DOI: https://doi.org/10.15407/ugz2026.01.028

Imamverdiyev, N. S. 0000-0002-5573-0209
Institute of Geography of the Ministry of Science and Education, Baku, Azerbaijan

Assessing Wind Energy Potential in Azerbaijan (Case of Shorabad Settlement, Khizi District)

UDC 621.548:551.55:27.19(479.24)(045)

Abstract. This study presents a comprehensive assessment of Azerbaijan's wind energy potential, using the Shorabad settlement in the Khizi district as a representative case study. The strategic importance of wind energy in the context of the global energy transition and climate change is highlighted, and the natural and geographical advantages of the area, as well as existing infrastructure opportunities, are examined. Analysis of long-term datasets from NASA POWER (1981–2024), the Global Wind Atlas, and local meteorological stations revealed an average annual wind speed of 5.46 m/s. This wind regime was further characterized using statistical modeling based on the Weibull distribution. The spatial variation of wind speed, land use, and proximity to the power grid was evaluated through GIS analysis. Energy yield modeling for the Vestas V90-2.0 MW turbine indicates an annual generation potential of 2.9–3.50 GWh, corresponding to a capacity factor (CF) of 0.20 under the prevailing wind conditions. Based on a conservative siting scenario (25 km² area, accommodating approximately 54 turbines with a total capacity of 108 MW), the annual energy production is estimated at 156.6–189.0 GWh/year, corresponding to approximately 0.55%–0.67% of Azerbaijan's annual electricity generation. The findings indicate that Shorabad possesses favorable characteristics, including flat topography, limited vegetation, and proximity to existing infrastructure, which collectively render it a suitable location for a wind power project (WPP).

Keywords: *Wind energy; Shorabad settlement; Khizi district; GIS analysis; Weibull distribution; Renewable energy.*

Introduction

Renewable energy sources (RES), particularly wind energy, have come to play an increasingly vital role in the global energy mix. Global goals such as ensuring energy security, combating climate change, and reducing carbon emissions have made wind energy a strategically important energy source. Over the past decades, technological developments have increased the efficiency of wind turbines and significantly reduced the cost of energy production. The global installed capacity of renewable energy has reached 4,443 GW, with most of this growth coming from solar (597 GW) and wind (117 GW) ***[1]***. In 2024, wind energy accounted for approximately 8.1% of global electricity production, or 2,494 TWh ***[2]***. In the global "clean energy" structure, wind energy accounted for 14%, and, according to the International Energy Agency, will grow at an annual rate of at least 17% by 2030, reaching 7,100 TWh ***[3]***.

Azerbaijan's energy policy has become even more relevant in light of commitments under the Paris Climate Agreement and the "green energy zones" established in Karabakh and Eastern Zangezur. The country's location on the western coast of the Caspian Sea is characterized by strong wind currents, making it one of the region's countries with the most favorable wind energy potential ***[4]***. In particular, the Khizi district and the Absheron Peninsula are character-

For citation:
Imamverdiyev, N. S. (2026). Assessing Wind Energy Potential in Azerbaijan (Case of Shorabad Settlement, Khizi District). *Ukrainian Geographical Journal,* 1, 28–40. [in English]. DOI: https://doi.org/10.15407/ugz2026.01.028

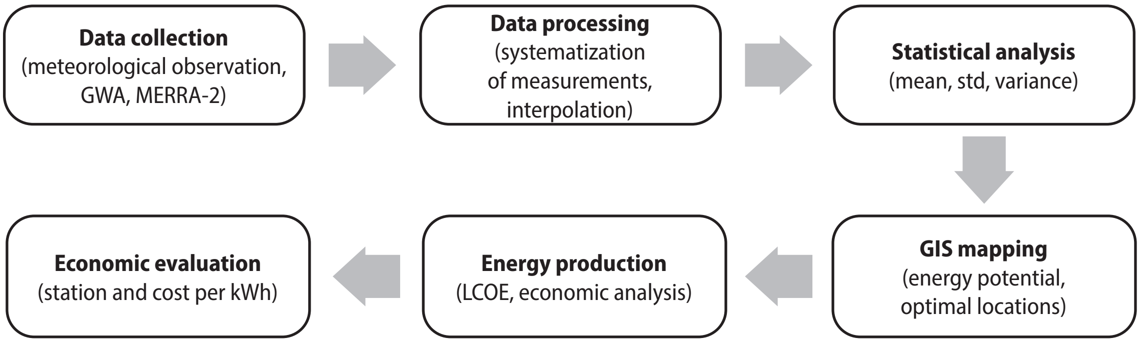

Fig. 1. Methodological workflow of the study

ized by high wind speeds. According to hydrometeorological observations, the average annual wind speed in these areas ranges from 5 to 8 m/s, which is an optimal indicator for the efficient operation of wind farms.

Shorabad, Yeni Yashma, and Sitalchay in the Khizi district feature flat terrain, sparse vegetation, and proximity to power and transport infrastructure. These physical, geographical, and infrastructural factors, particularly regarding transportation, wind turbine installation, and connection to the existing power grid, make the area a suitable location for wind farm construction. Despite the presence of operational wind farms in the district, the need to develop additional projects remains pressing, both to accommodate the country's annual growth in electricity demand (~1.5%), expand energy infrastructure, and enhance the contribution of RES.

The main objective of this study was to assess the wind energy potential of the Shorabad area from a technical and economic perspective and to justify the feasibility of a new WPP. However, existing studies on wind energy development in Azerbaijan exhibit several important limitations. Modern, high-resolution wind data remain scarce; the number of long-term meteorological stations is limited; and site-specific assessments that integrate infrastructure, environmental constraints, and techno-economic feasibility remain lacking. In particular, despite the presence of operational wind farms in the Khizi district, the Shorabad area has not previously been evaluated using a comprehensive, GIS-based, multi-source analytical framework. To address this gap, the methodology adopted in this study involved data collection, statistical processing, GIS mapping, Weibull modeling, and economic evaluation ***[5]***. ***Figure 1*** presents the study's methodological flowchart.

Azerbaijan's total electricity production in 2024 was 28.4 billion kWh. Of this production, 24.5 billion kWh (86%) was produced by thermal power plants and 3.8 billion kWh (14%) by RES. Among renewable energy sources, 5 wind farms (63.62 MW) accounted for 50.9 GWh (0.2%). In terms of installed capacity, the country's total RES capacity is 1.8 GW (21%) ***[6]***. The projected total production for 2025 is 29.1 billion kWh. Currently, thermal power plants are expected to produce 24.8 billion kWh (85.2%), and RES are expected to produce 4.3 billion kWh (14.8%). The contribution of wind energy to renewable energy is expected to increase to 85 GWh (0.29% of total generation) and to 2.1 GW (22% of the installed capacity of RES). Currently, three WPPs operate in the Khizi district, and one is under construction ***[7]***. This demonstrates that the area already benefits from established infrastructure and operational experience and that it is possible to fully utilize its potential by increasing the number.

"Yeni Yasma" station—A wind farm with a total capacity of 50 MW was built by the Azerbaijan State Agency for Renewable Energy Sources in the Yasma settlement of the Khizi district with 20 2.5 MW turbines.

The "Yashma Baglari" wind farm has a design capacity of 3.6 MW.

"Shurabad" wind farm, with a design capacity of 1.7 MW.

"Khizi-Absheron" wind farm—ACWA Power is implementing a 240 MW project. The project covers the villages of Chayli and Sitalchay and is planned to be fully operational by the end of 2025. The plant will generate approximately 907 GWh of electricity per year, meeting the energy needs of more than 300,000 households ***[4]***.

There are both global and local studies on Azerbaijan's renewable energy potential. According to the 2016 Strategic Roadmap of the Ministry of Energy, the country is planning to develop 350 MW of wind power, 50 MW of solar power, and 20 MW of bioenergy projects (Ministry of Energy, 2016) ***[8]***. However, the share of wind power in electricity generation in 2024 was only 0.2% ***[6]***. The renewable energy potential of Azerbaijan was analyzed using a systematic review, and opportunities for solar and wind power were assessed ***[9]***. The study highlights the country's strategy to transition from the oil and gas industry to carbon-free energy but notes obstacles, including a weak legal framework and a lack of specialized expertise. Having sufficient potential to increase the share of renewable energy supports energy security and the Sustainable Development Goals ***[10]***.

In previous studies, the Weibull distribution has been widely applied to assess wind resources. For example, the wind energy potential in Azerbaijan was analyzed based on ERA5 (1940–2023) data. In addition, 70 million hours of observations were analyzed using Python to study wind characteristics at 24 locations using the Weibull distribution. It was found that the coastal areas have high potential, with an average wind speed of 8.01 m/s and a power density of 628.5 W/m² in Baku ***[2]***.

Most techno-economic studies in the literature are based on meteorological station or satellite data, leading to an underestimation of wind energy potential and weakening the reliability of economic decisions ***[11]***. In contrast, a study conducted in the Bursa region of Turkey used real field measurements (12 stations, 100 m altitude, 10–minute intervals over 2 years) and evaluated Weibull distribution, turbulence, and power density parameters. The results show that the average monthly wind speed varies in the range of 4.6–11.7 m/s, has a high turbulence index (0.54), and the lowest LCOE was achieved with the Goldwind turbine. This approach emphasizes the importance of considering sector-specific measurements and alternative economic analyses, such as LCOE, in both political and economic decision-making processes ***[12]***.

Another article analyzed the wind energy potential in Turkmenistan using wind speed statistics. The average annual wind speed is 3–6 m/s, and in May–July it is 5–6 m/s. Analysis of Disa A300, Terex TW 600, and Direct Wind 900/52 turbines showed that energy production is higher during this period. The use of wind energy can improve social conditions and lower prices. The results create a theoretical basis for government programs ***[13]***. In another investigation, an analytical expression for wind power using Rayleigh, Weibull, and log-normal distributions was obtained via mathematical transformation and demonstrated that this method yields more accurate results. In an applied study conducted on Pirallahi Island, the Weibull distribution was found suitable for small-scale turbines, and the capacity factor was estimated at 44% ***[14]***.

Despite the growing body of international literature, most existing studies either focus on national-scale assessments or rely on single-source datasets. In contrast, site-specific hybrid assessments that integrate long-term reanalysis data, high-resolution wind atlases, and GIS-based spatial constraints remain limited in Azerbaijan. Therefore, this study addresses a clear methodological gap by combining multi-source wind datasets with geospatial modeling and techno-economic evaluation for a previously underexplored area ***[15]***.

The study area includes the settlement of Shorabad, located in the Khizi region of Azerbaijan on the western coast of the Caspian Sea (40°49′08″N, 49°28′19″E). Covering approximately 25 km², it has a flat landscape, minimal vegetation, and a semi-arid climate. Being surrounded by northerly and northeastern winds and located near the Caspian Sea, it experiences optimal wind speeds, with an annual average of 5–8 m/s ***[16]***. Being near transportation routes, electrical power lines, and existing wind farms enhances the technical feasibility of developing wind energy, thereby qualifying it as a case study site for assessing wind resources.

Materials and Methods

This study used a multi-stage approach to assess the technical and economic potential of wind energy development using the Shorabad area as a case study. Three turbine models were selected based on their technical suitability for the local wind regime and power characteristics. The selected turbines include the Vestas V90-2.0 MW, Siemens Gamesa SG 2.0 MW, and Nordex N100-2.4 MW. Among these, the Vestas V90-2.0 MW turbine was selected as the reference model due to its compatibility with moderate wind speed conditions. The turbine operates within a wind speed range of 4–25 m/s and reaches its rated power at 12 m/s. The hub height varies between 60 and 100 m, while the swept area is 6,362 m², determined solely by the rotor diameter (90 m) and independent of hub height ***[14]***.

Data sources

NASA POWER (1981–2024) datasets were analyzed to obtain daily, monthly, and annual average wind speed (m/s) and direction (°). For calculations, the average wind speed for the area was determined from long-term observations. As a result of the analysis of climate data for 1981–2024, the average annual wind speed for the Shorabad area is 5.46 m/s ***[17]***. Based on this indicator, the Weibull distribution ($k \approx 2.8$, $c = 6.12$ m/s) was applied. The Weibull distribution is the most commonly used statistical model in wind energy calculations, as it accurately describes the probability distribution of wind speeds ***[18]***.

The data used in the study were obtained from the following sources:

- Monthly average wind speed and direction data for the Khizi district of Azerbaijan for 2010–2024 were obtained from the Global Wind Atlas meteorological resources.
- Field observations and photographs-visual materials (infrastructure, relief, and vegetation) were collected by the author in 2025.
- Geographical Atlas of Azerbaijan (2018) and other literature sources.

Energy Calculations

- *Turbine:* Vestas V90-2.0MW
- *Hub height:* 90 m
- *Swept area:* 6,362 m² (depends on rotor diameter only)
- *Cut-in speed:* $V_{ci} = 4$ m/s
- *Rated speed:* $V_r = 12$ m/s
- *Cut-out speed:* $V_{co} = 25$ m/s
- *Average annual wind speed:* $\bar{V} = 5.46$ m/s
- *Standard deviation:* $\sigma = 2.1$ m/s

Weibull parameters (1):

$$k = \left(\frac{\sigma}{\bar{V}}\right)^{-1.086} \approx 2.82, \qquad c = \frac{\bar{V}}{1 + \Gamma\left(\frac{1}{k}\right)} \approx 6.13 \text{ m/s}, \tag{1}$$

where $\bar{V}$ is the mean wind speed, σ is the standard deviation, and Γ is the Gamma function. These parameters are used to determine the probability density of the wind speed according to the Weibull distribution. Equation (1) shows a standard methodology for initial parameter estimation. However, for the terrain-specific conditions of the Shorabad area, the refined parameters $k \approx 2.8$ and $c = 6.12$ m/s were used for all subsequent energy calculations. These refined parameters were adopted to better reflect terrain-specific wind conditions and to reduce bias associated with standard estimation methods in semi-arid, low-roughness landscapes.

Probability density functions according to the Weibull distribution (2):

$$\mathrm{f}(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \exp\left(-\left(\frac{V}{c}\right)^{k}\right), \tag{2}$$

where V is the wind speed, k and c are the Weibull parameters, f (V) is the probability density of the wind at speed V.

Annual Energy Production (AEP) (3):

$$\begin{aligned} E &= \int (V_{\mathrm{co}}, V_{\mathrm{co}})\ \mathrm{P}(V)\,\mathrm{f}(V)\,dV, \\ E &\approx \mathrm{P}_{\mathrm{rated}} \times \mathrm{CF} \times 8760 \text{ h/il} \\ &\approx 2\ \mathrm{MW} \times 0.20 \times 8760\ \mathrm{h} \approx 3.50\ \mathrm{GWh/il}, \end{aligned} \tag{3}$$

where $\mathrm{P}(V)$ is turbine power on the speed-power curve (kW); $\mathrm{f}(V)$ is the probability density function of wind speed on the Weibull distribution; V_{ci} and V_{co} are cut-in and cut-out speeds respectively; CF — capacity factor (effective turbine operating rate).

GIS Analysis

GIS analysis was performed in ArcGIS 10.8:

- the wind speed of the area was interpolated in a range of 200 m;
- distances to power lines, highways, and other infrastructure facilities were determined;
- land use/land cover analysis was performed;
- the optimal location points of the turbines were selected using a multi-criteria decision support system (MCDA).

Turbine density calculation

For optimal turbine placement, a conservative turbine spacing configuration (8D × 5D) has been applied in accordance with international standards, where D represents the rotor diameter (90 m). This approach minimizes aerodynamic shadowing between turbines and reduces energy losses. According to the calculations, each turbine requires an area of approximately 0.324 km² (720 m × 450 m). As a result, a maximum of 77 turbines can be placed on a potential area of 25 km². However, given practical constraints (relief, infrastructure, environmental factors), a conservative scenario of 54 turbines has been adopted for the project.

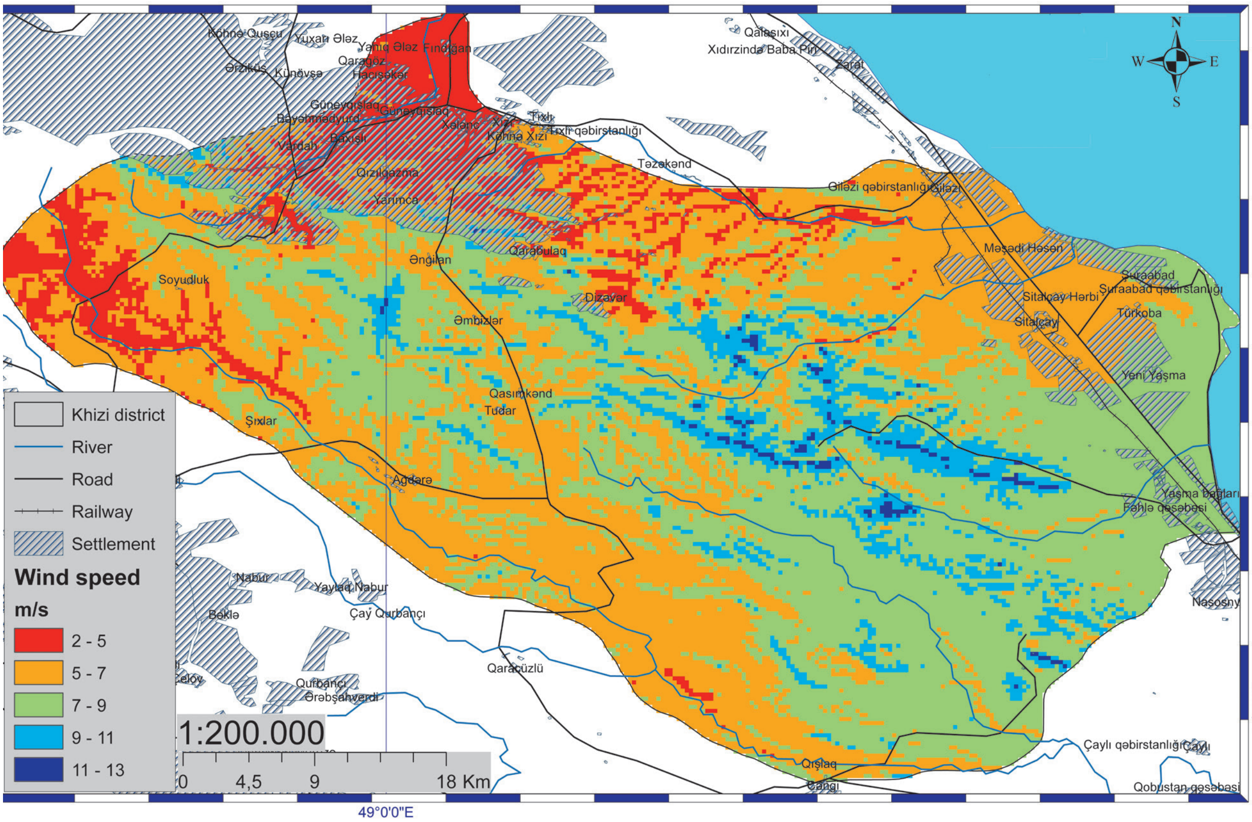

Fig. 2. Wind speed distribution in Khizi district (WS10M) (GWA, 2025)

This study applies an indirect, benchmark-based validation approach rather than classical in-situ validation, a methodological limitation inherent to data-scarce regions.

Statement of basic materials

Data comparison

Our analysis yielded an average annual wind speed of 5.46 m/s for the period 1981–2024. Data from NASA POWER (1981–2022) were deemed the most reliable long-term benchmark after comparison with GWA and local meteorological station data. First, the spatial distribution of wind resources in the Khizi district was analyzed using GWA v3 data ***(Table 1)***. These data were calculated at a spatial resolution of 250 m using the WRF mesoscale model and WAsP micro-relief corrections based on ERA5 reanalyses for 2008–2017. The results show that the average annual wind speed in areas such as Shorabad and Sitalchay is in the range of 7–11 m/s, and there are favorable conditions for the construction of WPPs ***(Fig. 2)***. Due to the limited resolution of NASA POWER and GWA data, some differences

Table 1. **Comparison of wind speed datasets for the Shorabad area**

Data Source	**Period**	**Spatial Resolution**	**Height (m)**	**Average Annual Wind Speed (m/s)**	**Notes**
NASA POWER	1981–2024	0.5° × 0.5° (~55 km)	10	5.46	Provides long-term, stable climate averages; coarse resolution may smooth local terrain effects.
Global Wind Atlas (GWA v3.3)	2008–2017	250 m	50	7–11	High-resolution model including WRF + WAsP micro-terrain corrections; can overestimate speeds in complex terrain.
Local Meteorological Station (Khizi)	2010–2023	Point measurement	10	5.5	Closest real measurements; supports NASA results for near-surface wind conditions.

Table 2. **3-year average wind speed (WS10M) for the period 1981–2024 at Shorabad *[17]***

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
1981/83	5.8	5.51	6.3	5.3	4.4	4.6	5.1	4.9	5.1	6.1	6	5.7	5.4
1984/86	6.1	5.5	5.6	5.1	4.5	4.7	5.1	5.8	5.8	6.1	5.7	5.8	5.5
1987/89	5.4	5.7	5.9	5.4	5.3	4.0	5.0	5.4	6.0	5.7	6.2	5.8	5.5
1990/92	5.3	6.1	5.3	5.2	5.0	4.1	4.7	5.1	6.0	6.1	6.0	5.4	5.4
1993/95	5.8	5.8	6.0	5.1	4.4	5.1	5	5.4	5.7	6.3	6.1	5.4	5.5
1996/98	5.1	6.4	5.9	5.2	4.4	4.6	5.0	5.3	6.4	6.2	5.6	5.8	5.5
1999/01	5.4	5.9	6.0	4.2	4.9	5.0	4.6	5.4	5.9	5.5	6.0	5.4	5.3
2002/04	5.2	5.4	5.3	5.1	4.0	5.2	4.4	4.8	5.3	6.0	5.6	6.2	5.2
2005/07	6.1	6.0	5.5	5.0	4.9	5.1	4.8	4.6	5.8	5.6	6.0	5.7	5.4
2008/10	5.9	5.8	5.5	4.8	4.1	4.4	4.9	4.5	5.5	6.0	5.8	5.9	5.3
2009/11	5.7	6.0	5.6	5.2	3.7	4.3	4.8	4.6	5.4	6.0	5.8	6.0	5.3
2012/14	5.4	6.0	6.4	4.9	4.0	4.8	4.7	5.1	5.6	5.9	5.4	6.2	5.4
2015/17	6.0	6.0	6.0	6.0	4.3	4.7	5.4	4.8	6.2	6.2	6.2	6.2	5.7
2018/20	5.7	5.6	6.0	5.6	5.0	4.6	5.3	5.2	5.2	5.8	5.8	5.8	5.5
2021/24	6.15	5.2	5.6	5.4	5.1	4.6	4.8	4.4	5.4	6.1	6.0	5.8	5.4

in micro-relief and local climatic conditions may occur.

Due to its coarse spatial resolution (0.5° × 0.5°), the NASA POWER dataset tends to smooth out microrelief and local aerodynamic variations, resulting in slightly lower wind-speed estimates. In contrast, GWA applies high-resolution (250 m) WRF-WAsP downscaling, which can yield higher values, especially in exposed or elevated terrain.

According to GWA data ***[19]***, the annual average wind speed is 2 m/s higher than the NASA POWER data at 50 relative altitudes. The 0.5° × 0.5° spatial resolution of the MERRA-2 datasets may not adequately capture micro-relief variations in small areas such as Shorabad. The average annual wind speed is also 5.5 m/s based on local meteorological observations (Geographical Atlas, 2018). The climatic characteristics of the area were further analyzed based on NASA POWER data ***[20]***.

According to NASA POWER data, the average WS10M (wind speed at 10 m height) at the site (Location: Latitude 40.8145, Longitude 49.478910) is 5.46 m/s, and the average WS50M (wind speed at 50 m height) at the site is approximately 6.8 m/s ***[17]***. Statistical analysis of WS data covering the period 1981–2024 allows us to trace the long-term dynamics of the wind regime in the region. The average monthly wind speed ranges from 3.5 to 7.0 m/s, indicating that the wind regime differs sharply across seasons. According to preliminary results, wind speed is higher in winter and autumn and lower in summer and spring. The annual average wind speed (ANN) ranged from 5.3 to 5.7 m/s, confirming the presence of wind energy potential in the region. Overall, the long-term trend shows a weak positive or neutral tendency.

WS50M data covering the period 1981–2024 allows us to study the long-term changes in the wind regime in the district. In general, the monthly average wind speed ranged from 5.0 to 9.5 m/s. The annual averages are mostly concentrated in the 6.5–7.2 m/s range. The seasonal distribution of WS50M average wind speeds is as follows:

- ***Winter (December-February)***: The highest speeds are recorded (for example, 9.46 m/s in March 2014, with similar increases in 2017 and 2016), strong baric contrasts and frontal activity intensify the regional wind regime during this period.
- ***Summer (June-August):*** Characterized by relatively weak winds (5.0-6.5 m/s). This is due to atmospheric stability and weak pressure gradients.
- ***Autumn (September-November):*** This is the phase when winds increase again, in October-November, the average speed was often above 7.0 m/s.
- ***Spring (March–May):*** It is a transitional period with very high (8.5-9.0 m/s) recorded in some years and average values in others.

The wind rose in ***Figure 3*** indicates that the predominant wind directions in the region are from the north and northeast, accounting for more than

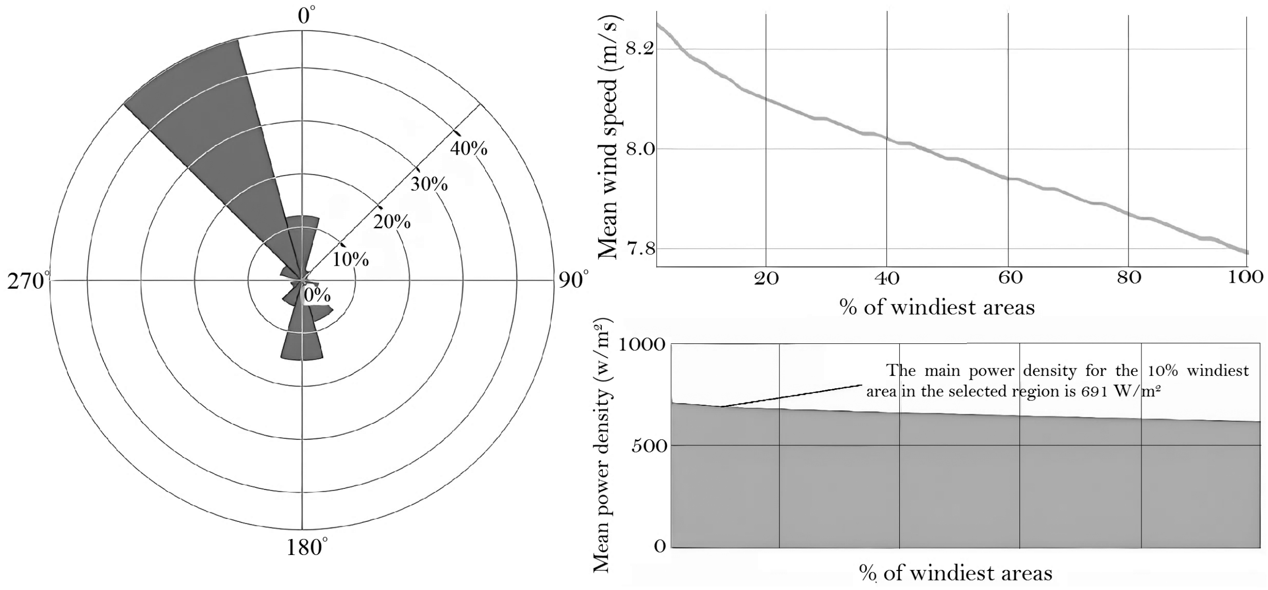

Fig. 3. Wind rose, average wind speed and power density distribution in windy areas

40% of the total. This factor indicates that it would be more efficient to place turbines in that direction. Calculations of wind speed distribution across the district confirm that the average speed in the most favorable 10% of the area is 8.2 m/s, and in weak-wind zones, it is about 7.8 m/s. Analysis of energy density also reveals important points. The average power density in the windiest 10% of the area reached approximately 691 W/m² ***[19]***. This figure is quite high compared to international criteria and creates a favorable opportunity for the use of large-capacity turbines. Although the indicators in other areas are relatively lower, they remain above 500 W/m² on average, which is economically acceptable.

A comparison of WS10M and WS50M shows more promising conditions for wind energy. Thus, the seasonal dynamics in both series are similar: winter-autumn is stronger, and summer-spring is weaker. WS50M values are consistently 1.0–1.5 m/s higher than WS10M, which can be explained by reduced surface friction at higher altitudes. Long-term trends are stable in both series, but WS50M has more "peak" years (2014, 2016, 2017) ***[17]***.

Energy production

Calculations based on the Weibull distribution ($k \approx 2.8$) show that under these conditions, the Capacity Factor varies in the range of approximately 0.20, and the annual energy production is approximately 2.9–3.50 GWh. This value is lower than the previous calculation based on the wind speed of 6.5 m/s (3.85 GWh) and gives a result more consistent with real conditions. In Figure 4, the blue curve shows the turbine power output (in kW) at different wind speeds, while the red curve shows the probability density of wind speeds observed in the Shorabad region based on the Weibull distribution. The graph shows that the turbine's maximum power output (2.0 MW) occurs at a wind speed of 12 m/s. Based on the Weibull parameters calculated for Shorabad ($k \approx 2.8$, $c = 6.12$ m/s), the annual energy production of the turbine is predicted to be in the range of 2.9–3.50 GWh.

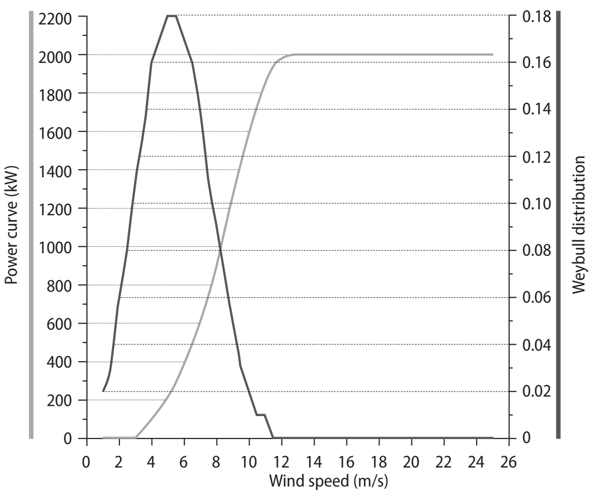

Fig. 4. Power curve and estimated energy production based on the Weibull distribution of the selected Vestas V90-2.0 MW turbine *[7]*

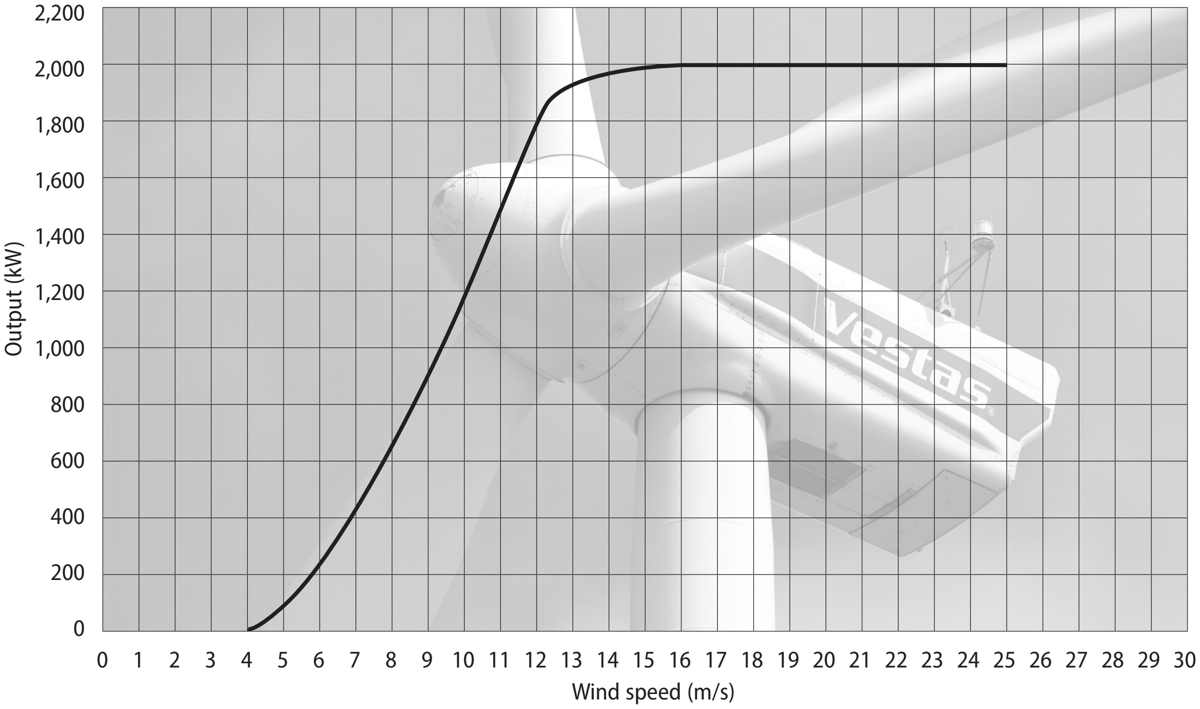

Fig. 5. Annual energy production graph for Vestas V90-2.0 MW ***[21]***

The technical data of the manufacturer of the selected turbine model—Vestas V90-2.0 MW—also supports these results. The turbine starts operating at a speed of 4 m/s, reaches its rated power at a speed of 12 m/s, and stops operating at a speed of 25 m/s ***(Fig. 5)***. These parameters are optimal compared to the average wind speed of Shorabad and indicate that the turbine provides stable energy production even when operating in sub-rated mode ***[21]***.

Analysis of the technical data shows that the swept area (6.362 m²) and hub height (80–125 m) of the V90-2.0 MW turbine are compatible with the terrain of the Shorabad area. This allows for both increased aerodynamic efficiency and simplified integration into the power grid. In addition, technological advantages such as Load and Power Modes, the CoolerTop® cooling system, and noise level control (Noise Modes) specified in the Vestas catalog make the turbine more compatible with the social and environmental environment ***[22]***. For example, reducing noise levels in areas close to residential areas is considered an important factor in semi-rural settlements such as Shorabad. This turbine, optimized for sites with average wind speeds of 6-8 m/s, has a nominal capacity of 2.0 MW ***(Table 3)***. The swept area (6.362 m²) and hub height (80–125 m) are highly compatible with the terrain and wind conditions of the Shorabad area ***[21]***.

Table 3. **Main technical parameters of the Vestas V90-2.0 MW turbine**

Parameter	Value (V90-2.0 MW)
Rated power	2.0 MW
Rotor diameter	90 m
Swept area	6.362 m^2
Cut-in speed	4 m/s
Rated wind speed	12 m/s
Cut-out speed	25 m/s
Hub height	80–125 m
Nominal rotation speed	14.5 rpm
Operating temperature	–20–40 °C
Sound level (Mode 0)	104 dB(A)
Wind class	IEC IIIA

The manufacturer provides a graph of AEP. Here, the gross AEP for an average speed of 5.46 m/s is estimated to be approximately 4.1–4.3 GWh, while the net AEP taking into account typical losses varies in the range of 2.9–3.50 GWh per turbine. For a Vestas V90-2.0 MW turbine, the gross AEP in the Shorabad area is 4.1–4.3 GWh, and the net AEP is 2.9–3.50 GWh due to losses. The losses are divided into categories: aerodynamic (8–12%,

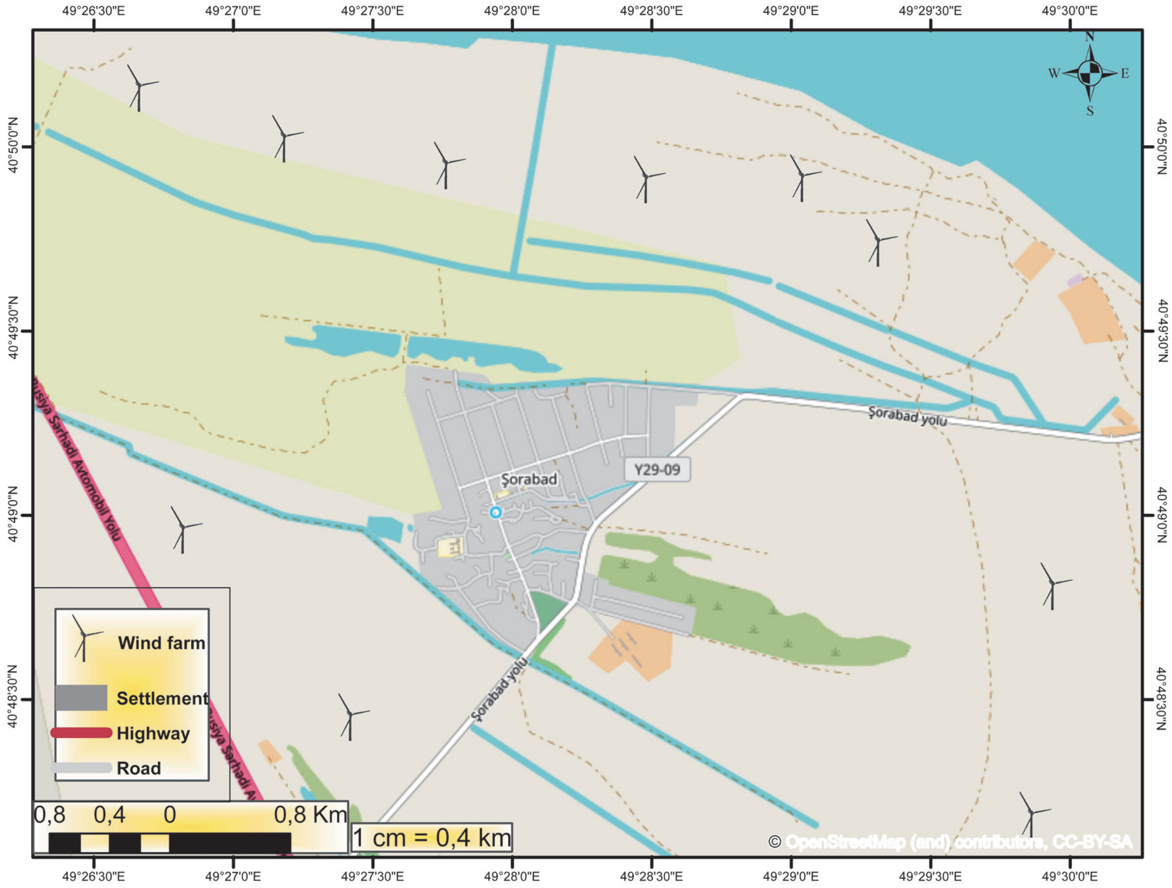

Fig. 6. Potential areas for the construction of wind turbines in Shorabad settlement **(based on GWA data)**

0.33–0.52 GWh), network (5–7%, 0.21–0.30 GWh), and technical outages (5–8%, 0.21–0.34 GWh). The total losses are 18–27% of the gross AEP, which is in line with international standards (typical losses: 15–25%).

In addition, reliability indicators are particularly important. The availability of the Vestas 2 MW platform, which exceeds 98%, and the 24/7 remote control system (SCADA) reduce future operating costs and minimize the risk of accidents.

Annual energy production is calculated using the 3rd equation with a capacity factor of 0.20 corresponding to the net CF range for 5.46 m/s. Based on the power generation curve of the Vestas V90-2.0 MW turbine, the gross AEP at a wind speed of 5.46 m/s is estimated as ≈ 4.1–4.3 GWh *[21]*. Taking into account typical losses (grid/electricity ≈ 5–7%, aerodynamic/parking effect ≈ 8–12%, and planned and sudden shutdown ≈ 5–8%), the net AEP will be ≈ 2.9–3.50 GWh. Accordingly, the net capacity factor is estimated to be ≈ 0.20. This value realistically represents the energy production potential of V90-2.0 MW turbines in the Shorabad wind conditions. The low CF is due to the relatively low wind speed of Shorabad (optimal: 6–8 m/s), seasonal variability (summer: 5.0–6.5 m/s, winter: 7.0–9.5 m/s), and losses (aerodynamic: 8–12%, network: 5–7%, technical: 5–8%).

A spacing of 8D × 5D (D = 90 m) was used in accordance with international wind farm layout standards. Under ideal, unconstrained conditions, this spacing allows for a theoretical maximum of 77 Vestas V90-2.0 MW turbines within the 25 km^2 study area. However, theoretical capacity does not reflect practical constraints. After excluding non-developable zones such as infrastructure corridors (roads, transmission lines), relief irregularities, ecological buffer zones, and areas where wake losses would significantly exceed acceptable thresholds, the realistic installable capacity is reduced to approximately 54 turbines. This "conservative scenario" reflects standard industry practice and provides a technically valid estimate for energy production calculations *(Fig. 6)*. The total installed capacity for this project reaches 108 MW. Since the annual production capacity of a turbine ranges from 2.9 to 3.50 GWh, the theoretical energy production for the entire park is estimated at 156.6 to 189.0 GWh/year. However, in real conditions, due to aerodynamic shading, network losses, technical outages, and other factors, this volume is expected to decrease by approximately 10–15% to 133–170 GWh/year.

The satellite images and maps presented in Figure 6 clearly show the spatial distribution of potential sites. The identification of these optimal sites considered not only wind resource availability but also key geographical and infrastructural factors. As illustrated, the study area is characterized by predominantly flat terrain and sparse vegetation. This topography minimizes aerodynamic obstacles, enhances turbine efficiency, and simplifies transportation and installation. Furthermore, the selected areas exhibit low agricultural activity and are close to existing infrastructure, such as roads and power transmission lines. This significantly reduces construction costs, facilitates grid integration, and creates logistical advantages during both construction and operation phases. Collectively, these characteristics enhance the project's overall feasibility and provide a strong basis for optimal wind farm siting, ensuring not only high energy yield but also socio-technical compatibility ***[5]***.

Discussion

Interpretation of wind regime and energy yield

From an interpretative perspective, the obtained wind regime characteristics of Shorabad can be explained by both atmospheric circulation patterns and local surface conditions. This limitation should be taken into account when analyzing the results. The consistently higher WS50M values compared to WS10M reflect the decreasing influence of surface roughness and aerodynamic barriers with increasing altitude. This vertical wind profile explains the observed capacity factor of approximately 0.20, which is typical for regions with moderate average wind speeds and pronounced seasonal variability. Winter and autumn months exhibit stronger wind conditions, whereas summer periods are characterized by weaker atmospheric dynamics, directly influencing annual energy yield.

The average annual wind speed of 5.46 m/s indicates that the area offers suitable conditions for the construction of WPPs from a technical and economic perspective. These results are consistent with local and international databases, especially those provided by GWA, and confirm once again that the Caspian littoral regions of Azerbaijan are high-potential wind zones ***[4]***.

Comparison with regional and international studies

When compared with the experience of neighboring countries, the capacity factor obtained for Shorabad (0.20) is on par with the indicators CF = 0.17–0.20 in Georgia and 0.16–0.19 in eastern Turkey (same turbines —Vestas V90). Higher hub heights (100–125 m) or more efficient turbines can increase the CF. In addition, according to international reports, LCOE values for wind projects of similar capacity range from 40 to 60 USD/MWh. which is economically justified compared to the current electricity cost in Azerbaijan (approximately 50–55 USD/MWh) ***[6]***.

Limitations and uncertainties

Despite the inherent uncertainties associated with wind resource estimation in data-scarce regions, the projected annual energy production of approximately 135–160 GWh suggests a potential economic value of 6–9 million USD, which should be interpreted as an indicative estimate rather than a definitive outcome. This fact is an important result for Azerbaijan, as the country aims to become a competitive renewable energy center in the district. On the other hand, the flat terrain of Shorabad, the sparse vegetation cover, and the proximity to power transmission lines are important factors that minimize the project's construction and operating costs. This makes the area more attractive for both local and foreign investors.

Differences observed between global datasets further underline the importance of cautious interpretation of wind resource assessments. The close agreement between NASA POWER data and local meteorological station measurements suggests that long-term reanalysis products realistically represent near-surface wind conditions in Shorabad. In contrast, the higher wind speeds reported by the Global Wind Atlas are largely associated with high-resolution WRF–WAsP downscaling, which may overestimate wind potential in small and topographically homogeneous areas. Therefore, these discrepancies should be considered an inherent uncertainty rather than a contradiction of results.

Socio-economic and environmental impacts

In addition to technical and economic feasibility, the Shorabad wind farm project's social and environmental implications are significant. The Shorabad wind farm project is expected to positively impact the local economy by creating approximately 50–100 new jobs during construction and operations. The development of infrastructure improves local energy security and delivers tangible socio-economic benefits. Environmentally, the project could reduce 60–70 thousand tons of CO_2 emissions per year. However, potential impacts on bird migration routes and local ecosystems should be considered. Therefore, measures such as an environmental impact assessment (EIA) and bird monitoring are recommended.

Chief among them is the coarse spatial resolution of global databases such as NASA Power and GWA, which may inadequately capture micro-scale local variations. Therefore, it is necessary to confirm the results with high-precision local measurements and conduct long-term monitoring. Since we did not conduct local field measurements in the region, the results need to be refined. In addition, selecting only one district as a sample imposes limitations on the generalizability of results on a national scale.

In semi-arid regions like Shorabad, the construction and operation of wind farms primarily affect the morphodynamic structure of the natural landscape, soil quality and properties, plant growth, and surface water movement. When soils are poor and there are few plants, these effects can be even stronger, and erosion can increase. Nevertheless, key native plant species such as Artemisia, Salsola tragus, and Poa Vulpina are well-adapted and usually regenerate naturally within one or two growing seasons.

The main environmental risks associated with operating a wind farm include noise (up to 45 dB), vibration, flickering shadows, and potential impacts on birds and insects. Studies have shown that the risk of bird collisions is very low (less than 0.01 per windmill per year) because the Shorabad is not on the main migratory route for birds. Proper spacing of turbines avoids airflow problems and reduces both energy loss and landscape changes. Overall, the Shorabad wind power project is environmentally suitable due to its relatively simple topography, sparse vegetation, and low levels of anthropogenic pressure. However, potential long-term risks remain, including soil salinization and landscape fragmentation. The diversity of plant communities and soil microbiota under solar and wind farms can change, increase, or decrease depending on local conditions ***[23]***. Appropriate landscape planning and targeted restoration measures can enhance soil stability and ecosystem resilience.

Conclusion

This study provided a comprehensive analysis and assessment of the wind energy potential of the Shorabad settlement of the Khizi district of Azerbaijan from both technical and economic perspectives. It determined the region's role in the RES market. Analysis based on long-term meteorological data, GWA, and local measurements confirms that the average annual wind speed in the Shorabad area is 5.46 m/s, which is technically viable for the efficient operation of wind turbines. Statistical modeling based on the Weibull distribution and spatial analysis supported by GIS technologies indicate that the area, with its flat terrain, sparse vegetation cover, and proximity to existing energy infrastructure, creates ideal conditions for the construction of new WPPs. The analysis confirms that the Vestas V90-2.0 MW turbines are well suited to the local wind regime, enabling the projected wind farm to produce 156.6–189.0 GWh annually under a conservative deployment scenario. While this represents a relatively modest share of Azerbaijan's overall electricity balance, it establishes an important practical and investment foundation for harnessing wind energy. These findings not only confirm the region's significant capacity to enhance energy security and reduce carbon emissions but also highlight its role as a tangible investment opportunity within Azerbaijan's renewable energy development strategy.

In addition to the technical results, the economic comparison also shows that the potential LCOE of the Shorabad wind farm is comparable to international indicators and competitive with current electricity costs in Azerbaijan. For future studies, the application of hybrid (wind-solar) energy systems, the study of higher hub heights, and a more in-depth analysis of socio-economic impacts are recommended. Consequently, the Shorabad settlement should be assessed as a priority investment area in Azerbaijan's "green energy" transition strategy. Overall, the analyses conducted show that the Shorabad wind farm has real and competitive project potential from both technical and economic perspectives. These results are of strategic importance for strengthening Azerbaijan's energy security and achieving its national renewable energy targets.

The primary limitation of this study is the absence of long-term in situ wind measurements at hub height, which constrains classical model validation. Nevertheless, the adopted hybrid geospatial and indirect benchmark-based validation framework provides a scientifically robust and transferable methodology for preliminary planning, site screening, and investment decision-making in data-scarce semi-arid coastal regions, including the Caspian basin.

Novelty

The current study is the first site-specific GIS-integrated wind assessment for Shorabad. From a scientific point of view, this work contributes to the existing literature in three directions:

1. The geographical focus was clarified by conducting a feasibility study on a specific location, such as Shorabad.
2. Wind resources were mapped using a GIS-based approach and visual materials (photographs, wind rose graphs).
3. Potential integration opportunities with existing wind farms were evaluated on a scientific basis.

From a practical perspective, the research results provide a concrete database for designing new WPPs and for informing investment decisions. Proximity to existing energy infrastructure allows for reduced construction and operational costs for the project. In addition, the incentives for reducing annual electricity demand and CO_2 emissions demonstrate the environmental advantages of such projects.

Acknowledgement

The authors would like to thank the Department of Climate Science of the Ministry of Ecology and Natural Resources and the Renewable Energy Agency of the Ministry of Energy for providing the relevant data sets.

References

1. Ritchie, H., Roser, M., & Rosado, P. (2025). Renewable energy. Our World in Data. URL: https://ourworldindata.org/renewable-energy.

2. Mustafayev, F., & Huseynov, R. (2024). Assessment of Azerbaijan's wind energy potential using ERA5 reanalysis data. *Renewable Energy.* 1(1). 1–15. DOI: https://doi.org/10.1000/renewable.2024.12345.

3. International Energy Agency (IEA). (2025). Wind energy. URL: https://www.iea.org/energy-system/renewables/wind.

4. Abbasov, R. K., & Aliyev, Z. S. (2023). Assessment of Wind Energy Potential in the Caspian Coastal Zone of Azerbaijan. *Renewable Energy,* 45(2), 123–135. DOI: https://doi.org/10.1016/j.renene.2023.05.012.

5. Alphan, H. (2021). Modelling potential visibility of wind turbines: A geospatial approach for planning and impact mitigation. *Renewable and Sustainable Energy Reviews,* 152, 111675.

6. *Energy of Azerbaijan* (2024). State Statistical Committee of the Republic of Azerbaijan — Baku: Statistical Bulletin. 164 p. [In Azerbaijanian].

7. AREA. 2024. Renewable energy plants. Agency for Alternative and Renewable Energy Sources. Retrieved July 2025. URL: https://area.gov.az/

8. Ministry of Energy of the Republic of Azerbaijan. (2016). Strategic Roadmap for the Development of Heavy Industry and Machinery in the Republic of Azerbaijan. URL: https://minenergy.gov.az/uploads/Proqramlar/syx/3.pdf.

9. Mustafayev, F., Kulawczuk, P., & Orobello, C. (2022). Renewable Energy Status in Azerbaijan: Solar and Wind Potentials for Future Development. *Energies*. 15(2). 401. DOI: https://doi.org/10.3390/en15020401.

10. Peri, E., & Tal, A. (2020). A sustainable way forward for wind power: Assessing turbines' environmental impacts using a holistic GIS analysis. *Applied Energy,* 279, 115829. DOI: https://doi.org/10.1016/j.apenergy.2020.115829.

11. Kassem, Y., Gökçekuş, H., & Abdalla, M. H. A. (2025). Wind energy resource assessment based on the use of multiple satellite data for sustainable energy production in Sudan. *Environment, Development and Sustainability,* 27(3), 7779–7815. DOI: https://doi.org/10.1007/s10668-023-04221-w.

12. Gugul. G. N., Demirhan B. G., & Baker. D. K. (2023). Techno-Economic Analysis for Wind Energy Projects: A Comparative Study with Three Wind Turbines Based on Real-Site Data. *Turkish Journal of Electrical Power and Energy Systems.* 3(3). 115–124. DOI: https://doi.org/10.5152/tepes.2023.23019.

13. Usmanov. I. Sh. Kurbanbekov. Sh. R. & Bekbaev. S. M. (2022). Assessment of the prospects for the use of wind power in the Turkestan region. *News of the Khoja Akhmet Yassawi Kazakh-Turkish International University. Mathematics. Physics. Computer Science Series.* 1(20). 1–10.

14. Gardashov, E., & Gardashov, R. (2024). On the derivation of an analytical expression for the wind power probability distribution function and the capacity factor of the turbine. *International Journal of Sustainable Energy.* 43(1). 2390447. DOI: https://doi.org/10.1080/14786451.2024.2390447.

15. Zahid, F., Tahir, A., Khan, H. U., & Naeem, M. A. (2021). Wind farms selection using geospatial technologies and energy generation capacity in Gwadar. *Energy Reports,* 7, 5857–5870. DOI: https://10.1016/j.egyr.2021.08.084.

16. *Geographical Atlas of the Republic of Azerbaijan.* (2018). Baku: Baku Cartography Factory. (Scientific editor: Mammadov R. M.). [In Azerbaijanian].

17. *NASA (National Aeronautics and Space Administration)*. (2025). POWER Data Access Viewer (MERRA-2). URL: https://power.larc.nasa.gov/data-access-viewer/.

18. Ismayilov, M. A., Aliyev, A. M., & Abbasov, S. H. (2025). Assessment of onshore wind energy potential in Azerbaijan using Weibull distribution analysis. *SOCAR Proceedings*. No.1 122–129.

19. *Global Wind Atlas.* (2025). World Bank Group & DTU Wind Energy. GWA (v3.3). Retrieved August 2025. URL: https://globalwindatlas.info/en/area/Azerbaijan/Khizy

20. Effat, H. A., & El-Zeiny, A. M. (2022). Geospatial modelling for selection of optimum sites for hybrid solar-wind energy in Assiut Governorate, Egypt. *The Egyptian Journal of Remote Sensing and Space Science,* 25(2), 627–637. DOI: https://doi.org/10.1016/j.ejrs.2022.03.005.

21. Vestas Wind Systems A/S. 2011. V90-1.8/2.0 MW product brochure. Randers. Denmark: Vestas Wind Systems A/S. Retrieved August. 2025. URL: https://www.ledsjovind.se/tolvmanstegen/Vestas%20V90-2MW.pdf.

22. Zehtabiyan-Rezaie, N. Iosifidis, A. & Abkar. M. (2022). Data-driven assessment of global wind energy resources. arXiv preprint arXiv:2203.13289. URL: https://doi.org/10.48550/arXiv.2203.13289.

23. Asadi, M. & Pourhossein, K., (2021). Neural network-based modelling of wind/solar farm siting: a case study of East-Azerbaijan. *International Journal of Sustainable Energy,* 40(7), pp. 616-637. DOI: https://doi.org/10.1080/14786451.2020.1833881.

The article was received by the editorial office on 09/10/2025, accepted for publication on 03/05/2026.

Імамвердієв Н. С. 0000-0002-5573-0209

Інститут географії Міністерства науки і освіти, Баку, Азербайджан

Оцінювання потенціалу вітрової енергетики в Азербайджані (на прикладі поселення Шорабаді, Хизинський район)

УДК 621.548:551.55:27.19(479.24)(045)

Це дослідження присвячене комплексному оцінюванню потенціалу вітрової енергетики Азербайджану на репрезентативному прикладі селища Шорабад, що в Хизинському районі. Підкреслюється стратегічна важливість вітрової енергетики в контексті глобального енергетичного переходу та змін клімату, а також розглядаються природні й географічні переваги території дослідження разом із наявними інфраструктурними можливостями. Аналіз довгострокових наборів даних з NASA POWER (1981–2024 pp.), Global Wind Atlas і місцевих метеорологічних станцій виявив середню річну швидкість вітру на рівні 5,46 м/с. Вітровий режим території дослідження було додатково вивчено за допомогою статистичного моделювання із застосуванням розподілу Вейбулла. Просторову варіацію швидкості вітру, особливості сучасного землекористування та близькість до електромережі було оцінено за допомогою ГІС-аналізу. Моделювання вироблення енергії для турбіни Vestas V90-2.0 MW демонструє річний потенціал генерації на рівні 2,9–3,5 ГВт · год, що відповідає коефіцієнту використання встановленої потужності близько 0,2 за наявних вітрових умов. На основі консервативного сценарію розміщення (площа 25 км^2, 54 турбіни із загальною потужністю 108 МВт) річне виробництво електроенергії було оцінено на рівні 156,6–189,0 ГВт · год/рік, що становить приблизно 0,55–0,67 % річного виробництва електроенергії Азербайджану. Отримані результати свідчать про те, що місцевість довкола поселення Шорабад має сприятливі характеристики: рівнинний рельєф, розріджений рослинний покрив і близькість до наявної інфраструктури, що в сукупності робить цю територію придатною для розвитку проєкту вітрової електростанції.

Ключові слова: *вітрова енергетика; поселення Шорабад; Хізинський район; ГІС-аналіз; розподіл Вейбулла; відновлювана енергія.*

Цитування:
Імамвердієв Н. С. (2026). Оцінювання потенціалу вітрової енергетики в Азербайджані (на прикладі поселення Шорабаді, Хизинський район). *Український географічний журнал,* 1, 28–40. DOI: https://doi.org/10.15407/ugz2026.01.028