detailed approach to turbine selection, considering Kazakhstani climatic conditions such as dust storms, as opposed to a general economic analysis. The focus of the work of Aravindhan et al. (2023) was on small turbines in urban environments, emphasizing the advantages of vertical axes in variable winds, which is partly consistent with the conclusions of this study on VAWT for low-speed zones, but not considering rural contexts and conditions. Enevoldsen and Jacobson (2021) investigated the power density of wind farms, confirming the assessment of this study of high potential areas, but with less detailed local factors, such as topography and microclimate, which in this study were analyzed using the Weibull model. Guo et al. (2021) considered the effect of the nacelle and tower on turbine performance, which overlaps with the recommendations of this study on optimizing the installation height, but with a greater focus on single turbines and not considering wind farm layouts that minimize the wake effect, as in this study. Chagas et al. (2020) analyzed the use of small turbines in the USA and Brazil, emphasizing their economic viability, which supports the conclusions of this study on small-scale projects, but does not consider the extreme climatic conditions of Kazakhstan, which require adaptive materials.

Zhang et al. (2023) analyzed the development of wind energy in New Zealand with an emphasis on government subsidies. This study proposes a wider range of measures, including the adaptation of turbines to Kazakhstani climatic conditions, while the above-mentioned work is less detailed in technical aspects. Darwish and Al-Dabbagh (2020) reviewed global technological advances in wind energy, which partially supports the recommendations of this study on improving converters, but without incorporating regional specifics, such as energy shortages in rural areas of Kazakhstan. Liu et al. (2023) analyzed the impact of turbine technology on wind energy potential in China, confirming the idea of design adaptation mentioned in this study, but focusing less on carbon emissions. The study by Maas and Raasch (2022) investigated the impact of turbine spacing in large wind farms, confirming the adherence to the norms of SP RK 4.04-112-2014, but the mentioned case does not consider socio-economic factors, such as the need for subsidies for small-scale projects, which are an important factor for design (Construction Standards… 2014).

In conclusion, the findings of this study highlight the significant potential for wind energy development in Kazakhstan, emphasizing the importance of region-specific factors such as wind speed variability, local topography, and climatic conditions. The analysis demonstrates that Kazakhstan's vast territory, with diverse wind regimes, offers opportunities for both large-scale wind farms in high-wind areas and small turbines for rural applications. While existing research on wind energy has provided valuable insights into the broader technological and economic aspects, this study offers a more tailored approach, considering the unique challenges of the Kazakhstani context, such as extreme climatic conditions, energy shortages, and the need for adaptive turbine designs. Moreover, the integration of hybrid systems, combining wind and solar power with storage, provides a promising solution to address the intermittency issues associated with renewable energy. Overall, the study underscores the need for a comprehensive approach to wind energy development, incorporating technological innovation, government support, and socio-economic considerations to ensure the successful deployment of wind energy projects and contribute to Kazakhstan's sustainable development and energy security goals.

Conclusions

This study has demonstrated that Kazakhstan's wind energy potential offers significant opportunities for the development of decentralized energy systems, particularly in remote rural areas, where approximately 90% of the country's 266,000 farms lack access to centralized power grids. The analysis, based on the Wind Atlas and the Weibull distribution model, revealed that 80% of Kazakhstan's territory has average annual wind speeds of 3–5 m/s, which is suitable for the development of wind farms. Regions such as Almaty and Kyzylorda, where wind speeds exceed 8 m/s, are particularly well-suited for high-capacity wind farms, with potential utilization rates of up to 40–50%.

The study emphasized that to optimize the efficiency of wind energy systems, turbine designs must be adapted to local climatic conditions, which include severe winters and dust storms. Additionally, the placement of turbines must comply with existing construction standards (e.g., SP RK 4.04-112-2014) to minimize the wake effect effect and ensure optimal energy generation. The introduction of modern control systems, such as Maximum Power Point Tracking (MPPT) for small turbines and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) for hybrid systems, enhances performance in variable wind conditions, improving energy efficiency. Furthermore, hybrid wind-solar power plants with integrated energy storage systems can mitigate seasonal and daily fluctuations, providing a stable and reliable energy supply to regions with energy shortages, such as South Kazakhstan.

The study also identified key socio-economic challenges that must be addressed for the successful deployment of wind energy in Kazakhstan. These challenges include the lack of domestic wind turbine production and a shortage of qualified personnel in the renewable energy sector. The development of local manufacturing capabilities and educational programs to train engineers is crucial to overcoming these obstacles. Government initiatives, including auctions, subsidies, and plans to commission 6.5 GW of wind and solar capacity by 2035, alongside the development of five large wind farms and smaller projects in eight regions by 2030, provide a solid foundation for the growth of Kazakhstan's wind energy sector.

By implementing these measures, along with continued advancements in turbine technology and integrated monitoring systems, Kazakhstan can fully harness its wind energy potential. This will contribute to the decarbonization of the economy, reduce dependence on coal-fired generation, and address the ongoing energy challenges in rural areas, ultimately supporting the nation's transition to a sustainable and resilient energy future.

The research offers helpful observations about the wind energy potential in Kazakhstan, but it does have a certain limitation in terms of the insufficient consideration of long-term climate change effects, which could significantly impact future wind regimes. Climate change is expected to lead to increased variability in weather patterns, potentially altering wind speeds and frequencies across different regions. While some areas may experience more frequent or intense windstorms, others could face reduced wind availability due to changes in atmospheric circulation patterns. Extreme weather events, such as stronger storms, droughts, or temperature extremes, could also affect the stability and reliability of wind energy systems, thereby influencing the operational efficiency of turbines and their ability to consistently meet energy demand.

To address these potential issues, future research should focus on developing more comprehensive forecasting models that incorporate various climate scenarios. These models should account for the expected shifts in wind patterns due to climate change, such as changes in seasonal wind variability, the frequency and intensity of extreme weather events, and potential long-term shifts in regional wind regimes. A more accurate understanding of these dynamics is essential for planning the long-term viability of wind energy projects, particularly in rural and remote regions where energy infrastructure is less developed and more vulnerable to environmental changes.

In addition to the limitations regarding climate change, the study could further elaborate on data limitations related to wind measurements and the quality of data used in the analysis. For instance, discrepancies in wind measurement accuracy across different regions of Kazakhstan, variations in wind data collection methodologies, or the use of outdated or inconsistent data sources could introduce uncertainty into the conclusions. Addressing these gaps would enhance the robustness of future studies and provide more reliable data for wind energy planning.

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References

Akbarova et. al. 2024 – Akbarova, S., Akbarli, R. and Namazov, Y. 2024. Trends in scientific research on technological aspects of green energy transition. *Reliability Theory and Applications* 19 (Special issue 6), pp. 1633–1641, https://doi.org/10.24412/1932-2321-2024-681-1633-1641.

Akhambayev et. al. 2025 – Akhambayev, R., Minazhova, S., Bekbayev, A., Zhumatova, A. and Ussipbekova, D. 2025. Enhancing energy efficiency in decentralized systems: A comprehensive approach to renewable energy use. *Energy Policy Journal* 28(2), pp. 73–90, https://doi.org/10.33223/epj/203621.

Ali et. al. 2022 – Ali, S., Rubino, G., Ciprini, L., Ali, R. and Marignetti, F. 2022. Comparative study among different rotor topologies of axial flux permanent magnet machines. *SMART 2022 – 2nd International Conference on Sustainable Mobility Applications, Renewables and Technology*. Cassino: Institute of Electrical and Electronics Engineers, https://doi.org/10.1109/SMART55236.2022.9990232.

Aravindhan et. al. 2023 – Aravindhan, N., Natarajan, M.P., Ponnuvel, S. and Devan, P.K. 2023. Recent developments and issues of small-scale wind turbines in urban residential buildings – A review. *Energy & Environment* 34(4), pp. 1142–1169, https://doi.org/10.1177/0958305X221084038.

Barthelmie, R.J. and Pryor, S.C. 2021. Climate change mitigation potential of wind energy. *Climate* 9(9), https://doi.org/10.3390/cli9090136.

Bianchini et. al. 2022 – Bianchini, A., Bangga, G., Baring-Gould, I., Croce, A., Cruz, J. I., Damiani, R., Erfort, G., Ferreira, C.S., Infield, D., Navid Nayeri, C., Pechlivanoglou, G., Runacres, M., Schepers, G., Summerville, B., Wood, D. and Orrell, A. 2022. Current status and grand challenges for small wind turbine technology. *Wind Energy Science*, 7(5), pp. 2003–2037, https://doi.org/10.5194/wes-7-2003-2022.

Bošnjaković et. al. 2022 – Bošnjaković, M., Katinić, M., Santa, R. and Marić, D. 2022. Wind turbine technology trends. *Applied Sciences*, 12(17), https://doi.org/10.3390/app12178653.

Brych et. al. 2023 – Brych, V., Borysiak, O., Halysh, N., Liakhovych, G., Kupchak, V. and Vakun, O. 2023. Impact of international climate policy on the supply management of enterprises producing green energy. *Lecture Notes in Networks and Systems* 485, pp. 649–661, https://doi.org/10.1007/978-3-031-08093-7_43.

Bulatov, A. and Neshina, E.G. 2020. Prospects for the development of wind energy in Kazakhstan. *Bulatov Readings* 6, pp. 67–69. [Online:] https://ecogosfond.kz/wp-content/uploads/2022/04/PERSPEKTIVY-RAZVITIJa-VETROJeNERGETIKI-V-KAZAHSTANE.pdf [Accessed: 2025-07-02].

Bureau of National Statistics Agency for Strategic Planning and Reforms of the Republic of Kazakhstan. 2025. *Energy statistics*. [Online:] https://stat.gov.kz/ru/industries/business-statistics/stat-energy/ [Accessed: 2025-07-09].

Bureau of National Statistics of the Agency for Strategic Planning and Reforms of the Republic of Kazakhstan 2024. *Key indicators of livestock development in the Republic of Kazakhstan* (*January–December 2023*). [Online:] https://stat.gov.kz/ru/industries/business-statistics/stat-forrest-village-hunt-fish/publications/113763/ [Accessed: 2025-07-03].

Chagas et. al. 2020 – Chagas, C.C.M., Pereira, M.G., Rosa, L.P., Da Silva, N.F., Freitas, M.A.V. and Hunt, J.D. 2020. From megawatts to kilowatts: A review of small wind turbine applications, lessons from the US to Brazil. *Sustainability* 12(7), https://doi.org/10.3390/su12072760.

Charabi, Y. and Abdul-Wahab, S. 2020. Wind turbine performance analysis for energy cost minimization. *Renewables: Wind, Water, and Solar* 7(1), https://doi.org/10.1186/s40807-020-00062-7.

Cholamuthu et. al. 2022 – Cholamuthu, P., Irusappan, B., Paramasivam, S.K., Ramu, S.K., Muthusamy, S., Panchal, H., Nuvvula, R.S.S., Kumar, P.P. and Khan, B. 2022. A grid-connected solar PV/wind turbine based hybrid energy system using ANFIS controller for hybrid series active power filter to improve the power quality. *International Transactions on Electrical Energy Systems*, https://doi.org/10.1155/2022/9374638.

Concept of Development of the Electric Power Industry of the Republic of Kazakhstan until 2035. 2022. [Online:] https://www.kazenergy.com/upload/document/electric/project2035.pdf [Accessed: 2025-07-09].

Construction Standards of the Republic of Kazakhstan (SP RK) 4.04-112-2014 "Planning of Wind Power-Station" 2014. [Online:] https://online.zakon.kz/Document/?doc_id=32727418 [Accessed: 2025-07-01].

Couto, A. and Estanqueiro, A. 2021. Assessment of wind and solar PV local complementarity for the hybridization of the wind power plants installed in Portugal. *Journal of Cleaner Production* 319, https://doi.org/10.1016/j.jclepro.2021.128728.

Darwish, A.S. and Al-Dabbagh, R. 2020. Wind energy state of the art: Present and future technology advancements. *Renewable Energy and Environmental Sustainability* 5, https://doi.org/10.1051/rees/2020003.

Deryaev, A. 2024. Integration of advanced technologies to improve the efficiency of gas condensate field development. *Machinery and Energetics* 15(1), pp. 33–42, https://doi.org/10.31548/machinery/1.2024.33.

Enevoldsen, P. and Jacobson, M.Z. 2021. Data investigation of installed and output power densities of onshore and offshore wind turbines worldwide. *Energy for Sustainable Development* 60, pp. 40–51, https://doi.org/10.1016/j.esd.2020.11.004.

Guo et. al. 2021 – Guo, T., Guo, X., Gao, Z., Li, S., Zheng, X., Gao, X., Li, R., Wang, T., Li, Y. and Li, D. 2021. Nacelle and tower effect on a stand-alone wind turbine energy output – A discussion on field measurements of a small wind turbine. *Applied Energy* 303, https://doi.org/10.1016/j.apenergy.2021.117590.

Hotra et. al. 2024 – Hotra, O., Kulyk, M., Babak, V., Kovtun, S., Zgurovets, O., Mroczka, J. and Kisała, P. 2024. Organisation of the structure and functioning of self-sufficient distributed power generation. *Energies* 17(1), https://doi.org/10.3390/en17010027.

International Energy Agency (IEA) 2024. *Renewables 2024: Analysis and forecasts to 2030*. [Online:] https://www.iea.org/reports/renewables-2024 [Accessed: 2025-07-10].

International Renewable Energy Agency (IRENA) 2023. *Renewable energy and jobs: Annual review 2023*. [Online:] https://www.irena.org/Publications/2023/Sep/Renewable-energy-and-jobs-Annual-review-2023 [Accessed: 2025-07-06].

International Renewable Energy Agency (IRENA) 2024. *Renewable capacity statistics*. [Online:] https://www.irena.org/Publications/2024/Mar/Renewable-capacity-statistics-2024 [Accessed: 2025-07-04].

Işık et. al. 2025 – Işık, C., Ongan, S., Yan, J. and Islam, H. 2025. Towards carbon neutrality & COP29 Baku / Azerbaijan - COP30 Belem / Brazil: Exploring the impacts of economic, environmental, social, and governance (ECON-ESG) factors on climate policy uncertainty (CPU) for sustainable development. *Heliyon* 11(3), https://doi.org/10.1016/j.heliyon.2025.e41944.

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

Juan et. al. 2021 – Juan, Y.H., Wen, C.Y., Chen, W.Y. and Yang, A.S. 2021. Numerical assessments of wind power potential and installation arrangements in realistic highly urbanized areas. *Renewable and Sustainable Energy Reviews* 135, https://doi.org/10.1016/j.rser.2020.110165.

Jung, C. and Schindler, D. 2023. Efficiency and effectiveness of global onshore wind energy utilization. *Energy Conversion and Management* 280, https://doi.org/10.1016/j.enconman.2023.116788.

Kasym, A.E. 2023. *Optimal areas of Akmolinks Region for wind power plant location by wind potential.* Astana: S. Seifullin Kazakh Agro Technical Research University.

Krechko, O. and Mikhaylov, A. 2025. Global electricity generation from renewable sources using fuzzy sets and spatial analysis: revolution in solar and wind energy in BRICS countries. *Quality and Quantity*, 59(2), pp. 1553–1571, https://doi.org/10.1007/s11135-024-02033-2.

Liu et. al. 2023 – Liu, F., Sun, F. and Wang, X. 2023. Impact of turbine technology on wind energy potential and CO2 emission reduction under different wind resource conditions in China. *Applied Energy* 348, https://doi.org/10.1016/j.apenergy.2023.121540.

Maas, O. and Raasch, S. 2022. Wake properties and power output of very large wind farms for different meteorological conditions and turbine spacings: A large-eddy simulation case study for the German Bight. *Wind Energy Science* 7(2), pp. 715–739, https://doi.org/10.5194/wes-7-715-2022.

Manaridis, G.D. and Efimova, O.N. 2021. Investigation of wind power plants designed to operate in low-speed wind currents. *Actual Scientific Research in the Modern World*, 1(69), pp. 196-200. [Online:] https://ecogosfond.kz/wp-content/uploads/2022/01/ISSLEDOVANIE-VETROJeNERGETIChESKIH-USTANOVOK.pdf [Accessed: 2025-07-06].

Marignetti et. al. 2023 – Marignetti, F., Di Stefano, R.L., Rubino, G. and Giacomobono, R. 2023. Current source inverter (CSI) power converters in photovoltaic systems: A comprehensive review of performance, control, and integration. *Energies* 16(21), https://doi.org/10.3390/en16217319.

Ministry of Energy of the Republic of Kazakhstan 2022. *Concept of development of the electric power industry of the Republic of Kazakhstan until 2035*. [Online:] https://www.gov.kz/memleket/entities/energo/documents/details/349883?lang=ru [Accessed: 2025-07-05].

National Centre for Atmospheric Research (NCAR) 2025. [Online:] https://ncar.ucar.edu/ [Accessed: 2025-07-08].

Nenko et. al. 2021 – Nenko, S., Tyukhtenko, N. and Krasnopolska, T. 2021. Administrative and legal support for the management of integrated economic structures in a globalized business processes. *Baltic Journal of Economic Studies* 7(4), pp. 145–152, https://doi.org/10.30525/2256-0742/2021-7-4-145-152.

Niyazbekova et. al. 2021 – Niyazbekova, S., Moldashbayeva, L., Kerimkhulle, S., Jazykbayeva, B., Beloussova, E. and Suleimenova, B. 2021. Analysis of the development of renewable energy and state policy in improving energy efficiency. *E3S Web of Conferences* 258, https://doi.org/10.1051/e3sconf/202125811011.

Order of the Minister of Energy of the Republic of Kazakhstan No. 104 “On Approval of the Energy Balance of the Republic of Kazakhstan until 2035” 2023. [Online:] https://online.zakon.kz/Document/?doc_id=37351758 [Accessed: 2025-07-01].

Panchenko et. al. 2021 – Panchenko, A., Voloshina, A., Titova, O. and Panchenko, I. 2021. The influence of the design parameters of the rotors of the planetary hydraulic motor on the change in the output characteristics of the mechatronic system. *Journal of Physics: Conference Series* 1741(1), https://doi.org/10.1088/1742-6596/1741/1/012027.

Panchenko, A. et. al. 2024 – Panchenko, A., Voloshina, A., Antoshchenkov, R., Halych, I. and Głowacki, S. 2024. Experimental studies of the wear on the rotors’ working surfaces of a planetary hydraulic motor. *Lecture Notes in Mechanical Engineering* 1, pp. 498–508, https://doi.org/10.1007/978-3-031-42778-7_46.

Rekioua et. al. 2024 – Rekioua, D., Mezzai, N., Mokrani, Z., Oubelaid, A., Kakouche, K., Logerais, P.O., Alshareef, M., Bajaj, M., Tuka, M.B. and Ghoneim, S.S.M. 2024. Effective optimal control of a wind turbine system with hybrid energy storage and hybrid MPPT approach. *Scientific Reports* 14(1), 30013, https://doi.org/10.1038/s41598-024-78847-9.

Rezaeiha et. al. 2020 – Rezaeiha, A., Montazeri, H. and Blocken, B. 2020. A framework for preliminary large-scale urban wind energy potential assessment: Roof-mounted wind turbines. *Energy Conversion and Management* 214, https://doi.org/10.1016/j.enconman.2020.112770.

Roga et. al. 2022 – Roga, S., Bardhan, S., Kumar, Y. and Dubey, S.K. 2022. Recent technology and challenges of wind energy generation: A review. *Sustainable Energy Technologies and Assessments* 52, https://doi.org/10.1016/j.seta.2022.102239.

Romankiewicz et. al. 2023 – Romankiewicz, B., Reguła, M., Różański, R., Potempska, M., Gaze, B., Knutel, B., Wojtko, P., Drozdovych, I. and Kawa, K. 2023. Analysis of energy consumption of the process of composting dairy sludge in hyperbaric conditions. *Rynek Energii* 2023(6), pp. 89–97.

Rubino, L. and Rubino, G. 2019. On the active clamp gate driver thermal effects. *ICCEP 2019 – 7th International Conference on Clean Electrical Power: Renewable Energy Resources Impac* 1, pp. 478–481, https://doi.org/10.1109/ICCEP.2019.8890213.

Seasonal climate forecast from CFSv2. 2025. [Online:] https://www.cpc.ncep.noaa.gov/products/CFSv2/CFSv2_body.html [Accessed: 2025-07-04].

Shorabeh et. al. 2022 – Shorabeh, S.N., Firozjaei, H.K., Firozjaei, M.K., Jelokhani-Niaraki, M., Homaee, M. and Nematollahi, O. 2022. The site selection of wind energy power plant using GIS-multi-criteria evaluation from economic perspectives. *Renewable and Sustainable Energy Reviews* 168, https://doi.org/10.1016/j.rser.2022.112778.

Torres-Madroñero et. al. 2020 – Torres-Madroñero, J.L., Alvarez-Montoya, J., Restrepo-Montoya, D., Tamayo-Avendaño, J.M., Nieto-Londoño, C. and Sierra-Pérez, J. 2020. Technological and operational aspects that limit small wind turbines performance. *Energies* 13(22), https://doi.org/10.3390/en13226123.

United Nations Development Programme (UNDP) Kazakhstan 2011. *Lessons learnt from the UNDP-GEF project "Kazakhstan – Wind power market development initiative"*. [Online:] https://www.undp.org/sites/g/files/zskgke326/files/migration/kz/UNDP_KAZ_wind_power_market.pdf [Accessed: 2025-07-06].

United Nations Development Programme (UNDP) 2022. Analysing the feasibility of implementing various of renewable energy technologies, including heating, cooling and hot water supply (HW), in different geographical zones, taking into account the resource potential (*Analiz vozmozhnosti vnedreniya razlichnykh tekhnologiy vozobnovlyayemoy energetiki, vklyuchaya teplosnabzheniye, okhlazhdeniye i goryacheye vodosnabzheniye (GV) v raznykh geograficheskikh zonakh, s uchetom resursnogo potentsiala*). [Online:] https://www.undp.org/sites/g/files/zskgke326/files/2022-09/Исследование%20ВИЭ%20в%20ЖКХ.pdf [Accessed: 2025-07-07] (*in Russian*).

Wilberforce et. al. 2023 – Wilberforce, T., Olabi, A.G., Sayed, E.T., Alalmi, A.H. and Abdelkareem, M.A. 2023. Wind turbine concepts for domestic wind power generation at low wind quality sites. *Journal of Cleaner Production* 394, https://doi.org/10.1016/j.jclepro.2023.136137.

WindPRO. 2025. [Online:] https://www.emd-international.com/software/windpro [Accessed: 2025-07-07].

Zhang et. al. 2023 – Zhang, Z., Liu, X., Zhao, D., Post, S. and Chen, J. 2023. Overview of the development and application of wind energy in New Zealand. *Energy and Built Environment* 4(6), pp. 725–742, https://doi.org/10.1016/j.enbenv.2022.06.009.

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Ocena potencjału energetyki wiatrowej Kazachstanu i zwiększenie efektywności turbin wiatrowych

Streszczenie

W ramach badania przeanalizowano potencjał energetyki wiatrowej w Kazachstanie oraz sformułowano zalecenia dotyczące poprawy wydajności turbin wiatrowych w kontekście zasilania odległych obszarów. Badanie obejmowało analizę danych z Atlasu Wiatrów, modelowanie rozkładu Weibulla oraz ocenę techniczną, ekonomiczną i społeczno-ekonomiczną. Badanie wykazało, że Kazachstan dysponuje ogromnym potencjałem energetyki wiatrowej, co sprawia, że energia wiatrowa może stanowić rozwiązanie w zakresie autonomicznego zasilania w odległych lokalizacjach, gdzie 90% gospodarstw domowych nie jest podłączonych do sieci energetycznej. Zgodnie z danymi z Atlasu Wiatrów oraz modelem rozkładu Weibulla 80% terytorium kraju charakteryzuje się średnią roczną prędkością wiatru wynoszącą 3–5 m/s, odpowiednią dla małych turbin wiatrowych (15–100 kW), podczas gdy regiony Ałmaty i Kyzylorda charakteryzują się prędkościami powyżej 8 m/s, co zapewnia wystarczającą gęstość energii wiatru dla dużych farm wiatrowych o współczynniku wykorzystania mocy zainstalowanej wynoszącym 40–50%. WindPro oraz baza danych Climate Forecast System w wersji 2 (CFSv2) (2014–2024) potwierdziły, że optymalizacja rozmieszczenia turbin zgodnie z normą SP RK 4.04-112-2014 może zminimalizować efekt cienia aerodynamicznego. Według badania wydajność turbin wiatrowych wzrasta wraz z lokalną adaptacją, w tym dzięki zastosowaniu lekkich materiałów kompozytowych i technologii sterowania. W badaniu podkreślono również potencjał hybrydowych systemów wiatrowych i słonecznych z magazynowaniem energii, które pozwalają dostosować się do zmian sezonowych i ustabilizować dostawy energii w miejscach dotkniętych niedoborem energii. Jedną z przeszkód społeczno-gospodarczych jest brak zasobów ludzkich i lokalnej produkcji turbin, co podnosi koszty logistyczne. Rząd planuje pobudzić rozwój energetyki wiatrowej, jednak według raportu do zapewnienia zrównoważonego wzrostu niezbędne są dotacje, programy szkoleniowe oraz lokalizacja produkcji.

SŁOWA KLUCZOWE: odnawialne źródła energii, elektrownie wiatrowe, efekt cienia aerodynamicznego, zasilanie odległych obszarów, moc teoretyczna, gęstość właściwa, model dystrybucji