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STRATEGIC FOUNDATIONS FOR THE DEVELOPMENT OF WIND POWER IN UZBEKISTAN AND ASSESSMENT OF REGIONAL WIND RESOURCES FOR SMALL-CAPACITY WIND SYSTEMS

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Abstract: The efficiency of small-capacity wind energy systems, including devices based on permanent magnet synchronous generators (PMSG), depends directly on the wind resources of the installation site. For this reason, the present article examines the strategic and legal foundations for the development of wind power in Uzbekistan and assesses the wind potential of 13 regions of the country. Using the two-parameter Weibull distribution function, the shape (k) and scale (c) parameters, the wind power density, and the prevailing wind directions were determined for each region. In addition, measurements taken at 10 metres were extrapolated to generator operating heights by means of the power law. The results revealed a considerable regional variation in wind potential: the highest values were recorded in the western and north-western regions, particularly in Karakalpakstan, Navoi, Kashkadarya and Bukhara. The obtained results provide a scientific basis for siting small-capacity PMSG systems and optimising their operating modes.

Keywords: wind power, permanent magnet synchronous generator, Weibull distribution, wind power density, regional potential, height extrapolation, small-capacity systems.

Introduction

Amid the intensification of climate change and the limited reserves of conventional fuels, countries worldwide are striving to place their energy supply on a sustainable footing. Renewable energy sources today cover roughly one third of global energy consumption, and this share is growing year after year [1]. Wind energy is one of the fastest-growing segments in this field, distinguished by its low operating costs, rapid installation and scalability [2, 3].

Uzbekistan has also actively joined this process. The country's energy policy up to 2030 envisages a considerable increase in the share of renewable energy sources, including the commissioning of dozens of wind power plants with a total capacity of 4.4 GW [4]. Projects involving major international operators are turning the country into one of the regional leaders in wind power.

Small-capacity wind energy systems mainly employ permanent magnet synchronous generators (PMSG). Their energy efficiency and operating mode depend directly on the wind speed and its distribution at the installation site, since the power produced by the generator varies in proportion to the cube of the wind speed. Therefore, before designing and siting a unit it is necessary to accurately assess the wind resources of the relevant region.

Although a number of studies on assessing wind potential have been carried out in Uzbekistan, most of them are either confined to a single region or rely on outdated data. Assessments that cover all regions of the country under a unified methodology, and that are adapted in particular to the operating heights of small-capacity generators, are rare. It is precisely this gap that determines the relevance of the present study.

The aim of this article is to analyse the strategic and legal foundations for the development of wind power in Uzbekistan, and to assess the wind resources of 13 regions of the country using the Weibull distribution in order to identify the most promising areas for siting small-capacity wind systems.

1. Strategic and Legal Foundations for the Development of Wind Power

In 2019 the legal foundation for wind power was established: by Presidential Decree No. PP-4477 the "Strategy for the Transition to a Green Economy for 2019–2030" was adopted, setting the target of raising the share of renewable energy sources above 25 per cent; in the same year, Law No. O'RQ-539 "On the Use of Renewable Energy Sources" granted producers a five-year exemption from taxes and a ten-year exemption from property and land taxes for installations [3]. Subsequently, under Presidential Decree No. PF-60 of 28 January 2022, the installation of 8 GW of solar and wind plants was planned, and Resolution No. PQ-57 of 16 February 2023 envisaged an additional 1.6 GW of wind capacity [4]. Over the past five years about 20 billion US dollars of foreign investment was attracted to the sector and 9.6 GW of new capacity (including 14 solar and wind plants — 3.5 GW) was commissioned; by 2030, contracts have been signed with international companies to build 10 wind power plants with a total capacity of 4.4 GW [4].

The target indicators for the development of wind power set by the state are summarised in Table 1.

Table 1. Key target indicators for the development of renewable energy in Uzbekistan [3, 4]

Indicator	2019	2025	2030
Share of RES in electricity, %	10–12	20	≥25–50
Wind power capacity, GW	0	1.6	4.4
Solar power capacity, GW	—	≥2.0	≥5.0
Attracted foreign investment, bn USD	—	≥20	≥25

Figure 1 shows the capacities and locations of the wind power plants planned for construction within the country in 2022–2030. The bulk of the projects are concentrated in the western and central regions — along the Karakalpakstan, Bukhara and Navoi axes — which is explained by the high wind potential of these areas.

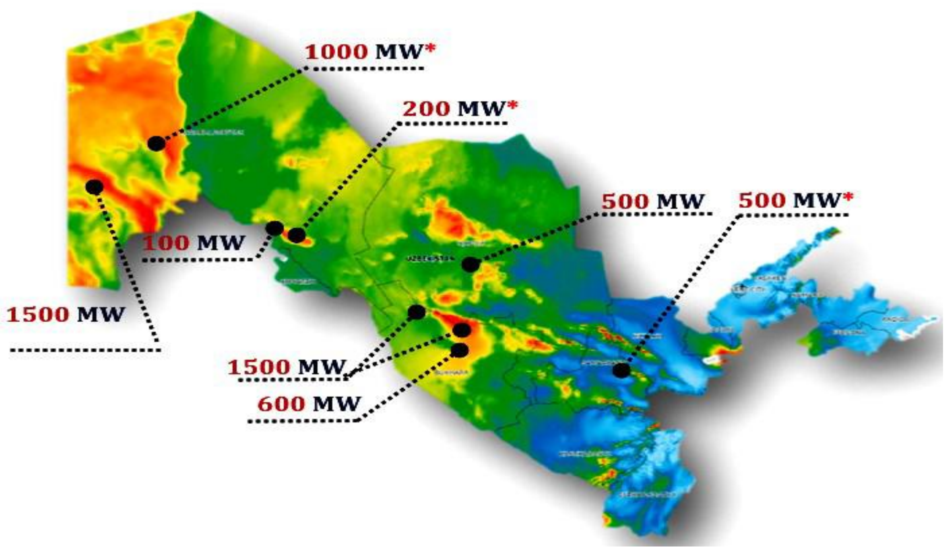

Figure 1. Wind power plants planned for construction in the Republic of Uzbekistan in 2022–2030 [6]

2. International Experience and Global Trends in Wind Power

Wind energy is the fastest-growing generation technology among renewable sources. The past decade has been the most productive period in the history of the sector: between 2015 and 2024 the cumulative installed wind capacity worldwide rose from 433 GW to 1136 GW, that is, almost trebled [1, 2].

This growth can be conditionally divided into three phases. In 2015–2019 annual new installations ranged between 51 and 64 GW, showing steady growth. In 2020–2022, owing to the activation of green-economy programmes, this figure reached 82–93 GW. In the third, record phase (2023–2024) more than 117 GW of new capacity was commissioned each year, and cumulative capacity exceeded the 1000 GW mark for the first time in history [1, 2]. In 2025 new installations exceeded 150 GW, setting yet another record.

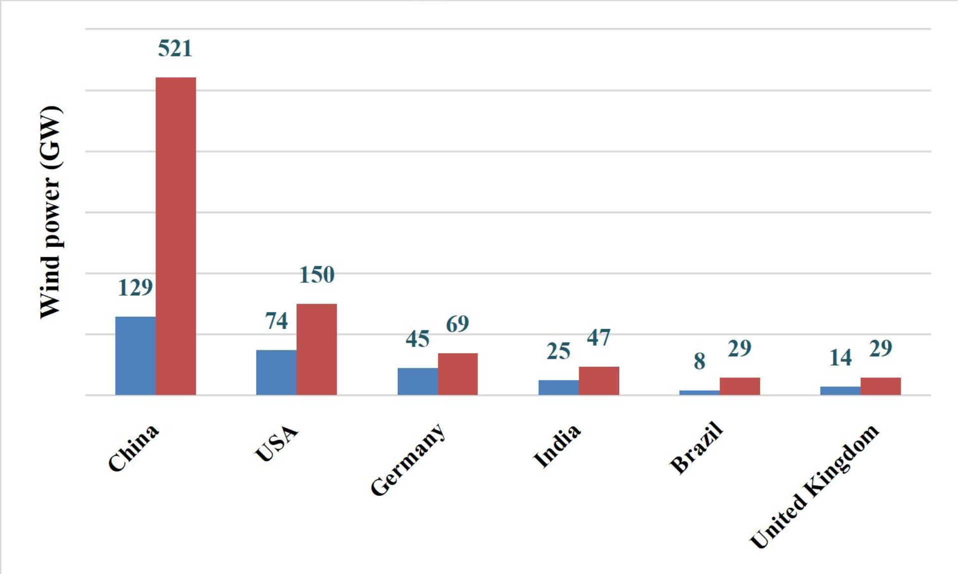

Figure 2. Cumulative wind capacity of leading countries: comparison of 2015 and 2024 (GW)

One of the most important features of the sector is the high degree of regional concentration. The capacity dynamics of the leading countries are presented in Table 2.

Table 2. Dynamics of cumulative wind capacity by leading countries (2015–2024) [1]

Country	2015 (GW)	2024 (GW)	Growth (%)
China	129	521	+304%
USA	74	150	+103%
Germany	45	69	+53%
India	25	47	+88%
Brazil	8	29	+263%
United Kingdom	14	29	+107%

The table data show the absolute leadership of China: in 2024 it accounted for about 46 per cent of the world's cumulative capacity. Together, the top-10 countries make up more than 82.5 per cent of global capacity [1]. In 2025 the Asian region covered about 60 per cent of the world's wind capacity, becoming the main centre of growth.

Although the global trends above relate mainly to large grid-connected units, the demand for small-capacity (0.5–5 kW) wind generators is also increasing. For remote areas and agricultural facilities such units hold a significant share of the world market. In this field, permanent magnet synchronous generators (PMSG) are recognised as the principal technological solution owing to their high efficiency, low maintenance requirements and ability to operate over a wide speed range.

3. Analysis of Previous Studies

The assessment of Uzbekistan's wind power potential has been carried out on the basis of many years of scientific research. The "Uzbekistan Energy Profile" report published by the IEA in 2021 states that the total gross wind energy potential of Uzbekistan amounts to 2.2 Mtoe, of which the technically usable part equals 0.4 Mtoe [5]. However, these figures were formed without taking into account subsequent climate change, and later studies have shown that the wind potential is considerably higher [6].

The first systematic studies were conducted by a group led by R.A. Zakhidov on the basis of data from 88 meteorological stations; they identified Karakalpakstan and Navoi as the most promising zones, but the work relied on the unupdated, pre-2005 data of the NASA database [7]. N.N. Sadullaev and A.B. Safarov, using the case of the Bukhara region, carried out a detailed analysis by means of the two-parameter Weibull distribution and found that the power density was 40.98 W/m² at 10 metres and 164.79 W/m² at 100 metres; the strength of this work is its height-extrapolation methodology, while its limitation is that it is confined to a single region [8].

In the 2025 work of Rakhimov E.Yu., Avezova N.R. and Jamoldinov F.Z., data collected every three hours from 77 meteorological stations of Uzbekistan over 2000–2022 were analysed by means of the Weibull distribution function. Compared with earlier studies based on NASA data, this approach made it possible to take modern climate change into account and provided a complete assessment of 13 regions [6].

The analysis carried out shows that the existing studies contain a number of originality gaps. First, most works are confined either to outdated data or to a single region. Second, studies that analyse wind resources specifically in connection with the operating heights and requirements of small-capacity (0.5–5 kW) generator systems are almost non-existent. Third, an approach integrating regional resource assessment with the efficiency of a permanent magnet synchronous generator has not yet been formed. It is precisely these gaps that determine the scientific novelty of the present study.

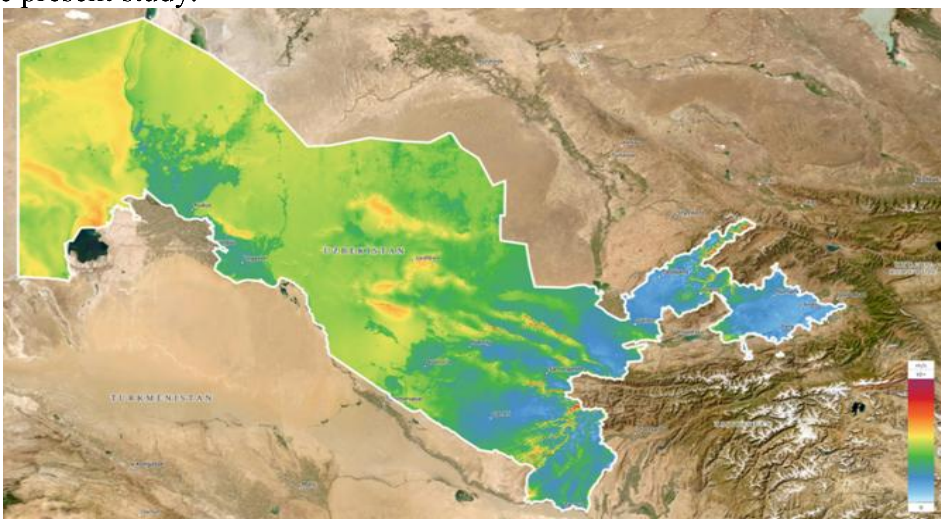

Figure 3. Map of the distribution of the average annual wind power density calculated at a height of 10 m over the territory of Uzbekistan [6]

4. Research Methods and Materials

To assess wind speed, the two-parameter Weibull distribution function was applied in this study. With its help, the average annual wind speed, power density and energy density at a height of 10 metres are evaluated. The Weibull probability density function is expressed as follows:

$$f_W(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \cdot e\left(-\left(\frac{v}{c}\right)^{k}\right);$$

where f(v) is the probability distribution function of wind speed, v is the wind speed, k is the shape parameter (dimensionless; its increase indicates a greater concentration of speed around the mean value), and c is the scale parameter (m/s).

The shape and scale parameters are determined through the mean speed $\bar{v}$ and the standard deviation σ:

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

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

where Γ is the gamma function. The power per unit area (the power density) is calculated on the basis of the Weibull parameters as follows:

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

where ρ is the air density (1.23 kg/m³ under normal conditions). Since generators are usually installed above 10 metres, the 10-metre measurements must be converted to the operating height.

As the data source, the Weibull parameters (k, c) and power density values calculated for 13 regions at a height of 10 metres for the period 2000–2022 by Rakhimov et al. (2025) were used [6].

5. Results and Their Analysis

The research results show that the highest wind power density (202.01 W/m²) was recorded in the Jaslyk district of the Republic of Karakalpakstan. Second and third places are occupied by the city of Navoi (94.50 W/m²) and the Dekhkanabad district of the Kashkadarya region (85.33 W/m²), respectively. The lowest value was observed in the Samarkand region (6.35 W/m²) [6]. The complete Weibull parameters by region are presented in Table 3.

Table 3. Weibull distribution parameters and wind power density by region [6]

No.	Region and meteorological station	k	c (m/s)	P/A (W/m²)
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, Lalmikor	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	1.97	4.47	85.33
8	Rep. 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	71.70
13	Khorezm region, Urgench	1.93	3.82	47.04

In terms of the multi-year average wind speed, the highest values were observed in the Republic of Karakalpakstan (Jaslyk — 3.9 m/s, Nukus — 3.8 m/s), the Bukhara region (3.54 m/s) and the Navoi region (3.3 m/s). A clear regularity appears in the spatial distribution: the western and north-western regions (Karakalpakstan, Navoi, Bukhara) have high potential, while the eastern regions and the Fergana Valley yield relatively low values [6].

Along with the power density, the shape parameter k is also of great importance. The Kashkadarya and Bukhara regions stand out not only for their high power density but also for their high k value (1.97) — this indicates that the wind speed is stably concentrated around the mean value and ensures steady energy production. Conversely, in the Bekabad district of the

Tashkent region k = 0.74 (P/A = 71.70 W/m²), which, despite the high average power, indicates strong variability of speed, that is, an unstable regime. Therefore, the prospects of a region should be assessed not by power density alone but together with the k parameter.

5.1. Prevailing Wind Directions

To site a wind generator and orient it correctly towards the flow, it is necessary to know the prevailing wind directions. The main directions and their frequency of recurrence by region are presented in Table 4. The data show that in most regions one or two main directions dominate, which makes it possible to set the turbine to a fixed orientation.

Table 4. Prevailing wind directions by region [6]

No.	Region	Sector	Frequency (%)
1	Andijan, Andijan	SW	8.6
2	Bukhara, Ayakagitma	N	18
3	Fergana, Kokand	WSW	13
4	Jizzakh, Lalmikor	NE	15
5	Namangan, Namangan	NW	26
6	Navoi, Navoi	E	29
7	Kashkadarya, Dekhkanabad	E	22
8	Karakalpakstan, Jaslyk	E	18
9	Samarkand, Samarkand	SE	15
10	Syrdarya, Yangiyer	SE	21
11	Surkhandarya, Termez	NNE/WSW	14
12	Tashkent, Bekabad	E	35
13	Khorezm, Urgench	NE	12.6

In the high-potential regions (Navoi, Kashkadarya, Karakalpakstan) the easterly (E) direction predominates, which means that in these areas efficiency can be increased by siting the turbines aligned to a single direction.

5.2. Variation of Wind Resources with Height

Small-capacity wind units are usually installed at a height of 10–50 metres. Using formulas (4), the scale parameter and power density for the five most promising regions were extrapolated to heights of 30 and 50 metres; the results are presented in Table 5.

Table 5. Variation of wind power density with height for high-potential regions (author's calculation based on formulas (4))

Region	c_{10} (m/s)	P/A_{10}	c_{30}	P/A_{30}	c_{50}	P/A_{50}
Karakalpakstan (Jaslyk)	4.17	203.7	5.45	333.7	6.18	422.8
Navoi	3.76	95.4	4.97	173.4	5.65	230.2
Kashkadarya (Dekhkanabad)	4.47	74.1	5.81	146.8	6.56	202.2
Bukhara (Ayakagitma)	4.20	61.5	5.49	124.0	6.22	172.2
Khorezm (Urgench)	3.82	47.3	5.04	97.7	5.73	137.1

The calculations show that as the height increases the power density rises sharply: when raised from 10 to 50 metres it more than doubles in Jaslyk (from 203.7 to 422.8 W/m²), and increases 2.5–3-fold in the other regions. This confirms that small-capacity units can be operated efficiently even in regions of moderate potential, provided they are installed at a sufficient height.

6. Discussion

Comparison of the obtained results with previous studies reveals a number of differences. For example, in the data adopted for the present study for the Bukhara region k = 1.97 and P/A = 61.13 W/m², whereas Sadullaev et al. (2019) reported k = 2.98 and P/A = 40.98 W/m² [8]. These discrepancies are explained by several reasons: first, the data period and measurement frequency differ (2000–2022, three-hour interval versus 2018–2019, 30-minute interval); second, differences in the statistical method and the choice of observation point; third, the consideration of modern climate change. Data covering a long period more accurately reflect the current wind regime.

The research results are of practical importance from the standpoint of small-capacity PMSG systems. Since the power density is proportional to the cube of the wind speed, the output power and efficiency of the generator depend directly on the c and k parameters of the installation site. In regions with high and stable speed (Jaslyk, Dekhkanabad) the PMSG operates close to its nominal mode, which increases its efficiency. In regions with low or unstable speed, the generator must be designed to suit local conditions and its control algorithms optimised.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of the study conducted, the following conclusions were reached:

The legal and strategic basis for the development of wind power in Uzbekistan has been fully formed: it is planned to raise the share of renewable energy sources to 50 per cent by 2030 and to commission 4.4 GW of wind capacity. The wind potential of the 13 regions of the country varies considerably. The highest power density was recorded in the western and north-western regions — Karakalpakstan (Jaslyk, 202.01 W/m²), Navoi (94.50 W/m²) and Kashkadarya (Dekhkanabad, 85.33 W/m²). In assessing the prospects of a region, the shape parameter k must be taken into account along with the power density: Kashkadarya and Bukhara, with a high k (1.97), ensure a stable regime. The height extrapolation showed that when raised from 10 to 50 metres the power density increases 2.5–3-fold, which makes it possible to operate small-capacity units efficiently even in regions of moderate potential.

As practical recommendations, the following are proposed: to introduce small-capacity PMSG systems first of all in the Karakalpakstan, Navoi and Kashkadarya regions; to install turbines aligned to the prevailing wind direction of the region; and to optimise the operating mode and control algorithms of the generator according to the c and k parameters of each region. These results serve as input data for the author's subsequent research devoted to improving the efficiency of the permanent magnet synchronous generator.

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