

Evaluation of Wind Energy Potential of Uzbekistan. Part I: Gross Potential Assessment

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Abstract

This study focuses on analyzing wind speeds in various regions of the Republic of Uzbekistan, aiming to comprehensively assess wind potential at a height of 10 meters above the ground level. The meteorological data from 77 ground-based stations nationwide, gathered between 2000 and 2022 at three-hour intervals, was utilized in the study. Wind power densities were calculated to assess wind potential, and average wind speeds were determined on a monthly and annual basis. Based on the data analysis from 13 regions, locations with high wind energy potential were identified, and wind power densities, as well as the Weibull distribution parameters for wind speeds, were computed. Additionally, maps of average annual wind speed and power distribution, along with wind rose diagrams, were created. These revealed predominant wind directions in different regions, which is critical for the optimal placement of wind turbines. The highest average wind speeds were recorded in the Republic of Karakalpakstan, Navoi, and the Bukhara regions, Dehkanabad district of Kashkadarya region, and Bekabad city in the Tashkent region. The highest wind potential was identified in the Jaslyk district of the Republic of Karakalpakstan (202.01 W/m²), Navoi city (94.05 W/m²), and Dehkanabad district of the Kashkadarya region (85.33 W/m²). These results indicate that the regions with high wind potential have significant opportunities for the efficient use of wind energy. To confirm the accuracy and reliability of the obtained data, a comparison with previous studies on wind potential in Uzbekistan was carried out, which confirmed a high degree of consistency. The obtained data can be used for optimal planning and strategic placement of wind energy installations, which will contribute to developing “green energy” further and enhance the Uzbekistan’s energy security.

Keywords: Wind potential, Weibull parameters, Wind rose analysis, Wind speed.

1. Introduction

In the recent years, the development of sustainable energy systems has become significantly important on a global scale. In this regard, countries worldwide are actively exploring and developing alternative energy pathways, striving to create more reliable and environmentally friendly energy systems that are resilient to climate change overall.

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environmentally-friendly energy systems that are resilient to climate change overall.

It is well-known that the share of “green energy”, based on Renewable Energy Sources (RESs) has reached almost 30% of the global energy system, with some European countries already exceeding 80-90% [1]. This indicates that various countries are aiming to further increase the share of RESs by 2030 and beyond.

Among all, wind energy is one of the fastest-growing segments of energy technologies worldwide. It is considered a potential RE capable of significantly meeting modern societal needs, reducing dependence on the coal and diesel fuel, and lowering greenhouse gas emissions.

Wind energy provides various benefits such as low operating expenses, quick deployment, and the ability to scale projects from small rural setups to large offshore wind farms [2, 3].

According to the recent studies conducted by the IEA in 2023, the wind energy potential could meet up to 25% of global electricity demand by 2040. In Europe, wind energy remains a key element in the strategy to achieve carbon neutrality by 2050, with the share of wind energy in total electricity production reaching 16% in 2023 [4].

In the developed countries such as China and India, wind energy continues to play a crucial role in enhancing energy security and reducing dependence on fossil fuels. According to the Global Wind Energy Council (GWEC), a new record was set in 2023 for the installation of a new wind power capacities—over 117 GW, which is 50% more than the previous year [4, 5].

Additionally, the GWEC report for 2024 shows a significant progress in the wind energy development in Africa and Latin America, where more than 10 GW of new capacity was brought online. This reflects a growing interest in renewable ESs in the developing regions. Onshore wind energy is expected to grow in other parts of the world, particularly in Japan, and emerging markets in Southeast and Central Asia. According to the GWEC MI, the Philippines, Kazakhstan, and Uzbekistan are expected to become key players in this process, accounting for 17% of new capacity to be installed in the region between 2024 and 2028. With active investments and favorable policy conditions, these countries have the potential to significantly expand their energy capacities, highlighting their potential to become leaders in wind energy in Asia [5].

The Republic of Uzbekistan is actively developing renewable RESs as part of its national strategies, by PR No. DP-60 dated January 8, 2022; the 2022–2026 strategy aims to reduce natural gas consumption by 3 billion cubic meters by increasing the share of RES to 25%. To achieve this, the plan includes installing solar and wind power plants with a total capacity of 8 GW, along with supporting citizens and entrepreneurs, who utilize RES [6]. According to PE No., PR-57 dated February 16, 2023, wind power plants with a total capacity of 1.6 GW will be constructed in Uzbekistan.

At the beginning of 2024, one of the WPPs in the Tomdi district of Uzbekistan was commissioned, and has already been connected to the national power grid [7]. This year, the country is actively developing wind energy, attracting significant

foreign direct investment to implement key projects. Saudi Arabia's ACWA power is constructing a 500 MW WPP in the Kungrad district of Karakalpakstan and a 300 MW WPP in the Gijduvan district of the Bukhara region, with a total investment of \$1.085 billion. In the Nurata district of the Navoi region, a 300 MW WPP is planned with the participation of China Gezhouba Group overseas investment Co. LTD, alongside 250 MW WPP projects and transmission lines in the Samarkand and Jizzakh regions, implemented by UE.

Moreover, the ACWA power is expanding its involvement in Uzbekistan's renewable energy sector by signing investment agreements to sell electricity to the "NE grid of Uzbekistan" for 25 years. This solidifies its status as the largest investor and strategic partner in the development of the country's green energy, with projects worth a total of \$7.5 billion including the world's largest WPP and a 1.5 GW combined cycle gas turbine power plant. The European Bank for Reconstruction and Development (EBRD) also supports the sector's growth by providing the ACWA Power Wind Karatau with a \$19.3 million loan for the construction and operation of a 100 MW WPP in Karakalpakstan. This will help increase the RES to 2,700 MW, and reduce CO₂ emissions by 178,000 tons annually.

At the planning stage, it is crucial to evaluate wind resource potential for the successful development and economic efficiency of the WPP projects. Determining wind characteristics and accurately evaluating its potential directly influence the technical and economic feasibility of projects, electricity production costs, and overall economic benefits [8, 9]. An essential aspect is not only the initial assessment but also the long-term monitoring of wind conditions. Continuous monitoring, regular data updates, and analysis of multi-year measurements collected by the SCADA systems contribute to maintaining the reliability of WPP operations and the timely detection of potential issues. Long-term forecasts of wind speed and direction play a key role in optimizing maintenance plans, reducing costs, and accounting for local climatic features that may significantly impact the future efficiency of the installations [10, 11].

In the recent decades, Earth's climate has undergone significant changes that have affected many natural processes including wind patterns and their characteristics. The wind energy potential, previously calculated based on historical data, may now differ significantly from current values due to climate change caused by global

warming. Uzbekistan has changes in wind speed and direction, potentially impacting forecast accuracy and wind energy efficiency.

Research shows that changes in climate conditions such as rising temperatures and variations in precipitation directly influence wind regimes. For example, a study [12] demonstrated that changes in global temperature patterns lead to the redistribution of air masses, which, in turn, alters wind patterns. These changes can either strengthen or weaken wind flows in different regions, impacting the availability of wind resources for energy generation.

Studies indicate that shifts in atmospheric circulation due to climate change will have a substantial impact on the wind energy potential in the future [14], while other works emphasize the importance of considering climate change when planning future wind farms [15]. Therefore, changes in the climate conditions could significantly affect the availability of wind resources, and consequently, the efficiency of wind energy production in the future.

For Uzbekistan, which has a significant potential for wind energy development, this is particularly important. Research-based on dynamic downscaling and adjustments to global climate models shows that the average wind speed and direction in Central Asia can vary significantly depend on the season and year, necessitating a revision of wind potential assessment methods [16].

Thus considering contemporary climate changes is crucial for accurate wind potential assessment and efficient use of wind energy resources in Uzbekistan. Updating data will enable more precise identification of the areas with the highest wind energy potential, a key factor for strategic planning and the development of green energy in the country.

2. Analysis of existing scientific research on wind energy potential in Uzbekistan

Preliminary Significant Studies on the assessment of wind energy potential in Uzbekistan were conducted by R.A. Zokhidov and his team, which included U.A. Tajiev, E.I. Kiseleva, M.U. Tajiev, and other researchers. Their work covered various aspects of studying and utilizing wind energy. A brief analysis of their research is provided below. The studies included calculations of the annual electricity production rates by horizontal wind turbines of different capacities (10, 30, 60, 100, 250, and 500 kW) using the wind speed data obtained from 88 meteorological stations across Uzbekistan [17]. Additionally, an assessment of

WERs at different heights was conducted in the Navoi and Karakalpakstan regions, using data from the Tamdy and Jaslyk meteorological stations. The data helped determine the technical and economic characteristics of wind turbines of various capacities based on the influence of near-ground atmospheric layers [18].

Additionally, the scientists conducted a quantitative analysis of the annual wind speed variations from 1983 to 1993 using the data from international databases to improve the efficiency of the Andijan hydropower plant by integrating wind energy installations [19]. An analysis of intra-annual wind speed variability, based on aerospace observation data, was performed in the Republic of Karakalpakstan, and other regions of Uzbekistan. The study identified provinces with similar annual wind speed variability and intensity of changes: the Republic of Karakalpakstan, Andijan, Namangan, Fergana, and Tashkent regions, as well as Bukhara, Samarkand, Navoi, Khorezm, Jizzakh, Kashkadarya, Surkhandarya, and the Syrdarya regions [20].

Under the guidance of academician RA, Zokhidov and his team, research was also conducted to study the origins of wind currents, their characteristics, the geographical parameters of the region, and the impact of synoptic processes in the atmosphere on wind flows. This involved analyzing the average wind speed and relative wind power at heights ranging from 10 to 80 meters using international databases that covered all regions of Uzbekistan [21]. According to the results of a study conducted for the Bukhara region, wind speed and wind power density at different heights (10 m, 40 m, and 80 m) were determined. At a height of 10 meters; the average annual wind speed ranged from 3.15 m/s to 3.57 m/s, corresponding to wind power density values between 19 and 28 W/m².

In 2015, studies were conducted in collaboration with the German companies “Intec-Copa” and “GEONET,” as well as JSC “Uzbekenergo”, to assess the wind energy potential across Uzbekistan, and to create a wind energy map [22]. The study employed 3D modeling techniques to develop a map of wind flows at an 80-meter height. Based on this map, the most promising regions for the development of wind farms were identified, with the territories of Karakalpakstan and the Navoi region being highlighted. In these regions, meteorological masts were installed to collect wind speed and direction data over two years. This data served as the basis for further analysis and the development of feasibility studies for the construction of wind energy installations.

The study revealed that in some areas of Uzbekistan, wind speeds at 80 meters exceed 6 m/s, indicating a high potential for wind energy utilization in these locations.

In their studies [17-22], the group of scientists utilized data from the NASA Surface Meteorology and Solar Energy (SSE) database (which provides wind data for the period from 1983 to 2005) [23] as well as reference materials (dated before 1983) that contain multi-year values of average monthly wind speed. This data enabled a detailed analysis of wind speed variations at different heights, the assessment of average annual values, and based on this, the determination of annual wind power density and wind energy potential across various regions of Uzbekistan. This approach contributed to a more accurate calculation of vertical wind speed profiles and wind power flow.

Bahrami et al. (2019) assessed the wind energy potential in Uzbekistan using hourly wind speed data collected at 17 different sites at a height of 10 meters during a Typical Meteorological Year (TMY). The collected data was fitted to the widely used two-parameter Weibull distribution function. The technical viability of wind installations was evaluated based on wind power density, annual energy density, and capacity factor. The economic assessment included calculating the Levelized Cost Of Electricity (LCOE). Additionally, a comparative analysis of 15 wind turbine models was conducted. The study found that the average annual wind speed at the evaluated sites ranged from 0.61 to 3.98 m/s, wind power density ranged from 1.74 to 88.55 W/m², and annual energy density ranged from 15.27 to 775.72 kWh/m² at a height of 10 meters. For example, the average annual wind speed at the Bukhara meteorological station was 3.67 m/s, with a wind power density of 74.82 W/m². The authors concluded that the most promising regions for wind energy development in Uzbekistan are the sites near Nukus, Kungrad, Ak-Baytal, and Bukhara [24].

In 2019-2020, Sadullaev et al. conducted a statistical analysis of wind potential in the Bukhara region of Uzbekistan using wind speed and direction data collected at a height of 10 meters in 2018 [25] (and in 2019 [26, 27]). The wind speed data was obtained from the meteorological station at Bukhara international airport, with measurements taken every 30 minutes. The authors used this data to calculate daily average wind speeds, which were then analyzed. Specifically, they calculated the average wind speed, its standard deviation, wind power density, and wind energy density. This data

enabled a more detailed analysis. Using the two-parameter Weibull distribution function, the researchers, similar to the previous studies assessed the average annual wind speed, wind power density, and wind energy density at different heights. According to the analysis, the average annual wind speed in the Bukhara region was 3.404 m/s at a height of 10 meters, and the average annual wind power density was 40.98 W/m². Monthly variations in wind speed were observed, with the highest values recorded in June. The wind energy density values were also calculated, with the highest value in June—67.09 kWh/m² at a height of 10 meters. The calculated wind power and energy density values at a height of 100 meters were 164.79 W/m² and 1443.59 kWh/m², respectively [25-27].

In 2023, Rakhimov analyzed wind speed and direction data at a height of 10 meters, obtained from ground meteorological stations located in the Bukhara (Ayakagitma) and Jizzakh (Yangiqishloq) regions, focusing on annual and seasonal variations [28]. The study used the data from 2005 to 2022, and applied the two-parameter Weibull distribution function to assess the average annual wind speed, wind power density, and wind energy density at a height of 10 meters.

The wind speed probability distribution function plays a key role in evaluating the efficiency of wind energy systems. The energy characteristics of these systems largely depend on how accurately the probability distribution function matches the wind speed variation in a specific region. Precise knowledge of wind speed distribution allows for a comprehensive analysis of the technical and economic feasibility of wind energy use, which forms the basis for informed decisions regarding the development of wind energy projects [29-31].

Currently, the two-parameter Weibull distribution function is widely used, and recognized for describing the wind speed distributions. The use of this allows for a high degree of accuracy when modeling wind characteristics. By determining the Weibull distribution parameters based on the empirical wind speed data, it is possible to assess the wind energy potential of a region through calculations of average wind power density and wind energy density. This enables the assessment of potential energy generation and the economic feasibility of wind energy installations [24, 25-28, 32].

Based on the data from NPG 2.01.01-22 “climatic and physico-geological data for design”, which provides information only on average and maximum wind speeds in January and July, as

well as wind direction recurrence, it is not possible to directly assess wind energy potential, as these data are intended for construction and design purposes rather than for determining the energy efficiency of wind resources [33].

Previous studies of wind energy potential, based on NASA SSE data from 1983 to 2005 and Typical Meteorological Years (TMYs), have limitations. The primary issue with NASA SSE data is its obsolescence, as it does not account for contemporary climate changes. This can lead to inaccurate assessments of wind potential, reducing the precision of forecasts and management decisions [34]. The TMY data also smooths natural fluctuations in wind conditions, and does not account for extreme weather events, which can reduce the reliability of wind turbine operations [35, 36]. Some studies have averaged data collected every 30 minutes into daily values, further smoothing short-term wind speed variations, which may reduce the accuracy of wind resource assessments.

Thus the NASA SSE and TMY data are more suitable for long-term climate assessments, but are less precise for short-term forecasts and detailed analysis, as they do not account for extreme weather conditions and modern climate changes. This can result in less accurate assessments of wind potential when designing wind energy installations [36].

In this study, unlike the previously mentioned works, a more detailed analysis was conducted on the surface meteorological data collected from 77 meteorological stations in Uzbekistan from 2000 to 2022, with data gathered at 3-hour intervals.

This approach provides a more accurate data for short-term forecasts and the assessment of current wind energy potential, taking into account modern climate changes and local specifics. As part of the research, average wind speed values on a monthly and annual basis, wind direction, and wind energy potential were evaluated using the two-parameter Weibull distribution function. This allowed for a more detailed assessment of average wind speed, power density, and energy at a height of 10 meters, as well as a comprehensive analysis of the country's wind energy potential, considering modern climate changes. Weibull distribution function graphs and wind rose diagrams were constructed based on wind speed data for 13 selected regions. Additionally, maps of average annual wind speed and average annual wind power distribution across Uzbekistan were created, which aid in the more precise planning of wind energy projects and the development of "green" energy. Therefore, this study provides essential data for the development of wind energy and the enhancement of the country's energy security.

2. Methodology

In this study, a multi-stage process was employed to assess the wind potential of various regions in the Republic of Uzbekistan. This process included the collection and analysis of the meteorological data, statistical processing, visualization, and regional analysis. The workflow utilized in this study is presented in two stages, as illustrated in figure 1.

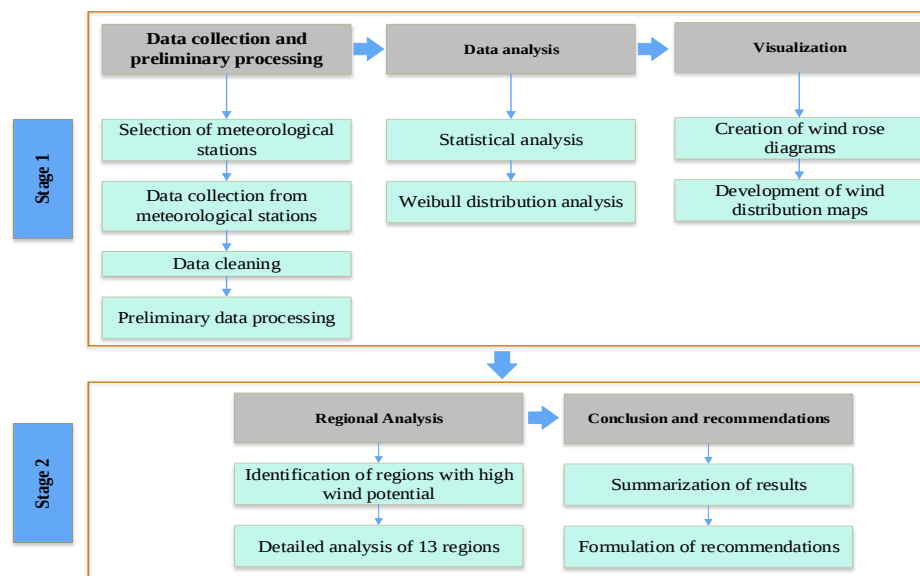


Figure 1. Workflow used in the study.

Stage 2.1 Data collection, analysis, and visualization

2.1.1 Data collection and preliminary processing

The study utilized wind speed values measured every 3 hours at a height of 10 meters, collected from an archive of 77 ground meteorological stations from 2000 to 2022. The data was stored at the agency of the hydrometeorological service (UzHydromet) under the Ministry of Ecology, environmental protection and climate change of

the Republic of Uzbekistan. The locations and names of these ground meteorological stations are shown in figure 2. Physical information including latitude, longitude, and elevation of the meteorological station locations is provided by Avezova and Rakhimov [37, 38].

Raw data was cleaned from outliers and missing values to ensure accuracy in the analysis. The data was then prepared for further analysis including the calculation of average wind speed values on a monthly and annual basis.

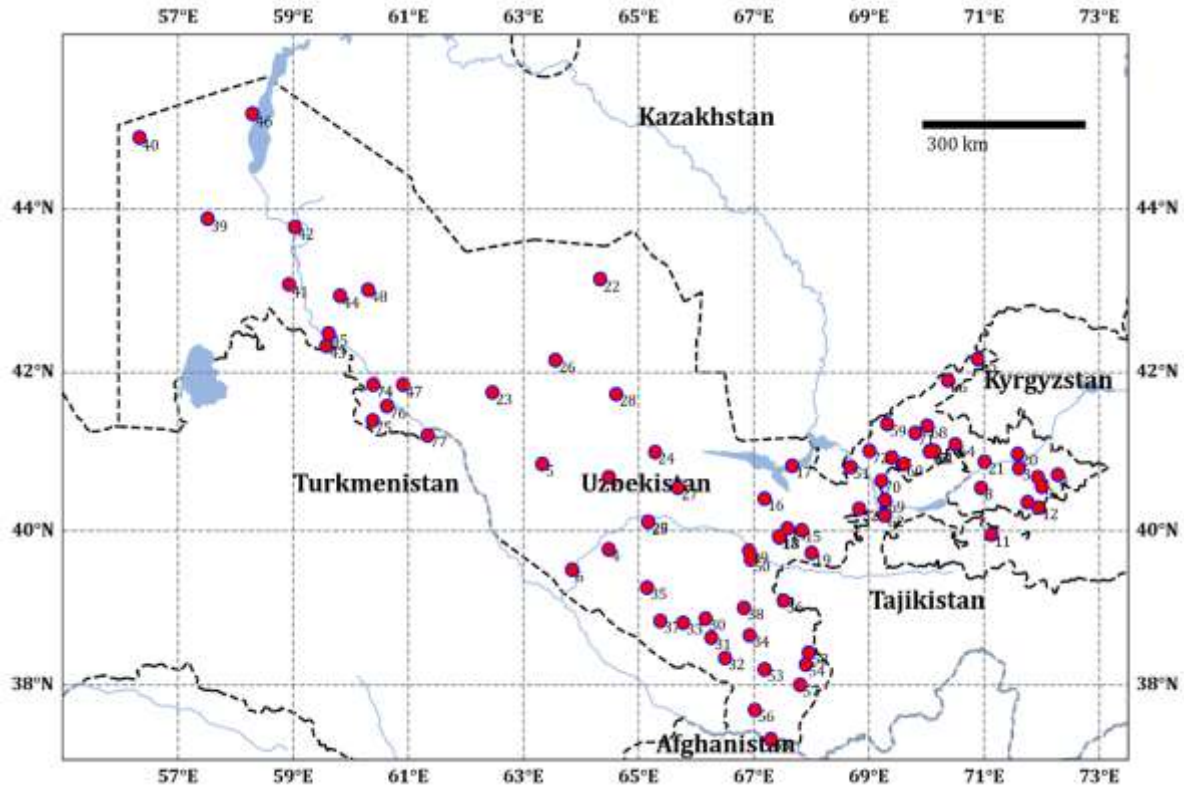


Figure 2. Map of the locations of ground meteorological stations in Uzbekistan.

2.1.2. Data analysis

The average wind speed values at a height of 10 meters were calculated for each month and year, based on the collected data. Additionally, wind direction analyses were conducted to identify prevailing wind directions in various regions. Statistical analysis is essential for obtaining a more accurate understanding of wind potential, as average wind speed values alone are insufficient for a complete evaluation of the wind potential at the selected location [39]. The proportion of time during which the prevailing wind speed is observed in the studied area is characterized using probability density.

In this study, the two-parameter Weibull distribution function was used to assess wind speed, which enabled the evaluation of the

average annual wind speed, wind power density, and wind energy density at a height of 10 meters, determined as follows [24-28, 32, 40]:

$$f_w(v) = \frac{k}{c} \left(\frac{v}{c} \right)^{k-1} \cdot \exp \left(- \left(\frac{v}{c} \right)^k \right) \quad (1)$$

where, $f_w(v)$ represents the probability density function of wind speed, v is the wind speed, k is the shape parameter (dimensionless)—the larger the value of k , the more concentrated the probability around the mean wind speed, and c is the scale parameter (m/s), which defines the average wind speed. The relationship between these parameters is defined as follows:

$$k = \left(\frac{\sigma}{\bar{v}} \right)^{-1.086},$$

$$c = \frac{\bar{v}}{\Gamma(1+1/k)},$$

$$\bar{v} = \frac{1}{n} \sum_{i=1}^n v_i,$$

$$\sigma = \left[\frac{1}{n-1} \sum_{i=1}^n (v_i - \bar{v})^2 \right]^{0.5},$$
(2)

where $\bar{v}$ represents the average wind speed, and σ is the standard deviation of wind speed.

The parameter of the Weibull distribution function closely aligns with the average wind speed, making the Weibull distribution suitable for data analysis [24-28, 32, 40, 41].

The wind energy power per unit area (W/m²) can be calculated as follows [24-28, 32, 40, 41]:

$$\frac{P}{A} = \frac{1}{2} \rho v^3 \quad (3)$$

Here, the symbol ρ represents air density, v denotes wind speed, and A is the area perpendicular to the wind speed direction.

The wind power density can be expressed based on the Weibull probability density function, as follows [24-28, 32, 40-42]:

$$\frac{P}{A} = \frac{1}{2} \rho \int_0^{\infty} v^3 f(v) dv = \frac{1}{2} \rho c^3 \Gamma \left(1 + \frac{3}{k} \right) \quad (4)$$

2.1.3. Visualization

Using the available wind speed data, a wind rose was constructed in the form of polar diagrams for each selected region. In this case, wind direction was divided into 16 sectors, each measuring 22.5°. Additionally, maps of the average annual wind speed and average annual wind power distribution were created for various regions of Uzbekistan. The wind rose charts display the distribution of wind speed across directions, helping to identify the direction with the highest frequency. For map generation, the Cartopy library in Python was used.

Stage 2.2. Regional analysis and recommendations

2.2.1. Regional analysis

Regions with the highest average wind speed and wind power density were identified, and a detailed analysis was conducted for 13 regions with significant wind energy potential. This analysis provided valuable insights for selecting the most suitable locations for wind energy projects,

contributing to the efficient development of renewable energy resources in Uzbekistan.

2.2.2. Conclusion and recommendations

The main results of the study were summarized, and presented in the conclusion. Recommendations for the development of wind energy in Uzbekistan were proposed based on the obtained data. This multi-stage method provided a comprehensive picture of Uzbekistan's wind potential, and allowed for well-founded recommendations to optimize wind energy usage across various regions of the country.

3. Results and discussion

3.1. Distribution of average wind speed

The study of monthly and annual average wind speeds obtained from 77 ground meteorological stations across various regions of the Republic of Uzbekistan revealed significant differences in wind potential throughout the country. The key findings and conclusions derived from the data in table 1 are summarized below.

The Dekhkanabad meteorological station in the Kashkadarya region has recorded high monthly average wind speeds, particularly in February, May, and June (4.0 m/s), resulting in an overall annual wind speed of 3.75 m/s. These observations indicate a high wind potential in this area. In Jaslyk (Republic of Karakalpakstan), the highest monthly wind speeds were recorded in March (4.9 m/s), April (4.7 m/s), February, and May (4.5 m/s). The annual wind speed was 3.9 m/s. Similarly, high values were noted in Nukus (Republic of Karakalpakstan), particularly in March (4.4 m/s) and April (4.3 m/s), with an annual wind speed of 3.8 m/s.

Moderate wind potential is observed in Bukhara (Bukhara region), where monthly wind speeds range from 2.6 m/s to 4.4 m/s, with an annual speed of 3.54 m/s. In Navoi (Navoi region), high values were noted in February (3.8 m/s), March (4.1 m/s), and April (3.8 m/s). The annual wind speed was 3.3 m/s. In Termez (Surkhandarya region), monthly wind speeds ranged from 2.3 m/s to 3.6 m/s, with an annual wind speed of 2.8 m/s.

Low wind potential is observed in Sarykand, where the lowest monthly wind speeds were recorded (from 0.5 m/s to 0.7 m/s), with an annual wind speed of 0.6 m/s. In Yubileynaya, monthly wind speeds ranged from 0.8 m/s to 1.4 m/s, with an annual wind speed of 1.0 m/s. Pap also showed a low wind potential, with monthly wind speeds ranging from 0.2 m/s to 0.6 m/s, and an annual wind speed of 0.4 m/s.

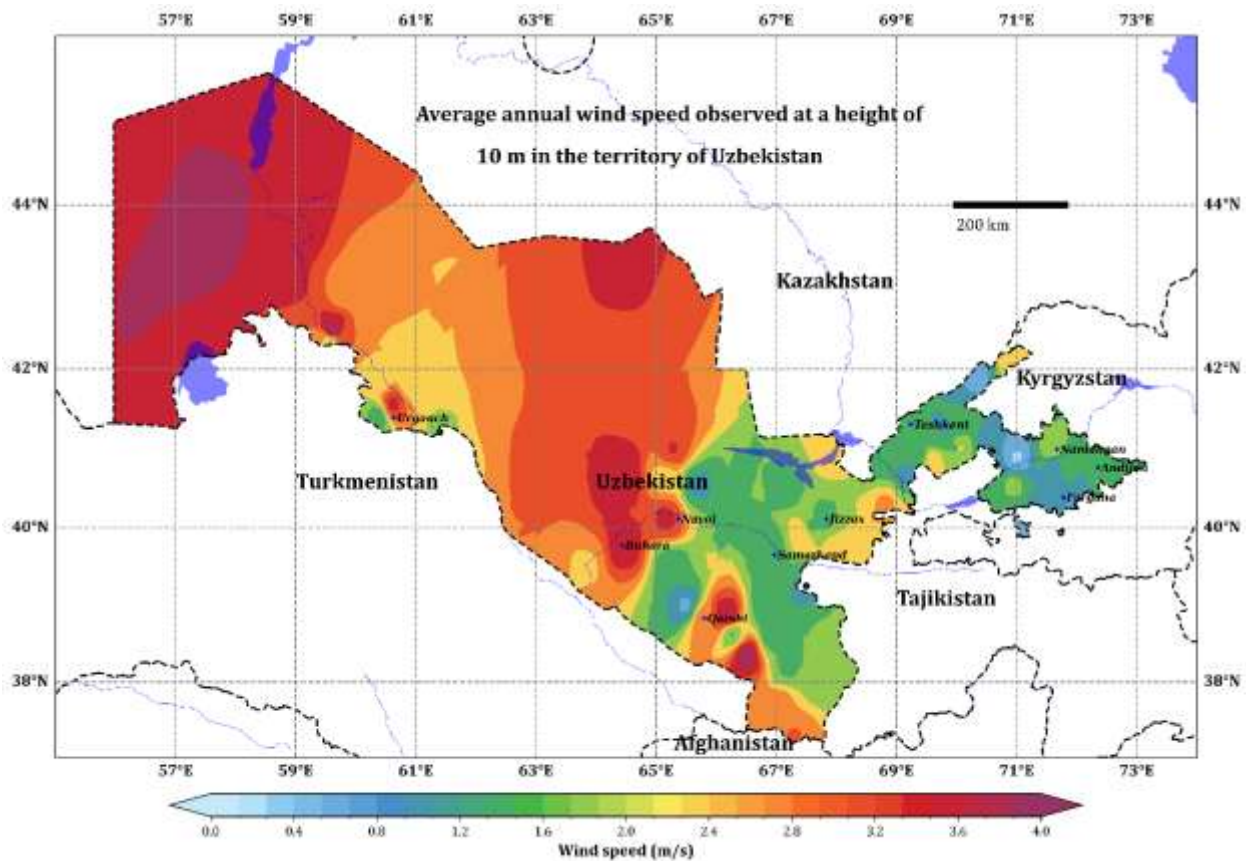


Figure 3. Map of the distribution of average annual wind speed at a height of 10 meters in the territory of Uzbekistan.

Temporal variations in wind speed showed that most regions experience a significant increase in wind speed in the spring (March-April), and a decrease during the summer period. Maximum wind speeds are most often recorded in the winter and spring months. Regional differences were also notable: central and western regions (e.g., Bukhara, Navoi) have higher monthly and annual wind speeds compared to the eastern and southern regions. Northern regions, such as Karakalpakstan, show high wind potential throughout the year.

Figure 3 displays a map of the average annual wind speed at a height of 10 meters across Uzbekistan. According to the data in table 2, there are significant regional variations in wind speed.

It can be seen from figure 3 that the highest average annual wind speeds (3 m/s and above) are recorded in the western and northwestern parts of the country, particularly in areas of the Republic of Karakalpakstan, such as Jaslyk (3.9 m/s) and Nukus (3.8 m/s). Central regions, like Navoi (3.3 m/s) and Bukhara (3.5 m/s), also show high values.

In the eastern regions, including Tashkent Province and the Fergana Valley, the average annual wind speed ranges from 1.0 to 2.5 m/s, for

example in Tashkent (2.5 m/s) and Fergana (1.68 m/s). The lowest values were recorded in Pap (0.4 m/s) and Sarykanda (0.6 m/s).

These data confirm the significant differences in wind potential across various regions of Uzbekistan, which is crucial to consider when planning wind energy projects.

3.2. Weibull distribution and power density

Given the extensive amount of data, one promising area with high potential was selected for each region, and the results of studies conducted in these locations are presented. The identified parameters of the Weibull distribution function for each region are shown in table 1, covering 13 regions.

As shown in table 1, the parameters of the Weibull distribution function vary significantly depending on the region, indicating differences in wind potential across Uzbekistan. The shape parameter k , which characterizes the concentration of wind speed around the mean value, ranges from 0.74 in the Tashkent region (Bekabad) to 1.97 in the Bukhara and Kashkadarya regions (Ayakagitma and Dekhkanabad). This suggests a greater variability in wind speed in the Tashkent

region compared to more stable conditions in the, Bukhara and Kashkadarya regions.

Table 1. Parameters of the Weibull distribution function by region.

№	Location and name of the weather station	k	c (m/s)	Power density P/A (W/m ²)
1	Andijan region, Andijan	1,69	2,15	10,00
2	Bukhara region, Ayakagitma	1,97	4,20	61,13
3	Fergana region, Kokand	1,16	1,90	15,49
4	Jizzakh region, Lalmikar	1,35	2,83	34,77
5	Namangan region, Namangan	1,48	2,69	24,32
6	Navoi region, Navoi	1,26	3,76	94,50
7	Kashkadarya region, Dekhkanabad	1,75	4,47	85,33
8	Republic of Karakalpakstan, Jaslyk	1,08	4,17	202,01
9	Samarkand region, Samarkand	1,85	1,93	6,35
10	Syrdarya region, Yangiyer	1,16	2,81	39,35
11	Surkhandarya region, Termez	1,55	3,29	41,60
12	Tashkent region, Bekabad	0,74	1,65	71,702
13	Khorezm region, Urgench	1,93	3,82	47,04

The scale parameter c , which defines the average wind speed, also varies: from 1.65 m/s in the Kashkadarya region to 4.47 m/s in the Kashkadarya region (Dekhkanabad). The highest values of the scale parameter are observed in areas with high wind potential, such as the Republic of Karakalpakstan (Jaslyk), and the Navoi region.

The power density of wind, expressed as P/A (W/m²), varies significantly between regions, reflecting substantial differences in the available wind energy. For instance, the highest power

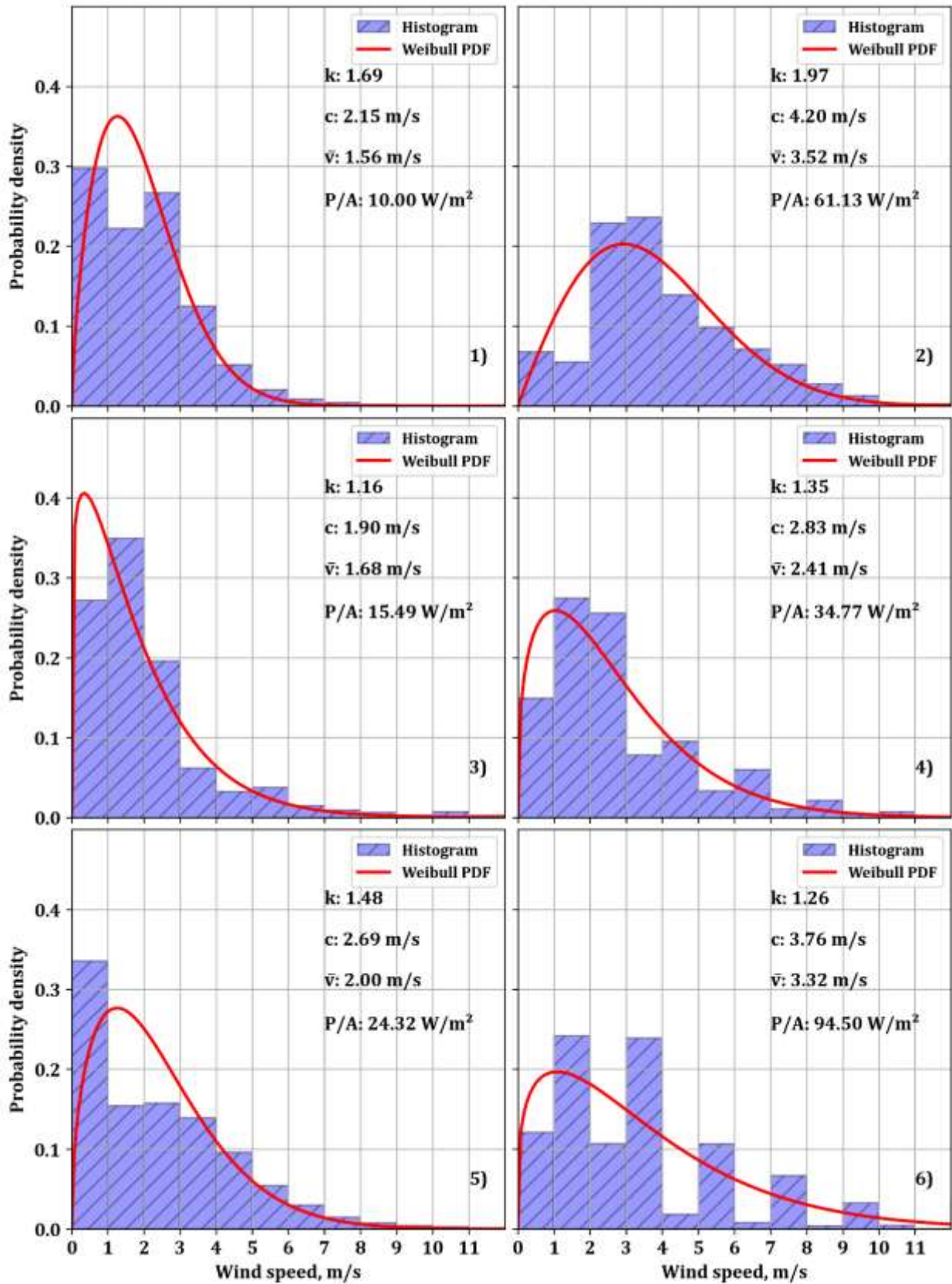
density (202.01 W/m²) is observed in Jaslyk (Republic of Karakalpakstan), making this region one of the most promising for wind energy development. Meanwhile, the lowest power density (6.35 W/m²) was recorded in the Samarkand region, indicating a lower wind potential in this area.

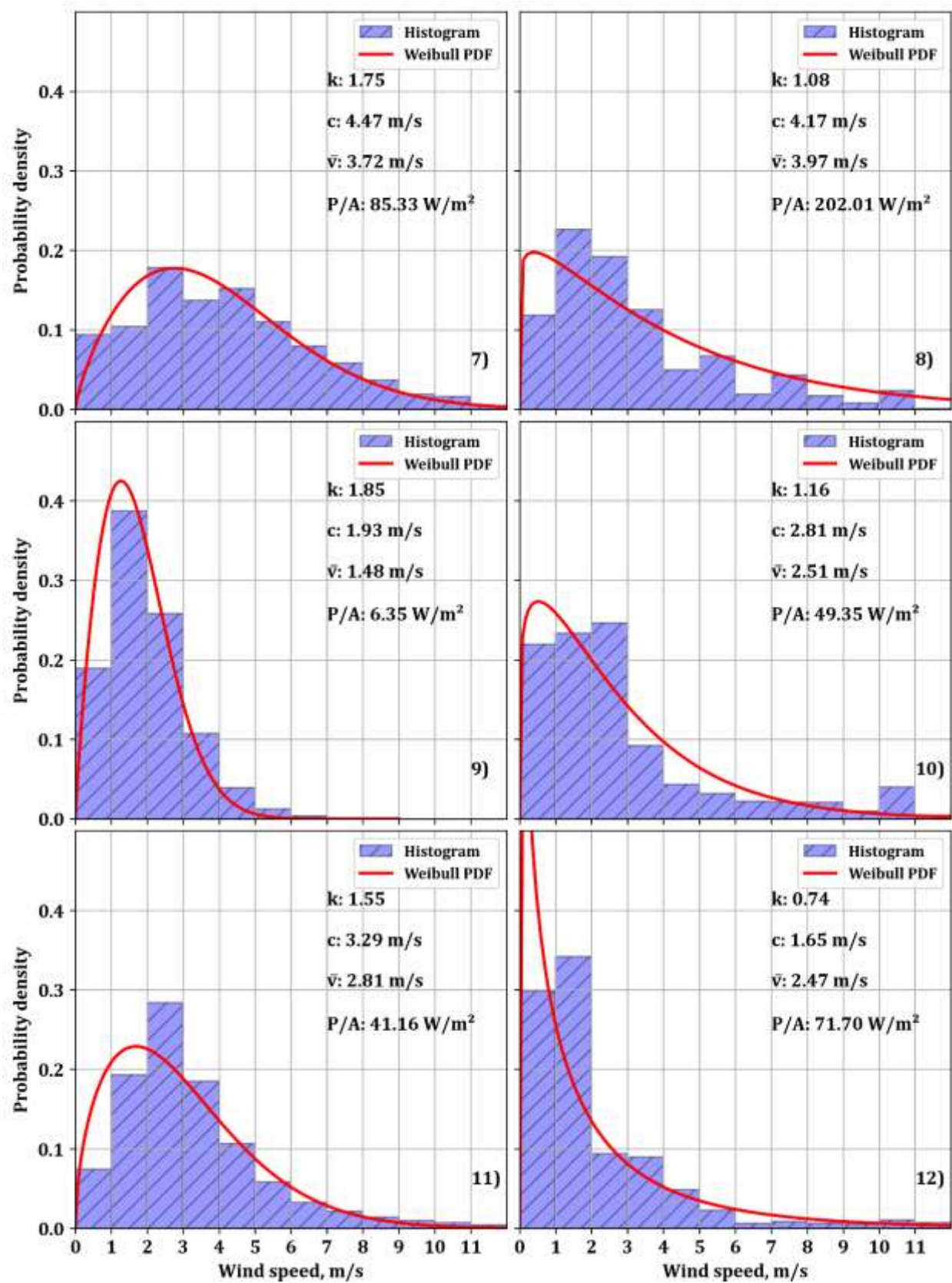
Additionally, figure 4 presents the Weibull distribution curves for wind speed in the selected regions.

Table 2. The value of average monthly and annual speeds determined by regions (m/s).

No	Meteorological station name	Location	Months												Annual
			I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
1	Andijan	Andijan region	1,1	1,3	1,6	1,8	2,0	2,1	1,9	1,7	1,5	1,2	1,1	1,1	1,5
2	Kurgantepa		1,3	1,5	1,6	1,6	1,7	1,7	1,5	1,4	1,4	1,3	1,3	1,3	1,5
3	Yubileynaya		0,8	1,1	1,4	1,3	1,1	1,0	0,9	0,8	0,8	0,8	0,9	0,9	1,0
4	Bukhara	Bukhara region	2,9	3,4	3,5	3,5	3,5	4,0	4,4	4,1	3,8	2,9	2,6	2,9	3,5
5	Jangeldi		2,8	3,1	3,3	3,0	3,1	3,2	3,4	3,2	3,1	2,9	2,9	3,0	3,1
6	Karakul		2,2	2,4	2,5	2,4	2,4	2,6	2,8	2,5	2,3	2,0	2,0	2,1	2,4
7	Ayakagitma	Fergana region	3,2	3,6	3,7	3,8	3,7	3,9	4,0	3,7	3,4	3,2	3,1	3,2	3,5
8	Kokand		1,3	1,8	2,2	2,3	1,8	1,7	1,7	1,6	1,6	1,5	1,4	1,4	1,7
9	Kuva		0,6	0,8	1,0	1,1	1,1	1,1	0,9	0,8	0,8	0,8	0,7	0,7	0,9
10	Fergana	Fergana region	0,8	0,9	1,1	1,1	1,1	1,2	1,1	1,0	0,9	0,8	0,8	0,8	1,0
11	Sarykanda		0,6	0,6	0,6	0,7	0,7	0,6	0,6	0,6	0,6	0,5	0,5	0,5	0,6
12	Shakhimardan		0,6	0,6	0,7	0,9	0,8	0,9	0,7	0,7	0,7	0,7	0,6	0,6	0,7
13	Bakhtmal	Jizzakh region	1,8	2,0	2,1	2,2	2,1	2,2	2,2	2,3	2,3	2,1	1,9	1,9	2,1
14	Gallyaarl		1,1	1,6	1,7	1,7	1,5	1,8	1,9	1,7	1,5	1,3	1,2	1,2	1,5
15	Jizzakh		1,4	1,6	1,7	1,7	1,6	1,6	1,5	1,4	1,3	1,2	1,3	1,3	1,5
16	Dustlik	Jizzakh region	1,6	1,8	1,7	1,6	1,6	1,4	1,2	1,2	1,2	1,3	1,4	1,7	1,5
17	Arnasay		2,4	2,5	2,5	2,4	2,5	2,3	2,3	2,3	2,3	2,3	2,4	2,7	2,4
18	Lyalmikor		2,0	2,4	2,6	2,7	2,4	2,8	3,0	2,7	2,5	2,1	2,0	2,0	2,4
19	Yangikishlok	Namangan region	2,2	2,3	2,4	2,4	2,4	2,4	2,4	2,3	2,1	2,1	2,0	2,1	2,3
20	Namangan		1,6	1,8	2	2,3	2,2	2,1	2,2	2,2	2,3	1,9	1,7	1,6	2,0
21	Pap		0,2	0,4	0,6	0,6	0,5	0,4	0,4	0,3	0,3	0,3	0,3	0,2	0,4
22	Kamchik	Namangan region	1,5	1,9	2,2	2,3	2,4	2,5	2,3	2,1	2,1	2,0	1,7	1,5	2,1
23	Akbaital		2,9	3,2	3,6	3,6	3,5	3,5	3,4	3,4	3,1	2,8	2,8	3,0	3,2
24	Buzubay		2,4	2,8	3,0	3,0	3,0	2,9	3,0	3,0	2,8	2,5	2,4	2,5	2,8
25	Mashikuduk	Navoi region	3,1	3,4	3,4	3,2	3,2	3,4	3,4	3,4	3,2	2,9	3,0	3,1	3,2
26	Navoi		3,5	3,8	4,1	3,8	3,3	3,4	3,6	2,8	2,7	2,7	2,8	3,0	3,3
27	Uchkuduk		2,9	3,0	3,3	3,3	3,3	3,3	3,4	3,4	3,4	3,0	2,7	2,8	3,1
28	Nurata	Navoi region	1,1	1,3	1,3	1,3	1,2	1,1	1,1	0,9	0,8	0,8	1,0	1,0	1,1
29	Tamdy		3,1	3,3	3,2	3,0	2,9	2,9	2,8	2,7	2,6	2,7	2,8	3,1	2,9

30	Sentob Nurata		2,1	2,6	2,7	2,6	2,4	2,4	2,2	2,0	1,9	2,1	2,1	2,0	2,3
31	Akrobat		4,1	4,5	4,4	3,6	3,1	3,1	3,3	3,2	3,2	3,3	3,8	4,1	3,6
32	Guzar		1,5	1,8	2,0	1,7	1,7	1,7	1,6	1,5	1,4	1,4	1,3	1,5	1,6
33	Dekhkanabad		3,8	4,0	3,9	3,9	4,0	4,0	3,9	3,8	3,5	3,4	3,2	3,7	3,8
34	Karshi	Kashkadarya region	2,5	2,8	3,0	2,8	2,9	3,3	3,6	3,0	2,5	2,3	2,2	2,2	2,8
35	Mingchukur		1,1	1,2	1,2	1,2	1,3	1,4	1,4	1,3	1,3	1,2	1,1	1,1	1,2
36	Muborak		1,0	1,2	1,4	1,4	1,4	1,6	1,8	1,4	1,2	1,1	1,0	1,0	1,3
37	Kul		1,0	1,2	1,3	1,2	1,2	1,2	1,1	1,1	1,1	1,1	1,1	1,1	1,1
38	Chimkurgan		0,8	0,9	1,0	0,8	0,8	0,8	0,7	0,7	0,6	0,6	0,7	0,7	0,8
39	Shahrisabz		1,1	1,2	1,4	1,3	1,4	1,4	1,4	1,3	1,3	1,2	1,1	1,1	1,3
40	Jaslyk		3,9	4,5	4,9	4,7	4,5	4,1	3,5	3,4	3,4	3,1	3,1	3,6	3,9
41	Karakalpakiya		3,4	3,5	4,0	3,9	3,4	3,2	2,7	2,4	2,8	3,1	3,0	3,4	3,2
42	Kungrad		3,0	3,5	4,0	4,2	3,7	3,5	3,0	2,8	2,8	2,8	2,8	3,0	3,3
43	Muynak		3,4	3,8	4,1	4,2	3,8	3,6	3,3	3,4	3,3	3,2	3,1	3,3	3,5
44	Takhia-Tash	Republic of	1,9	2,3	2,5	2,5	2,2	1,9	1,7	1,5	1,7	1,6	1,7	1,7	1,9
45	Chimbay	Karakalpakstan	2,6	3,0	3,3	3,2	2,9	2,7	2,3	2,0	2,1	2,1	2,2	2,4	2,6
46	Nukus		3,6	4,0	4,4	4,3	4,0	4,0	3,9	3,8	3,4	3,1	3,2	3,4	3,8
47	Aktumusk		3,9	4,0	3,9	3,6	3,4	3,4	2,9	2,8	2,8	2,8	3,1	3,5	3,3
48	Buston		2,0	2,3	2,3	2,2	2,2	2,2	2,1	2,1	2,0	1,8	1,8	1,9	2,1
49	Takhtakupyr		2,4	2,7	3,0	3,0	2,7	2,5	2,3	2,1	2,2	2,1	2,2	2,3	2,5
50	Dagbit	Samarkand region	1,3	1,5	1,6	1,5	1,4	1,3	1,1	1,0	1,2	1,3	1,2	1,3	1,3
51	Samarkand		1,4	1,6	1,7	1,7	1,6	1,6	1,6	1,4	1,5	1,3	1,3	1,3	1,5
52	Syrdarya	Syrdarya region	1,4	1,6	1,7	1,6	1,5	1,6	1,5	1,4	1,3	1,3	1,3	1,4	1,5
53	Yangiyer		3,6	3,7	3,1	2,5	2,3	2,1	1,7	1,5	1,4	2,2	2,5	3,4	2,5
54	Baysun		1,4	1,5	1,6	1,6	1,6	1,6	1,6	1,5	1,6	1,6	1,5	1,4	1,6
55	Denau		1,7	1,8	1,8	1,7	1,7	1,6	1,5	1,4	1,4	1,5	1,6	1,8	1,6
56	Termez	Surkhandarya region	2,6	3,3	3,6	3,3	3,0	2,9	2,9	2,7	2,3	2,4	2,3	2,5	2,8
57	Sherabad		2,6	2,8	2,9	2,9	2,9	2,7	2,5	2,5	2,5	2,6	2,6	2,6	2,7
58	Shurchi		1,9	2,3	2,3	2,1	1,9	1,7	1,5	1,4	1,4	1,5	1,6	1,8	1,8
59	Sariasia		1,9	2,1	2,1	2,0	2,0	2,2	1,9	1,8	1,7	1,7	1,7	1,7	1,9
60	Tashkent		1,2	1,3	1,4	1,4	1,3	1,3	1,3	1,2	1,2	1,1	1,1	1,1	1,2
61	Almalyk		2,1	2,4	2,7	2,5	2,7	2,8	2,5	2,3	2,2	2,1	2,0	2,0	2,4
62	Angren		1,4	1,6	1,7	1,7	1,6	1,7	1,7	1,6	1,4	1,3	1,3	1,4	1,5
63	Bekabad		4,6	4,5	3,5	2,2	1,8	1,6	1,1	0,9	1,0	2,1	2,7	4,4	2,5
64	Dukan		0,8	0,9	1,1	1,4	1,6	1,8	1,8	1,6	1,5	1,1	0,8	0,7	1,3
65	Bashkizylsay		1,0	1,1	1,1	1,2	1,2	1,2	1,1	1,1	1,1	1,1	1,0	1,0	1,1
66	Oygayng	Tashkent region	1,9	2,3	2,0	2,0	2,1	2,1	2,5	2,7	3,1	2,6	2,1	2,0	2,3
67	Pskem		0,3	0,4	0,6	0,7	0,6	0,7	1,1	1,3	1,3	0,8	0,5	0,4	0,7
68	Tuyabuguz		1,2	1,5	1,6	1,6	1,5	1,6	1,5	1,5	1,5	1,4	1,3	1,2	1,4
69	Chimgan		1,0	1,2	1,3	1,4	1,4	1,4	1,5	1,5	1,5	1,2	1,0	1,0	1,3
70	Dalverzin		1,6	1,9	2,1	1,9	1,7	1,7	1,5	1,3	1,2	1,3	1,4	1,6	1,6
71	Kukaral		0,9	1,0	1,1	1,1	1,0	0,9	0,8	0,7	0,7	0,7	0,8	0,8	0,9
72	Sukak		0,9	1,0	1,1	1,2	1,2	1,2	1,1	1,3	1,3	1,1	1,0	1,0	1,1
73	Yangiyul		1,2	1,5	1,8	1,7	1,7	1,6	1,5	1,4	1,4	1,3	1,3	1,2	1,5
74	Gurlan		2,3	2,4	2,8	2,5	2,2	2,1	1,8	1,7	1,9	1,9	2,3	2,5	2,2
75	Khiva	Khorezm region	1,4	1,5	1,6	1,6	1,4	1,3	1,3	1,3	1,3	1,2	1,3	1,5	1,4
76	Urgench		3,4	3,8	3,9	3,8	3,5	3,3	3,1	2,9	2,9	2,7	3,0	3,3	3,3
77	Tuyamuyun		1,8	2,2	2,4	2,5	2,3	2,0	1,9	1,7	1,7	1,5	1,5	1,8	1,9





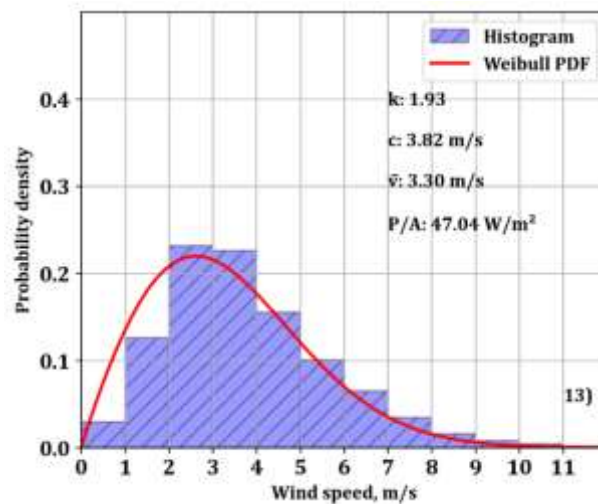


Figure 4. Weibull distribution graphs of wind speed for selected regions: 1) Andijan region, 2) Bukhara region, 3) Fergana region, 4) Jizzakh region, 5) Namangan region, 6) Navoi region, 7) Kashkadarya region, 8) Republic of Karakalpakstan, 9) Samarkand region, 10) Syrdarya region, 11) Surkhandarya region, 12) Tashkent region, and 13) Khorezm region.

Based on the Weibull distribution parameters (Figure 3), the following regions can be classified as areas with high average wind speed: Karakalpakstan, Kashkadarya, Navoi, Bukhara, and Urgench in the Khorezm region. It is notable that the Kashkadarya and Bukhara regions demonstrate high average wind speeds, and a

good concentration of wind speed around the mean value. According to the obtained data, regions with high wind potential include Jaslyk district in the Republic of Karakalpakstan–202.1 W/m², the city of Navoi in the Navoi Region – 94.50 W/m², and the Dekhkanabad district in the Kashkadarya region–85.33 W/m².

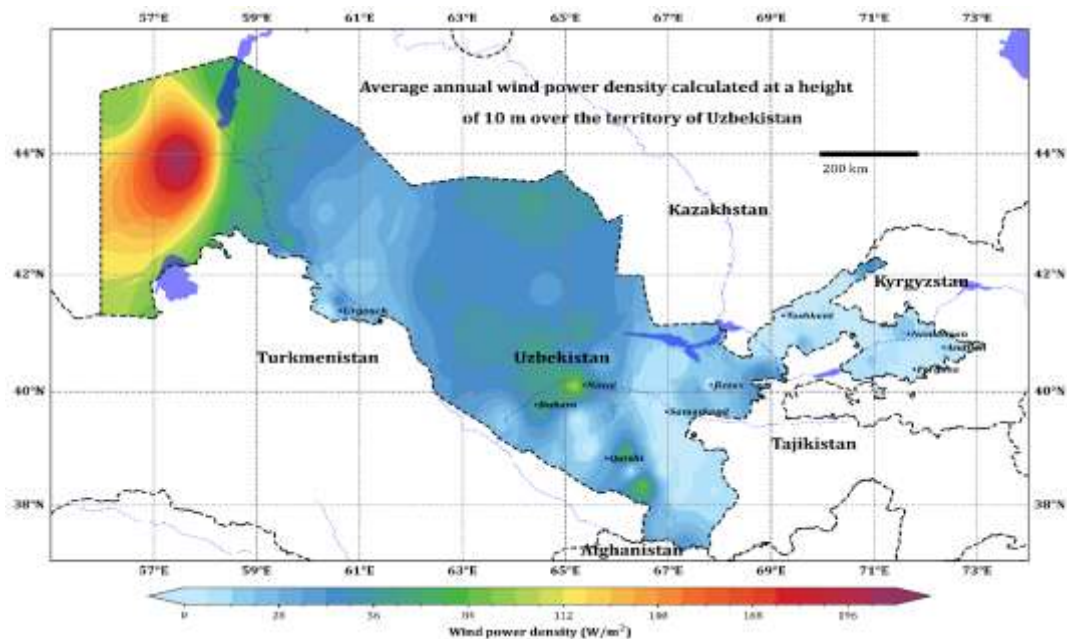


Figure 5. Map of the distribution of the average annual wind power density calculated at a height of 10 meters on the territory of Uzbekistan.

In summary, to determine the gross wind potential (based on the data obtained from 77 ground meteorological stations), Figure 5 presents a map showing the average annual wind power density, calculated at a height of 10 meters across Uzbekistan.

3.3 Wind direction

The determination of wind direction is a crucial aspect of the optimal utilization of wind energy. The wind rose illustrates how wind speed and direction are distributed over a specific area.

The wind rose is important for selecting the type of wind turbine to be installed at a given location, as well as determining its orientation relative to the wind flow [43].

To facilitate analysis, a table has been created, reflecting the priority wind directions in each

region as a percentage (see table 3). The wind roses, based on data from 13 selected regions, are presented in figure 6. The height and shade of the diagram reflect the frequency of wind speed occurrences in different directions.

Table 3. Priority wind directions by region.

№	Region	Angle (°)	Sector	Frequency (%)
1.	Andijan region, Andijan	315	SW	8,6
2.	Bukhara region, Ayakagitma	0	N	18
3.	Fergana region, Kokand	235	WSW	13
4.	Jizzakh region, Lalmikar	45	NE	15
5.	Namangan region, Namangan	315	NW	26
6.	Navoi region, Navoi	90	E	29
7.	Kashkadarya region, Dekhkanabad	90	E	22
8.	Republic of Karakalpakstan, Jaslyk	90	E	18
9.	Samarkand region, Samarkand	135	SE	15
10.	Syrdarya region, Yangiyer	135	SE	21
11.	Surkhandarya region, Termez	22,5; 157,5	NNE, WSW	14
12.	Tashkent region, Bekabad	90	E	35
13.	Khorezm region, Urgench	45	NNE, NE	12,6

As illustrated in figure 6, most regions of Uzbekistan display clearly defined dominant wind directions, significantly influencing the wind energy potential in these areas. In many regions, one or two primary wind directions prevail with a high frequency of occurrence.

More specifically, in the Andijan region, winds predominantly blow from the west (W) and west-northwest (WNW), accounting for about 9%. In the Bukhara region, northern (N) and northeastern (NE) winds dominate, with frequencies of 18% and 14%, respectively, indicating the prevalence of northern airflows. In the Fergana region, northeastern winds (NE) are the most common, with a frequency of 13%, and winds from the west (W) and west-northwest (WNW) are also notable. In the Jizzakh region, northern (N) winds dominate with a frequency of 15%, followed by northeastern (NE) winds at 12%. In the Namangan region, the highest wind frequency is observed from the north (N) at 26%, with northeastern (NE) and west-northwest (WNW) winds also present.

In the Navoi region, winds predominantly blow from the northeast (NE) (29%) and the east (E) (23%). In the Kashkadarya region, winds from the east (E) (22%) and northeast (NE) (17%) dominate, with a noticeable presence of north-northwest (NNW) winds. In the Republic of Karakalpakstan, the primary wind directions are northern (N) winds (18%) and northeastern (NE) winds (15%), with an influence from eastern (E) winds as well. In the Samarkand region, northern (N) winds (15%) and northeastern (NE) winds (12%) prevail, with significant influence from eastern (E) winds. In the Syrdarya region, northern (N) winds (21%) and northeastern (NE)

winds (17%) are the most frequent, alongside north-northwest (NNW) winds.

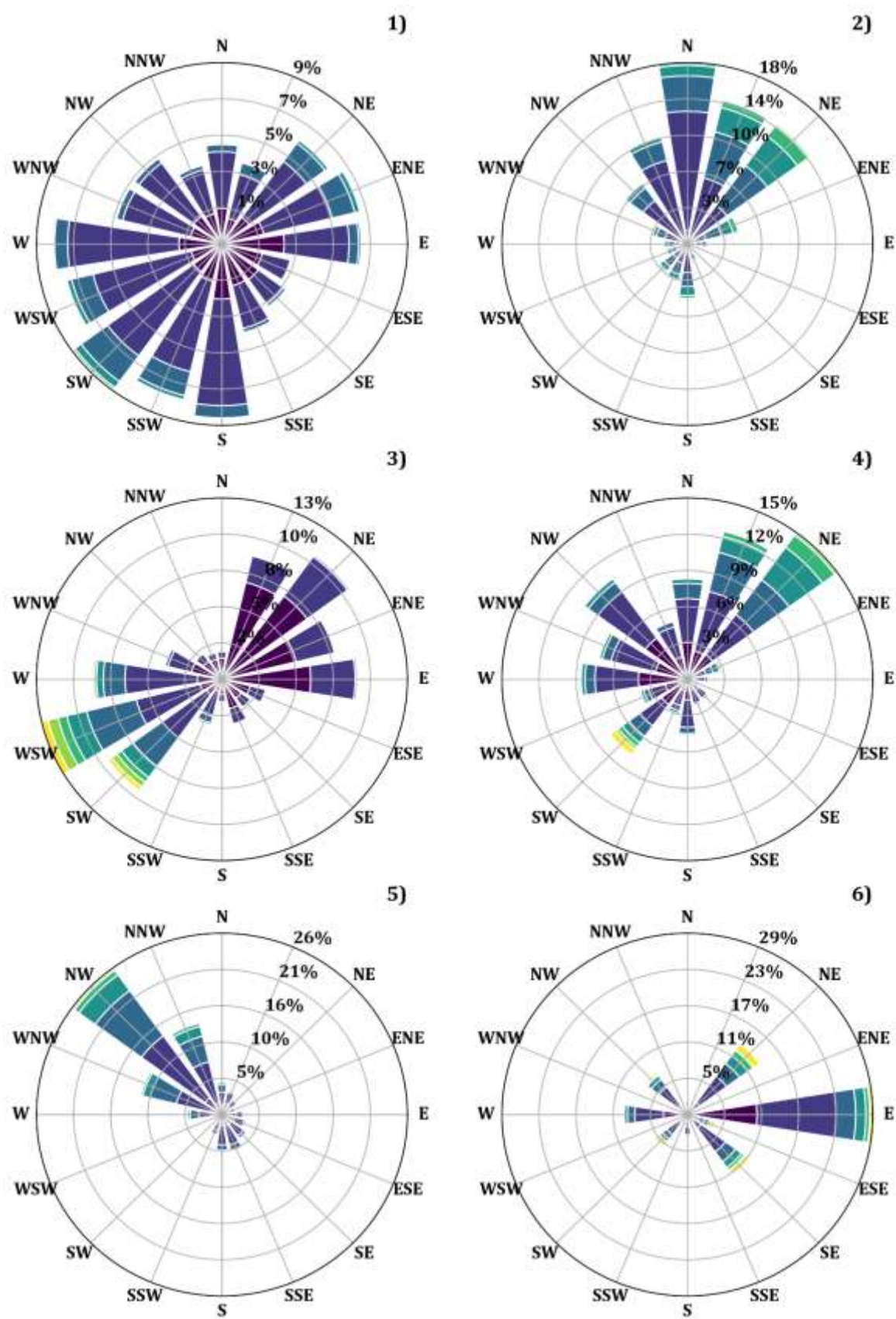
In the Surkhandarya region, western (W) winds (14%) and northwestern (NW) winds (11%) dominate, with a significant presence of southwestern (SW) winds. In the Tashkent region, the most frequent winds come from the north (N) (35%) and northeast (NE) (28%), with eastern (E) winds (21%) also being substantial. In the Khorezm region, winds predominantly blow from the northeast (NE) with a frequency of 13%, while notable winds come from the north (N) (10%) and east-northeast (ENE) (7%), with some influence from the west (W) and west-northwest (WNW), although their frequency is lower.

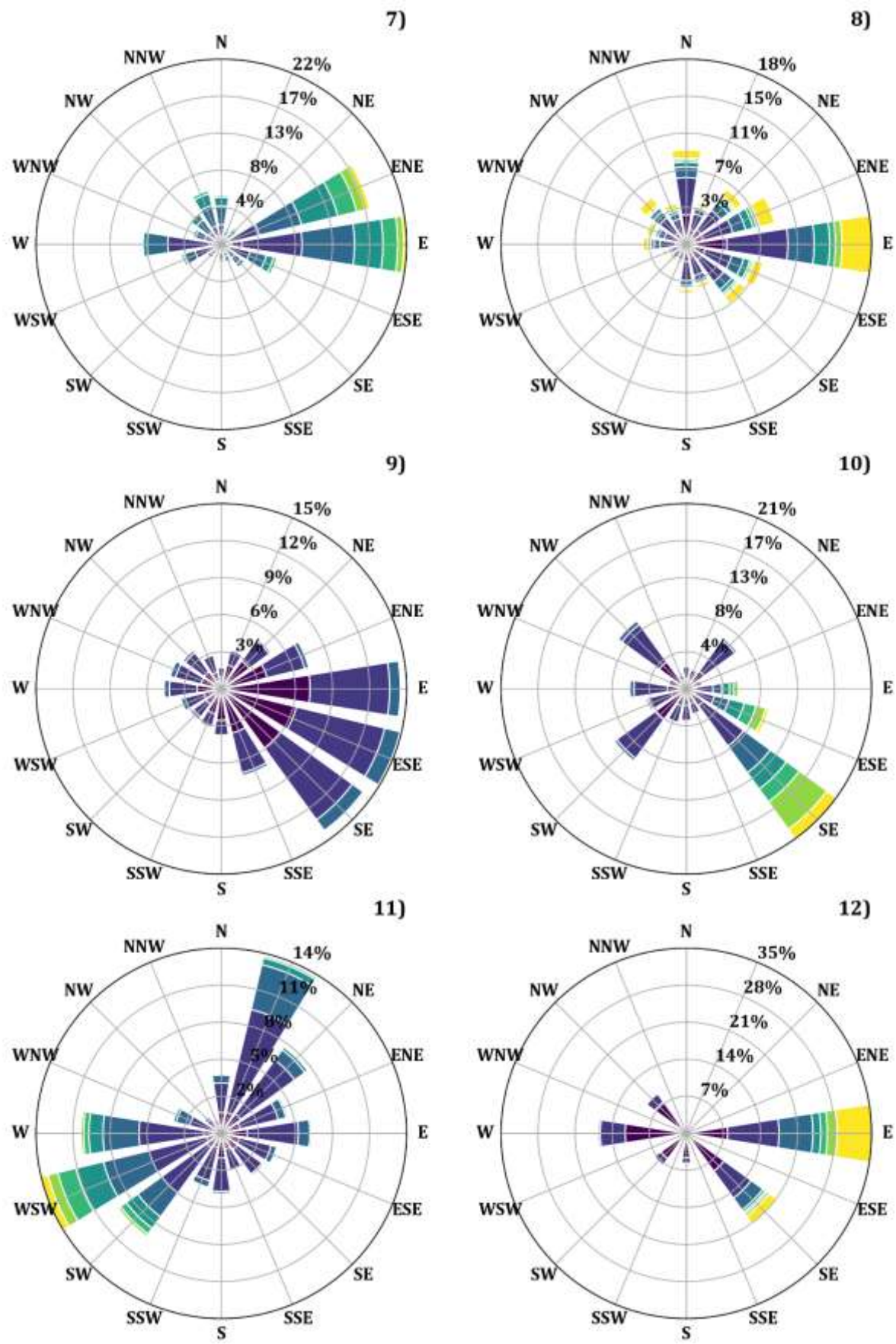
These observations show that wind direction and distribution are influenced by the unique geographical and climatic conditions of each region. This data highlights significant regional differences in wind patterns, which must be taken into account when planning and designing wind energy installations. Winds that frequently blow in a specific direction can greatly enhance the efficiency of wind turbines in those areas.

To assess the reliability of the conducted research, and confirm the accuracy of the obtained results, a comparative analysis of wind potential data from various regions of Uzbekistan was performed, as presented in different studies. Table 4 provides a comparative analysis of the results including data obtained in this study (2000–2022 based on ground observations), and the findings presented by RA Zakhidov and his co-authors (based on international data up to 2005), Bahrami et al. (2019) (based on a typical meteorological year–TMY) and N.N. Sadullaeva, A.B. Safarova, and

their colleagues (based on ground observations from 2018–2019). Despite the shared focus on assessing wind potential, the results demonstrate significant

differences, which require further explanation of the causes of such deviations.





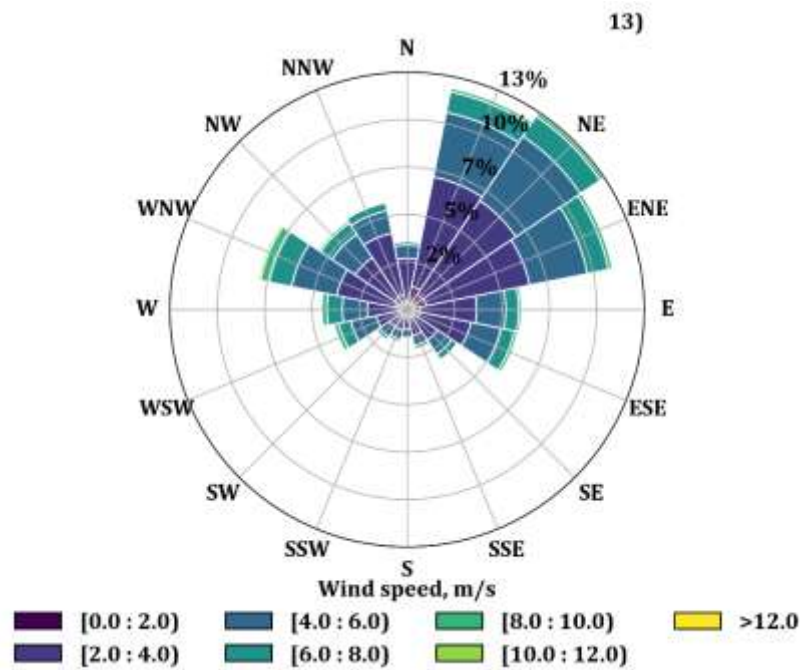


Figure 6. Wind roses for the selected regions: 1) Andijan region, 2) Bukhara region, 3) Fergana region, 4) Jizzakh region, 5) Namangan region, 6) Navoi region, 7) Kashkadarya region, 8) Republic of Karakalpakstan, 9) Samarkand region, 10) Syrdarya region, 11) Surkhandarya region, 12) Tashkent region, and 13) Khorezm region.

Table 4. Comparison of average wind speed ($\bar{U}$) and wind power density (P/A) in various regions of Uzbekistan based on data from different studies.

Name of the weather station	Data from this study (2000-2022)		According to the works of R.A. Zakhidov et al. (based on international data up to 2005) [17-22]		Based on the work of Bahrami et al. (based on TMY) [24]		According to the work of N.N. Sadullaev et al. (based on ground-based observations 2018-2019) [25-27]	
	$\bar{U}$ (m/s)	P/A (W/m ²)	$\bar{U}$ (m/s)	P/A (W/m ²)	$\bar{U}$ (m/s)	P/A (W/m ²)	$\bar{U}$ (m/s)	P/A (W/m ²)
Fergana	0,96	2,05	2,92-4,34	15-50	0,97	3,54		
Namangan	2,3	24,32	3,63-4,79	24-68	1,95	28,59		
Tashkent	1,23	2,39	4,26-4,79	48-68	2,31	34,70		
Karshi	2,75	31,30	2,38-3,31	22-45	2,72	43,99		
Bukhara	3,45	59,28	3,15-3,57	19-28	3,67	73,73	3,4	39,62
Samarkand	1,48	6,36	2,28-3,26	8-21	2,94	47,73		
Akbaytal	3,23	57,16			3,32	58,64		
Buzubai	2,77	50,31	3,3-4,18	22-45	2,79	43,94		
Nukus	3,76	72,28			3,98	89,98		
Kungrad	3,26	68,35	3,92-4,76	37-66	3,65	73,97		
Urgench	3,29	47,04	3,21-3,95	21-38	2,94	47,63		
Termez	2,81	41,16	2,47-3,32	9-23				

Reasons for differences in the results:

1. Timeframes and data sources: One of the main factors influencing the variation in results is the timeframe and data sources. The study conducted by Zakhidov et al. used multi-year wind speed data from international databases like NASA SSE up to 2005. These data covers a long period but do not account for recent climate changes. Meanwhile, the NN Sadullaeva's study is based on observations conducted in 2018–2019 with a 30-minute interval, allowing for detailed short-term changes but limited to one year. In contrast,

this study uses data from 2000 to 2022 with a 3-hour interval, providing a more comprehensive representation of long-term wind conditions, considering recent climate changes. This might explain why some values of average wind speed and wind power density in this study differ from those in RA Zakhidov's and N.N. Sadullaeva's works.

2. Methodological approaches and analysis models: Each researcher employed different methodological approaches for assessing wind potential. For example, the work by Zakhidov et

al. focused on regional analysis covering entire areas without considering specific data for individual meteorological stations. This could lead to averaged values for entire regions, which may not reflect local wind conditions. NN Sadullaeva's work used data collected every 30 minutes, but then averaged to daily values, potentially smoothing short-term wind speed fluctuations. In contrast, this study applied the two-parameter Weibull distribution function to analyze data with a 3-hour interval, allowing for a more accurate assessment of wind variability and energy potential.

3. Geographic coverage and selection of observation sites: Differences in results may also stem from variations in geographic coverage and site selection. Bahrami et al. (2019) study considered data from 17 sites, while this study used data from 77 meteorological stations, offering broader coverage and capturing the diversity of wind conditions across Uzbekistan. This difference in geographic scope might explain discrepancies in wind speed and wind power density values for the same regions, particularly evident in the Bukhara and other areas.

4. Climate change and its consideration in research: Finally, an important factor is the consideration of recent climate changes. This study, covering the period from 2000 to 2022, accounts for more recent climate shifts, which may lead to different results compared to studies using data up to 2005 or data from 2018–2019. For instance, Bahrami's study shows a higher wind power density values in some regions, possibly due to the use of TMY data, which represent averaged climate conditions over many years and do not reflect recent climate trends.

4. Conclusion and recommendations

4.1. Summary of results

This study conducted a comprehensive analysis of wind energy potential across various regions of Uzbekistan at a height of 10 meters above ground level, an important step toward developing renewable energy sources in the country. The study is based on data collected from 77 meteorological stations across Uzbekistan, providing representative coverage and reliability of the results. The key findings of the study are as follows:

The highest average wind speeds were recorded in the western and northwestern regions of Uzbekistan including the Republic of Karakalpakstan, Navoi, Kashkadarya, and Bukhara regions. The average wind speed in these

regions ranges from 6.5 to 7.5 m/s, exceeding the minimum threshold required for the efficient operation of wind turbines. These regions demonstrate significant potential for wind energy utilization due to stable and high wind speeds, making them attractive for investment in the wind energy projects;

The data analysis revealed that the highest wind power density is observed in areas such as the Jaslyk district in Karakalpakstan (202.01 W/m²), the city of Navoi (94.5 W/m²), and Dekhkanabad District in Kashkadarya (85.33 W/m²). These figures significantly exceed the threshold values necessary for economically viable electricity production from wind, underscoring the importance of these regions for wind energy development;

Wind rose charts identified the prevailing wind directions in various regions of Uzbekistan. For example, in the western regions, winds predominantly come from the west and northwest, while in the southern and central regions, winds are primarily from the southwest and south. These data are key for the optimal placement of wind turbines, as correctly orienting the turbines can significantly improve their efficiency and lifespan, minimizing equipment wear, and reducing maintenance costs;

Maps of average annual wind speed distribution and wind power density for the entire territory of Uzbekistan were developed. These maps provide a visual representation of the wind potential across various regions, serving as a critically important tool for planning and implementing wind energy projects, as well as for attracting investments.

4.2. Recommendation

Based on the analysis conducted, the following steps are recommended to optimize the use of wind resources:

- Data collection optimization requires using measurements at higher frequencies (e.g. every 10 minutes), which will allow for more accurate assessments of short-term wind speed fluctuations and more precise modeling of wind potential. This approach will significantly improve the forecasting and management of wind energy installations;

- Integration of various data sources such as meteorological stations, satellite observations, and numerical models is important for forming a more comprehensive and accurate understanding of wind resources. This will allow for consideration of local features and microclimatic conditions, which are critical for effective wind energy project planning;

- Detailed regional studies at the meteorological station level are necessary to accurately determine the local wind energy potential. This will help to make the most efficient use of available resources and improve the economic return on wind energy investments;

- When updating wind potential maps, it is important to consider modern climate changes such as rising global temperatures and changing precipitation patterns. This will ensure the long-term sustainability and adaptability of Uzbekistan's energy system, accounting for possible changes in wind patterns in the future.

The results of the study indicate a significant potential for wind energy utilization in Uzbekistan. To fully realize this potential, the following measures are recommended:

- Ensuring regular updates and adjustments to wind speed and direction data. This is necessary to account for changes in wind patterns and quickly adapt to new conditions, which is especially relevant in the context of a changing climate. This approach will improve forecast accuracy and enhance the reliability of wind energy project planning;

- Conducting an in-depth analysis of the economic feasibility of wind energy projects, it is important to carry out comprehensive economic analysis to determine the profitability and payback of projects, taking into account local conditions and current market trends. This will help more accurately assess economic risks and benefits and select the most promising sites for wind energy investment;

- Developing and implementing local strategies for efficient wind energy utilization. It is necessary to design and implement regionally adapted strategies and support programs aimed at the development of wind energy in areas with the highest potential, such as Karakalpakstan, Navoi, Kashkadarya, and Bukhara regions. These measures will help create a sustainable energy infrastructure and contribute to strengthening the country's energy security.

This study opens up new opportunities for the development of wind energy in Uzbekistan, which will contribute to enhancing the country's energy security, reducing dependence on traditional energy sources, and lowering the carbon footprint.

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