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Wind Energy Suitability Mapping in Azerbaijan through GIS -Based Spatial Analysis

Nijat Imamverdiyev
Institute of Geography, Ministry of Science and Education of Azerbaijan
131 H. Javid Ave. Baku AZ1073, Azerbaijan
imamverdiyev.nicat@gmail.com

Abstract. This study applies an integrated geospatial modelling framework to evaluate Azerbaijan's wind energy potential and identify optimal locations for wind power plant deployment. Long-term meteorological records (1981–2020) from 84 stations, MERRA-2 satellite observations, and Global Wind Atlas data were combined within a GIS-based multi-criteria analysis. The results reveal that 10.7 % of the national territory (9,200 km²), primarily along the Caspian Sea coast and the Absheron Peninsula, exhibits average annual wind speeds of 5.6–8.5 m/s and power densities of 390–975 W/m² at 50 m hub height. The estimated technical potential is 800 MW, equivalent to 2.4 billion kWh/year, or 8.6 % of Azerbaijan's 2022 electricity production. Performance modelling of 2 MW and 3.45 MW turbines indicates annual generation of 3.4–4.96 million kWh per unit, with hub heights of 100 m increasing yields by up to 38.5 %. Despite the current utilization of only 2.2 % of the technically exploitable 3,000 MW potential, large-scale deployment could raise this share to 20 % within the next decade, significantly reducing fossil fuel dependency and avoiding substantial CO_2 emissions. The integrated methodology – combining multi-source wind datasets, altitude-specific wind mapping, and turbine performance simulations – offers a replicable decision-support tool for sustainable energy planning in Azerbaijan and similar regions.

Keywords: wind energy potential, GIS-based spatial analysis, renewable energy, Azerbaijan, MERRA-2, Global Wind Atlas

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Картографирование пригодности ветроэнергетики в Азербайджане посредством пространственного анализа на основе ГИС

Имамвердиев Н.
Институт географии Министерства науки и образования Азербайджана
Азербайджан, AZ1073, Баку, Проспект Г. Джавида, 131
imamverdiyev.nicat@gmail.com

Аннотация. В данном исследовании применяется интегрированная структура геопространственного моделирования для оценки ветроэнергетического потенциала Азербайджана и определения оптимальных мест для размещения ветряных электростанций. Многолетние метеорологические данные (1981–2020 гг.) с 84 станций, спутниковые наблюдения MERRA–2 и данные Глобального атласа ветров были проанализированы с применением ГИС-технологий. Результаты показывают, что на 10,7 % территории страны (9200 км²), в основном вдоль побережья Каспийского моря и Апшеронского полуострова, наблюдается среднегодовая скорость ветра 5,6–8,5 м/с и удельная мощность ветрового потока 390–975 Вт/м² на высоте 50 м. Расчетный технический потенциал составляет 800 МВт, что эквивалентно 2,4 млрд кВт·ч/год, или 8,6 % от производства электроэнергии в Азербайджане в 2022 году. Моделирование производительности турбин мощностью 2 МВт и 3,45 МВт показывает годовую выработку от 3,4 до 4,96 млн кВт·ч на единицу, при этом высота ступицы 100 м увеличивает выработку до 38,5 %. Несмотря на то, что в настоящее время используется лишь 2,2 % технически реализуемого потенциала в 3000 МВт, крупномасштабное внедрение может увеличить эту долю до 20 % в течение следующего десятилетия, снизив зависимость от ископаемого топлива и избежав значительных выбросов CO_2. Интегрированная методология, объединяющая наборы данных о ветре из разных источников, использование картографического материала и моделирование производительности турбин, предлагает воспроизводимый инструмент поддержки принятия решений для планирования устойчивой энергетики в Азербайджане и аналогичных регионах.

Ключевые слова: возобновляемая энергетика, производство энергии, ГИС–анализ, устойчивое развитие, пространственный анализ ГИС, MERRA–2.

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Introduction

Wind energy is among the fastest-growing renewable energy sources globally, offering significant potential for reducing greenhouse gas emissions and decreasing dependence on fossil fuels. The global technical wind energy potential was estimated at approximately 170×10^{18} kWh, although only about 4 % is currently exploitable due to technical, environmental, and land-use constraints. Maximizing this resource requires accurate, location-specific assessments that integrate wind regime analysis with topographic and infrastructural considerations.

In Azerbaijan, several studies have investigated wind resources from meteorological, technical, and economic perspectives. Eyyubov [1997] examined the climate and wind regime of the Absheron Peninsula, focusing on prevailing wind directions and their influence on human health. Salmanova F.A. [2012] analyzed the combined use of solar and wind power to improve rural living conditions. Salmanov O.M. [2009] assessed the country's wind energy resources and their utilization possibilities, and Rzayeva et al. [2003] developed simple wind and solar devices suitable for local conditions. Khammadov [2012] evaluated the feasibility of hybrid photovoltaic–wind systems in Azerbaijan, and Huseynov examined public acceptance of wind energy. Chuvarli and Jesman [2003] studied the conversion and utilization of wind and solar energy in the national context. More recently, Pashayev [2022] analyzed the development prospects of the "green economy" in the Karabakh and East Zangezur economic regions, and Abdullayev et al. [2018] proposed technological improvements for vertical-axis magnetic levitation wind turbines.

Internationally, advanced spatial decision-making tools have been applied to wind energy suitability analysis. Georgopoulou et al. [1997] used the Analytic Hierarchy Process (AHP) to classify Greek islands according to wind potential. Watson and Hudson [2015] applied *GIS-based* multi-criteria evaluation (MCDM) to assess regional suitability for wind and solar farms. Janke [2010] modeled wind and solar farm locations in Colorado using *GIS*, while Jianu and Rosen [2012] investigated noise pollution mitigation for wind turbines. Berken [2009] used *GIS* to analyze turbine siting within utility service areas, and Perkins and Everett [2011] examined offshore wind power development.

Despite these contributions, most previous Azerbaijani studies relied on limited temporal datasets or single-source measurements, lacking integration of long-term, multi-source wind observations with high-resolution *GIS* zoning and turbine performance simulations. This gap constrains the accuracy of site selection and hinders alignment between technical assessments and strategic renewable energy planning.

Azerbaijan's geographical location – bordering the Caspian Sea with diverse terrain ranging from coastal plains to high mountain ranges – produces distinct wind patterns and strong spatial variability. Absheron and certain offshore areas experience some of the highest average wind speeds in the country, exceeding 6 m/s at 50 m hub height, with more than 270 windy days per year [Geography Atlas, 2014]. Yet, despite an estimated 3,000 MW of technically usable potential, only 64 MW (2.2 %) is currently operational, contributing 0.39 % of national electricity production [Energy of Azerbaijan, 2023].

To address these limitations, this study integrates:

1. Long-term meteorological observations (1981–2020) from 84 stations (MERRA-2 satellite reanalysis data)
2. Global Wind Atlas datasets;
3. GIS-based multi-criteria spatial analysis and wind turbine performance modelling.

The novelty of this research lies in producing the first high-resolution, altitude-specific wind potential maps for Azerbaijan (10, 50 and 100 m) and directly linking wind resource assessment with capacity factor estimations for modern turbine models. The results aim to provide policymakers, engineers, and investors with a scientifically grounded, location-specific framework for wind energy development – maximizing technical output while minimizing environmental and economic risks.

Materials and methods

This study employs a geospatial modelling approach to assess the wind energy potential of Azerbaijan and to identify optimal locations for wind power plant (WPP) development. The methodology integrates multiple datasets and computational tools to analyze wind patterns and their interaction with the country's diverse topography.

The research database comprises:

1. Long-term meteorological observations – Wind speed, direction, and intensity data from national meteorological stations (1981–2020).
2. Global Wind Atlas (GWA) – High-resolution wind resource maps and power density data [GWA, 2025].
3. MERRA–2 satellite reanalysis – NASA's Modern-Era Retrospective Analysis for Research and Applications, Version 2 (1981–2022).
4. Field measurements – Conducted within the framework of this study for validation and comparison.

These datasets provide both temporal and spatial coverage, enabling a comprehensive understanding of wind characteristics.

The Absheron region was selected as the primary model area for ArcGIS-based wind flow assessment, due to its complex terrain and high wind potential. The integration of ArcGIS spatial analysis tools with GWA data allowed for precise evaluation of wind resources in relation to Azerbaijan's relief characteristics.

Key analytical steps included:

- GIS-based spatial analysis and overlay modelling – Combining wind regime and wind speed distribution data from MERRA–2 with topographic features such as elevation, slope, and surface roughness.
- Cartographic methods – Assessing the influence of mountainous areas, valleys, and coastal zones on wind direction and intensity.
- Multi-criteria classification – Applying GIS-based multi-criteria evaluation (MCE) techniques to integrate GWA and NASA Power datasets, producing a suitability index for potential WPP sites.

By combining wind resource data with physical and environmental constraints, this approach ensures that wind energy projects are located in areas with: optimal wind conditions for electricity generation; minimal environmental and land-use conflicts; and high economic feasibility for long-term operation.

This methodology provides a replicable framework for renewable energy site selection in Azerbaijan and similar geographic contexts.

Results and discussion

Wind Energy Potential in Azerbaijan

Analysis of meteorological and satellite datasets reveals that only 10.7 % of Azerbaijan’s territory (approximately 9,200 km²) meets the technical criteria for wind power plant (WPP) installation. These optimal zones exhibit average annual wind speeds of 5.6–8.5 m/s and power densities of 390–975 W/m² at a 50 m hub height. The highest potential areas are concentrated along the Caspian Sea coastline, particularly on the Absheron Peninsula, including Sitalchay, Yeni Yashma, Shurabad, and Pirallahi Island.

Wind speed analysis for 1981–2020 indicates that:

- Areas with > 6.5 m/s winds are primarily located along the eastern coastal strip.
- Wind speeds at 50 m height are approximately 20 % higher than at 10 m, while speeds at 100 m are on average 38.5 % higher than at 50 m.
- Pirallahi Island records the highest average wind speed (9.67 m/s), while Gabala experiences the lowest (1.68 m/s).

These findings align with earlier localized observations [Eyyubov, 1997; Geography Atlas, 2014] but provide higher spatial resolution through the integration of multi-source datasets. The wind energy potential of Azerbaijan was determined by calculating the possible intervals and correlation coefficients based on the wind speed indicators received from meteorological stations. The wind speed and power density were calculated at relative heights of 10, 50, and 100 meters, with weak, medium, and high. After analyzing the wind speed data of meteorological observation stations at a height of 50 meters, we determined that only 10.7 %, or 9,200 km² of the country's territory (5.5 m/s and above), is suitable for the placement of wind turbines (Fig. 1). In the mentioned areas, the average annual wind speed is 5.6 m/s, and the average power density is 390 W/m² [GWA, 2025]. According to these indicators, the wind potential was calculated as 800 MW, depending on the geographical location, natural conditions, and economic infrastructure of the country. Based on a power factor of 18 % for 10 meters–high turbines in Azerbaijan, the potential electricity generation would be 2.4 billion kWh. This is equivalent to 8.6 % of the 29.04 billion kWh of electricity generated in 2022.

The average annual wind speed indicators in Azerbaijan for the years 1981–2020 were analyzed by us using a spatial analysis tool in GIS and divided into eight parts, and the size of wind energy potential areas was calculated [NASA Power Data, 2024]. Thus, the area of areas with wind speeds of 2.5–3.5 m/s for the placement of wind turbines is three thousand km² (3 %) and 13.5 thousand km² (16 %) for divisions I and II, respectively. Areas with weak power (3.51–4.5 m/s) energy production potential are grouped within divisions III and IV and are calculated as 20 thousand km² (23 %) and 16 thousand km² (18 %) separately. The area of medium power areas in divisions V and VI, with wind speeds between 4.51 and 5.5 m/s, is 8 thousand km² (9 %) and 17 thousand km² (20 %), respectively. The areas of the territories within the VII and VIII divisions with high wind power reserves (5.51–6.5 m/s) and technical potential for the construction of wind power plants are 5.1 thousand (6 %) and 4.1 thousand km² (5 %) (Fig. 2). The potential areas, which total 9.2 thousand km², are considered the most suitable areas for the construction of WPPs, mainly covering the coast of the Caspian Sea, including Sitalchay, Yeni Yashma, Shurabad, etc. Figure 1 indicates that wind speeds above 6.5 m/s are concentrated along the Caspian coastline, highlighting its suitability for high-capacity turbines.

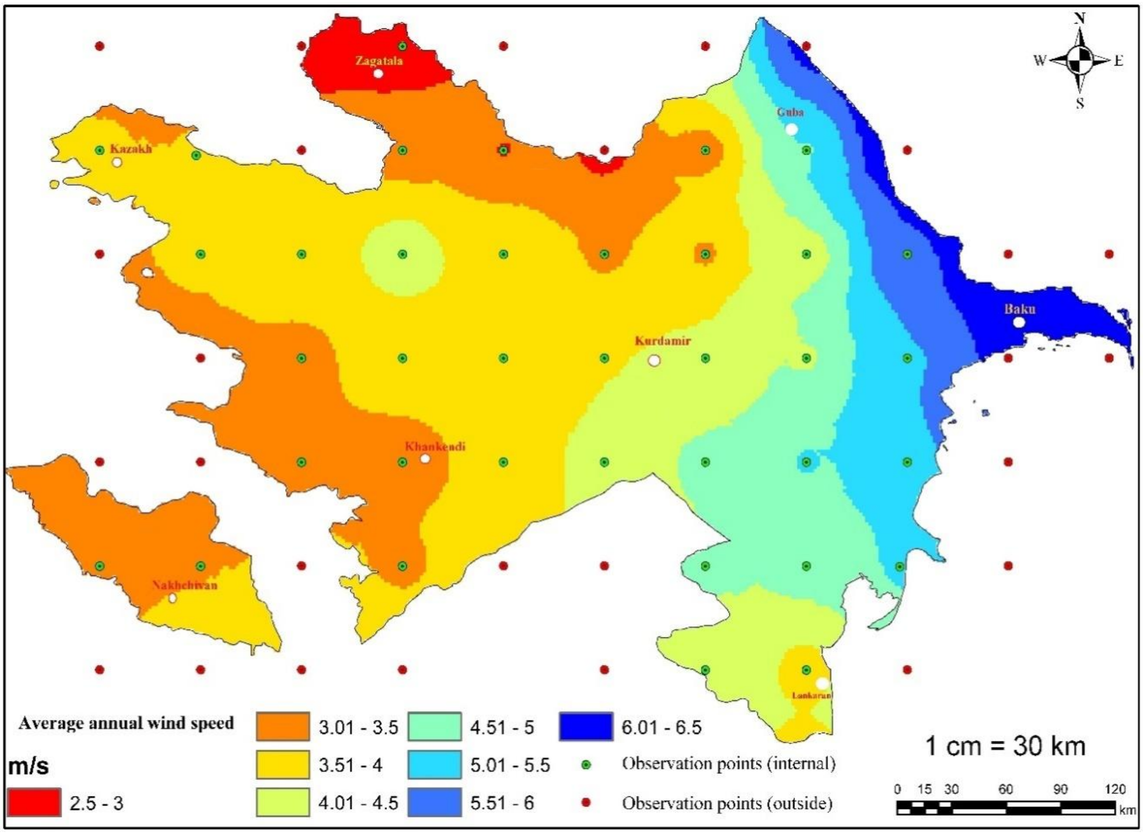


Fig. 1. Wind speed distribution in the Republic of Azerbaijan (50 m relative altitude)
Рис. 1. Распределение скорости ветра в Азербайджанской Республике (относительная высота 50 м)

A wind speed map was prepared by comparative analysis of the data of existing measurement observation stations in Azerbaijan, the Global Wind Atlas, MERRA–2 satellites, the Climate Atlas, the Ecological Atlas, and the Geographic Atlas of the Republic of Azerbaijan. Based on the MERRA–2 satellite database, wind speed data for 1981–2020 were analyzed for 84 stations in the country, and the average annual wind speed was determined to be 4.41 m/s. As can be seen from the dynamics given in Fig. 2, although an increase of 0.1 m/s was observed in the average annual wind speed (from 4.4 to 4.5), the speed remained stable in comparison with the overall period [NASA Power Data, 2024]. In addition, the maximum average speed in the country was 9.67 m/s on Pirallahi Island, and the minimum speed was 1.68 m/s in the Gabala district [Ecological Atlas, 2009].

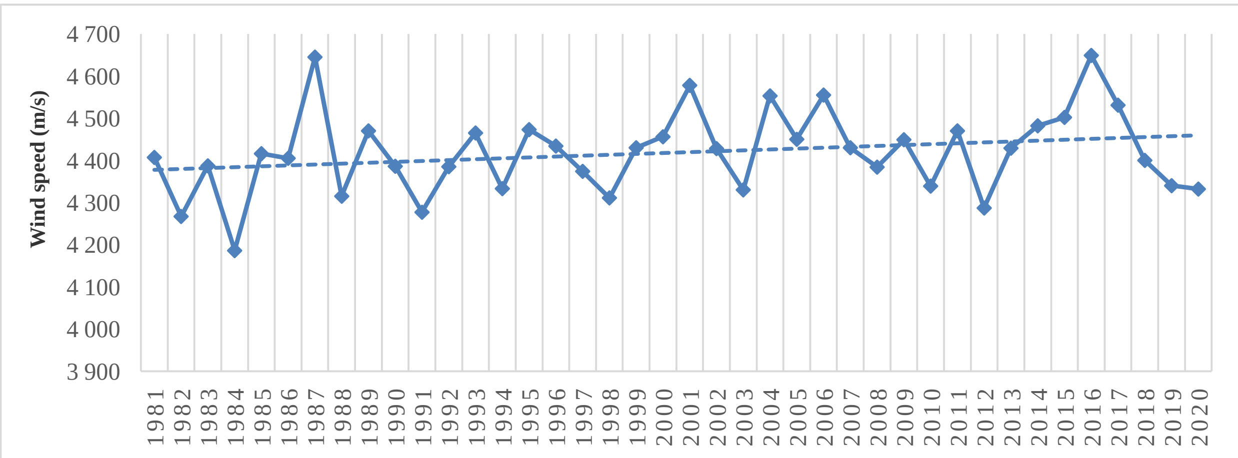


Fig. 2. Average annual wind speed in Azerbaijan for 1981–2020 [NASA Power Data, 2024]
Рис. 2. Среднегодовая скорость ветра в Азербайджане за 1981–2020 гг.

In meteorological observation data, the average annual minimum wind speed was calculated as 1.95 m/s, the maximum as 5.6 m/s, and the average as 3.6 m/s [GWA, 2025]. Areas with an average wind speed higher than 3.5 m/s mainly cover the Absheron Peninsula (Fig. 1). As a result of the analysis of this data, it was determined that the wind speed measured by satellite is 0.81 m/s lower than the data from the existing observation points. For this purpose, the wind energy potential was studied based on the basic data of another source, the Global Wind Atlas. The height of modern wind turbines with blades is 50 meters and above. For this purpose, we based the wind speed measurement data at a relative height of 50 m (Fig. 3 and 4), and prepared a wind speed map. Because of the analysis of wind speed data at a relative height of 10 m and 50 m, it was determined that the speed at a relative height of 50 meters is 20 % higher [GWA, 2025]. When wind turbines are placed at a height of 50 m, energy production will be correspondingly higher. As can be seen, the total area of areas with an average annual wind speed of more than 6.0 m/s in the republic is 5.5 thousand km² (Fig. 3 and 4).

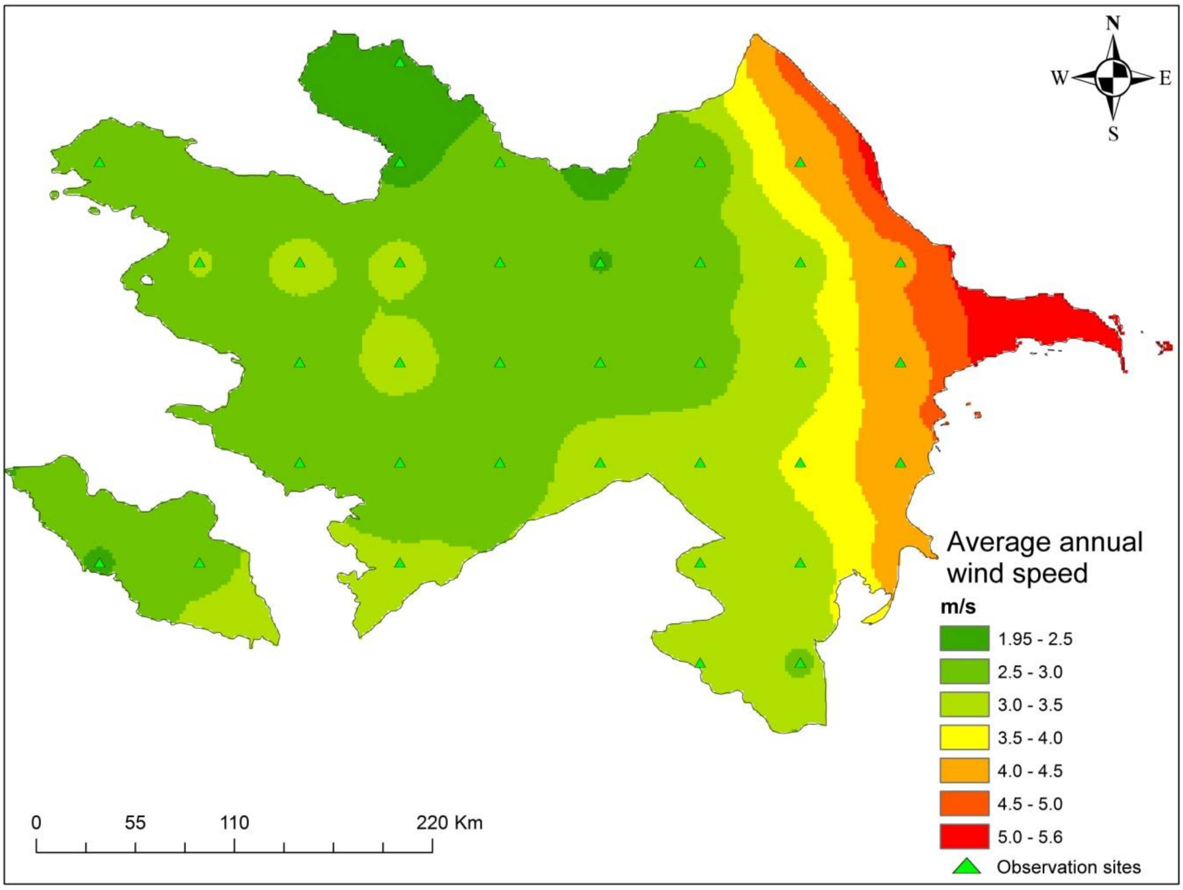


Fig. 3. Wind speed at 10 m relative heights in Azerbaijan
Рис. 3. Скорость ветра на относительных высотах 10 м в Азербайджане

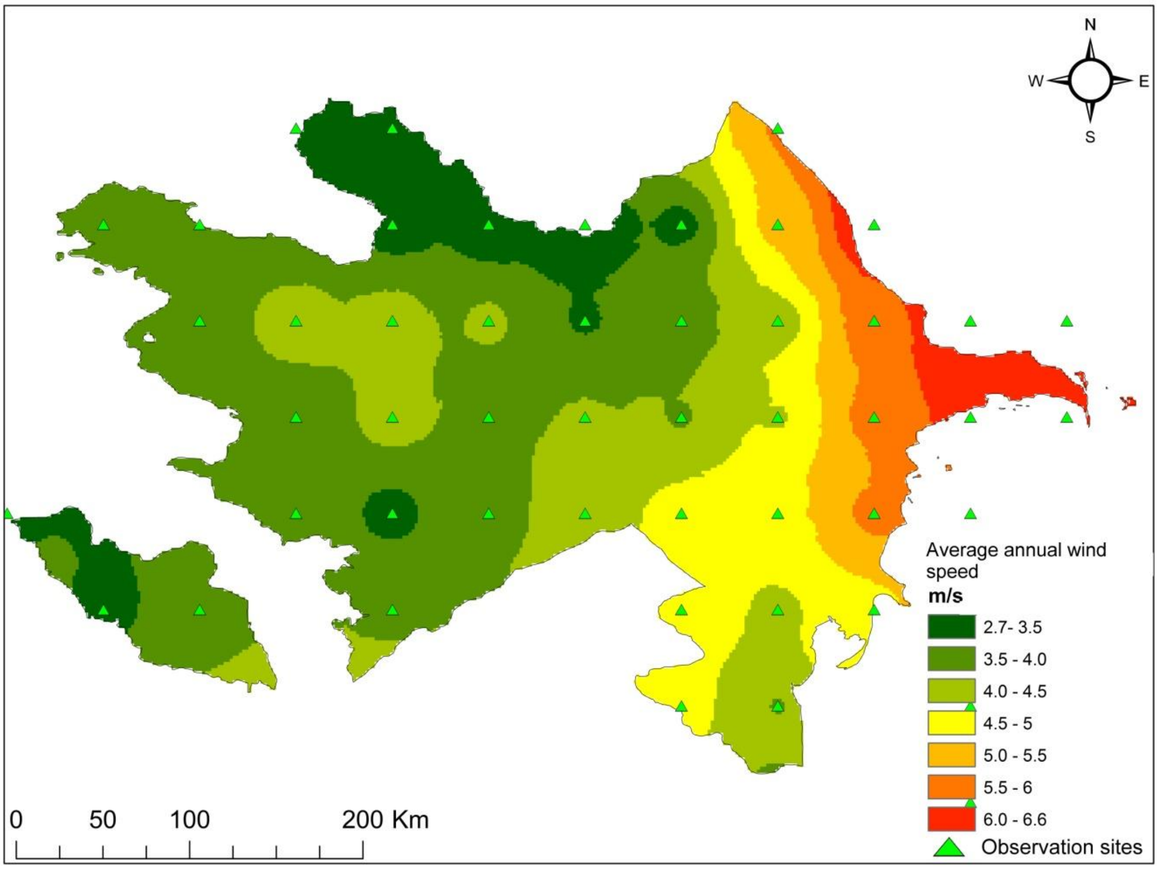
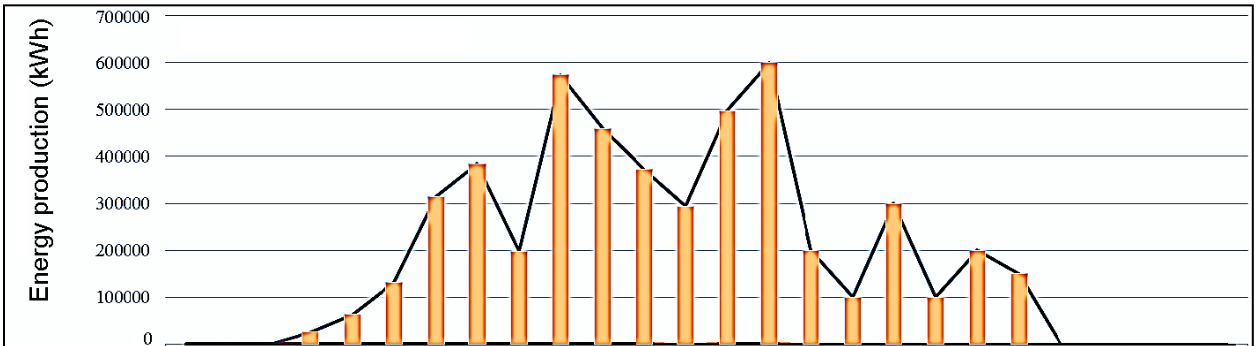


Fig. 3. Wind speed at 50 m relative heights in Azerbaijan
Рис. 3. Скорость ветра на относительных высотах 50 м в Азербайджане

The amount of energy production in the country according to the wind speed was calculated using the Wind pro program using a 2 MW wind turbine of the "Camesa G90" type as an example according to the following graph [Imamverdiyev, 2020]. The amount of energy production varies depending on the duration of windy hours, with wind speeds between 3 and 21 m/s. For this purpose, the dependence of wind energy production on wind speed and duration is analyzed in Fig. 5.



speed (m/s)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
hour/year	450	400	700	1200	750	1200	900	640	220	450	300	200	150	250	300	100	50	150	50	100	75	125	0	0	0	0
Energy prod. (kWh)		0	0	2640	6375	1320	3150	3840	1980	5733	4599	3726	2940	4975	5994	2000	1000	3000	1000	2000	1500	0	0	0	0	0

Fig. 5. Dependence of wind energy production on wind speed and duration
Рис. 5. Зависимость выработки ветровой энергии от скорости и продолжительности ветра

As can be seen from the graph, in areas with a high wind speed of 6 m/s, the annual duration will be 1200 hours and the amount of energy production will be 132 thousand kWh. In areas with a stable wind speed of 8–12 m/s, energy production is considered optimal for the construction of turbines with an average capacity of 2000 kW. In this case, as an example of areas with favorable wind speeds in the country, the maximum annual energy production of 2000 kW KES will be 4.96 million kWh (EFI 18 %).

Technical Potential and Energy Yield

Using WindPRO simulations for selected turbine models:

- *Gamesa G90 – 2 MW:* Annual generation of 3.4–4.96 million kWh per unit (capacity factor: ~18 %).
- *Generic 3.45 MW – IEC Class 2:* Annual generation of up to 3.4 million kWh in high-potential areas (capacity factor: ~28 %).

Pirallahi Island alone could accommodate 118 turbines of 2 MW capacity, producing 260 million kWh/year. With 9.5 MW Vestas V-164 turbines, potential output could reach 1.3 billion kWh/year. In areas with efficiency indicators in the selection of wind power plants, the average wind speed at a relative height of 50 m is 6.82 m/s, and the power density is 572 W/m² [GWA, 2025]. The total area of the areas with the highest wind potential, with an average annual wind speed of 8.5 m/s at a height of 50 meters and a power density of 975 W/m², is 5400 km². For example, by installing a "Generic 3.45 MW–IEC Class 2" type wind turbine in these areas, it is possible to obtain 3.4 million kWh/year (EFI 28 %). When comparing the height indicators and capital cost of wind turbines, it was determined that the optimal height in the area is between 50 and 100 meters. These areas are the Absheron Peninsula and the Caspian Sea coast, where the maximum number of windy days is 270/year [Ahmadov, Novruzova, 2019]. Examples of these areas include Pirallahi, Bina, Jilov Island, and Neft Dashlari, where the average annual wind speed is between 6 and 7 m/s. However, the wind speed indicators decrease towards the west of the peninsula. Thus, in the areas of Gizil Burun, Khizi, Gobustan, etc., the average annual wind speed drops to 4–4.6 m/s [Geography Atlas, 2014; Mammadova, 2015].

Wind speed indicators at a relative height of 100 meters in the republic were studied, and the average speed in potential areas was determined to be 7.8 m/s-year, and the wind power was determined to be 702 W/m. This is 2.5 m/s, or 38.5 % more than at a height of 50 meters [GWA, 2025]. In areas with an average annual wind speed of 7.8 m/s, it is possible to produce 1.3 million kWh of energy per year with a turbine with a diameter of 90 m of 2 MW blades. At this power, 6.4 thousand m² of land is needed for each turbine. Theoretically, it is possible to build 118 wind turbines of this type outside the restrictive areas on Pirallahi Island (17.6 km²), which has the highest potential in the country, which is equal to a total energy production of 260 million kWh (14 % of the FIE). If 9.5 MW Vestas V-164 wind turbines are installed in the same area, energy production will be 1.3 billion kWh.

The areas with average wind speed indicators are the Sharur, Julfa, and Ordubad districts of the Nakhchivan Autonomous Republic. In this region, only 560 km² of land at a relative height of 50 meters has wind potential. The average annual wind speed of Nakhchivan varies between 3 and 3.5 m/sec, which is weaker than that of the Absheron region [Mammadova, 2015]. The geographical position of the NAR allows it to be affected by the movement of two interacting airflows (cold air of arctic origin from the north and warm air mass of tropical origin from the south), which creates a high pressure in the Julfa and Ordubad districts, causing medium-strength winds.

In the Ganja-Dashkasan zone, the average annual wind speed is 3–3.5 m/s, and the number of windy days is 95 [Ahmadov, Novruzova, 2019]. Winds of 2–5 m/s are observed in the plain part of Ganja-Kazakh, and winds of 6–10 m/s on certain days at the foothill part. There is also sufficient wind energy potential in the southeastern coastal areas of the Mingachevir reservoir. In the mountainous areas of the Greater Caucasus, winds of 0–1 and 2.5 m/s in the northeast and southwest directions account for 80–85 %. Although strong and hurricane-like winds are rare in these areas, their speed does not exceed 20 m/s. In Lankaran-Astara, due to breeze and mountain-valley circulation, westerly and southeastern winds with speeds of 0–1 and 2–5 m/s (80 %) prevail. In the Lerik-Kelvez zone, the wind speed at a relative height of 50 m is 5.5–6.5 m/s [Aliyev, 2015]. It should be noted that, since the 1930s, a decreasing trend has been observed in both wind speed and the number of windy days. The average annual wind speed in the country decreased by 12 % in 1961–1990 compared to climate norms. The decrease in speed is observed more in the Kura-Araz lowland (47 %), coastal areas (22 %), and foothill and low mountainous zones (9 %). The number of strong windy days (15 m/s and more) has increased more than 2 times in most stations (81 %) compared to the norms before 1960, and in other stations (19 %) it has decreased by an average of 12 % [Geography Atlas, 2014]. The number of days with strong winds is 52 days/year, the highest in Absheron (Pirallahi – 129 days), the lowest in the Lankaran lowland (6 days), and the Kura-Araz (10–64 days).

The technical energy potential in the republic, depending on the wind speed, is 1500 MW. 70 % of this (1050 MW) falls on the Caspian Sea coast, mainly on the Absheron peninsula. Here, northern, northwestern and southern winds are observed, while winds from other directions are a minority. The speed of the prevailing winds in Absheron is 6–19 m/s, and in rare cases, winds of 2–5 m/s blow. Strong and hurricane-like winds blow from the north and northwestern on the peninsula, their speed sometimes reaches 30–40 m/s [Geography Atlas, 2014]. Taking these factors into account, it is imperative to choose structures that are more resistant to strong winds when placing turbines.

The prevailing wind direction in the Absheron region is mainly from the north, with 65 % of the year. The physical and geographical conditions of the coastal strip influence the wind speed in the area. Here, the speed is typically between 0.5 and 12 m/s, with only 30 % of the winds being greater than 8 m/s. Days with wind speeds exceeding 15 m/s on the peninsula are observed more often in winter. Strong windy days (21 m/s) are observed 35 days in Baku, 37 in Sumgait, and 40 in Pirallahi. Northern winds prevail here, and on certain days the speed reaches 30–40 m/s [Geography Atlas, 2014]. In winter, solar radiation is significantly reduced due to the influence of cold air masses. Thus, the number of days above 25°C in Baku is 50, and the number of days above 20 is 120. The number of days with an annual temperature between –5 and 10 is 5, the number of days between –5 and 0 is 3, and the number of days above 35 is 16 [Geography Atlas, 2014].

Seasonal and Regional Variability

Meteorological records covering 1981–2020 reveal that wind intensity across Azerbaijan changes noticeably with the seasons. The strongest winds occur in winter, particularly from December to February, when mean speeds along the Absheron Peninsula and the Caspian shore often exceed 6.5 m/s at a 50 m height. In these months, many modern turbines can achieve efficiency levels of 25–30 %, making this period the most productive for electricity generation from wind. During summer, however, inland regions typically see weaker winds, averaging 4.0–4.5 m/s, which limits output to roughly 12–18 % of installed capacity. Spring and autumn tend to be more balanced, with speeds of 5.0–5.8 m/s providing steady but moderate production [NASA Power Data, 2024; GWA, 2025]. This seasonal cycle means that wind power plants contribute more to meeting electricity demand in colder months, while solar plants become the main renewable source in summer. The complementary nature of these patterns can improve the stability of Azerbaijan's overall renewable energy supply. This seasonal complementarity supports hybrid renewable energy systems, with wind generation dominating in winter and solar in summer.

Seasonal analysis shows distinct wind patterns:

- Winter (Dec–Feb): Strongest winds (> 6.5 m/s in coastal Absheron), yielding capacity factors of 25–30 % for modern turbines.
- Summer (Jun–Aug): Inland areas experience weaker winds (4.0–4.5 m/s), reducing capacity factors to 12–18 %.
- Spring & Autumn: Moderate, steady production potential (5.0–5.8 m/s).

Current Utilization and Development Prospects

As of 2023, Azerbaijan's installed wind capacity is 64 MW, representing only 2.2 % of the technically exploitable 3,000 MW potential. The share of wind in total electricity generation is

0.39 % [Energy of Azerbaijan, 2023]. The government aims to expand wind capacity to 20 % of total generation within the next decade, supported by domestic and foreign investment in both onshore and offshore projects. In 2022, the total production capacity of 7 stations built for the use of wind energy was 64 MW and the electricity production was 83.3 million kWh [Energy of Azerbaijan, 2023]. This is 2.2 % of the technically usable wind energy potential of 3000 MW. Currently, the share of wind power plants in the country's total energy production is 0.39 % (table 1).

Table 1
Таблица 1

Wind power plants in Azerbaijan (2023)
Ветряные электростанции в Азербайджане (2023)

Station	Construction date	Capacity, MW	Location	Implementing organization	Million kWh	Turbine type and number
Yeni Yashma	2009 (2018)	50	Khizi (Yeni Yashma)	Caspian management systems and Aztrog LLC	109	Fuhrlander FL 2500 (20 units)
Yasma Baglari	2009	3,6	Khizi district Shurabad village	"Caspian Technology"	7	Vestas V90 (4 units)
Shurabad	2009	1,7	Shurabad sett. (Khizi)	Berlin Wind	11.6	Vestas V90 (2 units)
Hokmali	2011	8	Hokmali sett.	"Alten Group" LLC	17.5	Gamesa G78 (4 units)
Gobustan HPP	2011	2.7	Gobustan district	AREA	5.9	PowerWind 56 (H. 60 m)
Julfa HES	2021	0.3	Julfa	"Gamigaya Holding"	0.26	China "ANE" 10 units

Prepared based on data from the State Agency for Renewable Energy Sources under the Ministry of Energy of the Republic of Azerbaijan.

The locations of renewable power plants in the Republic of Azerbaijan, including wind power plants, can be clearly seen on the map we have prepared. This map provides a visual representation of the current distribution of these facilities across the country, highlighting the regions where renewable energy generation is already in operation (Fig. 6). In total, there are 46 stations of various sizes, seven of which are dedicated to wind energy.

Although wind energy production in the republic was 22.1 million kWh in 2017, this volume has increased 4 times in 5 years, reaching 83.3 million kWh. Thus, from 2009 to 2020, 164.3 million AZN was invested in wind energy, and 63.6 million AZN in 2014 alone, and a total of 514.4 million kWh of electricity was produced through wind turbines by 2023 [Energy of Azerbaijan, 2023]. It is planned to build 5 more stations over the next 10 years, thereby bringing the share of wind power in total production to 20 %.

Environmental and Economic Benefits

Each 1 MW of installed wind capacity:

- Saves approximately 14,500 tonnes of coal or 46,000 barrels of oil over 10 years;
- Prevents emission of 20,000 tonnes of CO_2, 100 tonnes of SO_2, and 2 tonnes of N_2O;
- Reduces reliance on natural gas, saving an estimated 365 million m^3/year if 400 MW of capacity is installed.

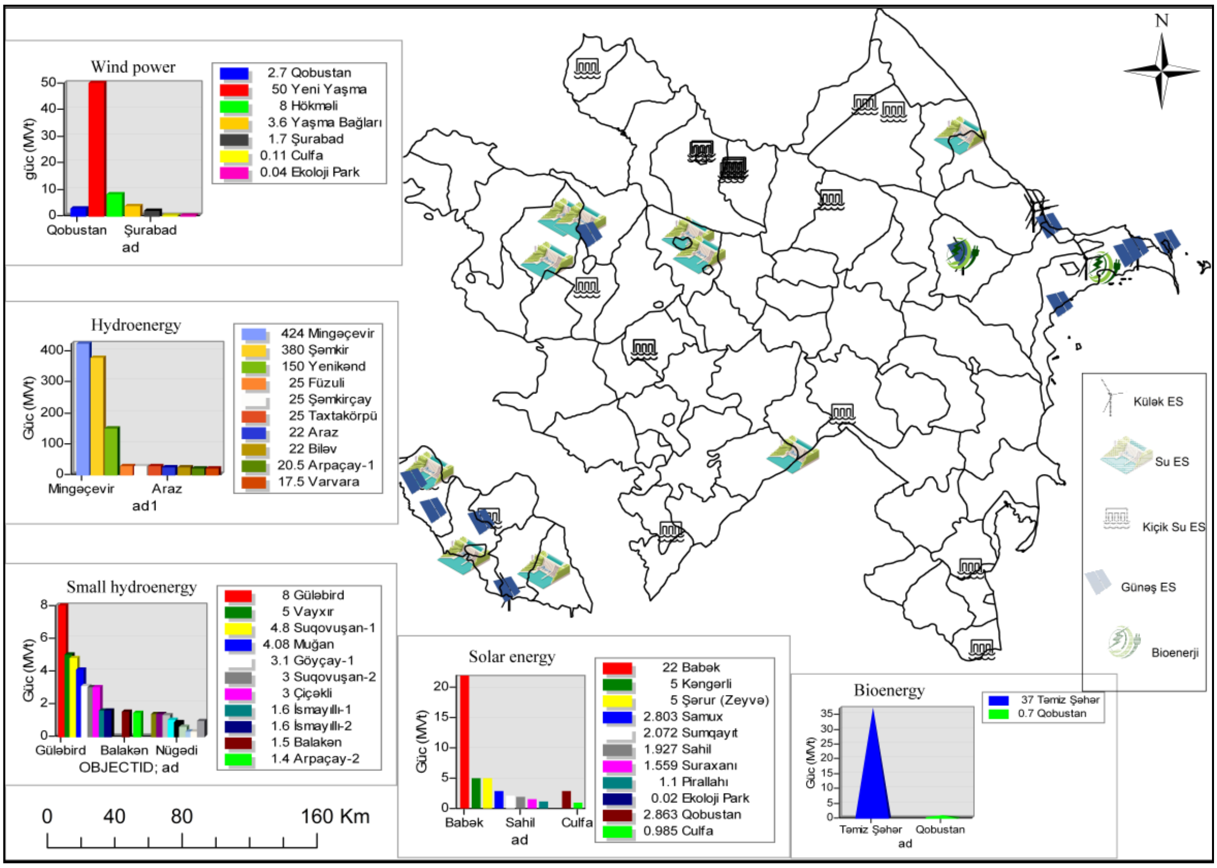


Fig. 6. Areas where renewable energy power plants are located in Azerbaijan
Рис. 6. Районы Азербайджана, где расположены электростанции, работающие на возобновляемых источниках энергии

These benefits align with global trends in decarbonization and enhance Azerbaijan's energy security by diversifying its energy mix. Although the economic benefit of wind power plants in the country is only 7.5 million AZN in terms of energy sales, they also have environmental benefits, such as not polluting the environment and eliminating dependence on hydrocarbon fuels. More precisely, each MW power plant saves 14.5 thousand tons of coal and 46 thousand barrels of oil over 10 years and prevents 20 thousand tons of CO_2, 100 tons of SO_2, and 2 tons of N_2O gases from being emitted into the atmosphere. The main part of the gases that cause the heat effect is carbon dioxide, 57 % of which is generated during the production of traditional energy. In general, 81 % of the electricity in the world is obtained by burning fuels that cause environmental pollution (31 % natural gas, 12 % oil, and 38 % coal). In Azerbaijan, 0.24 m³ of gas is consumed for each kWh of electricity production in thermal power plants. The electricity production of thermal power plants is 26.5 billion kW/h, which is equal to 5.7 billion m³ of gas consumption [Environment in Azerbaijan, 2023]. Thus, as a result of the combustion of 1 m³ of natural gas, 1.78 kg of carbon dioxide is emitted into the atmosphere. In general, as a result of the combustion of hydrocarbon fuels in thermal power plants, a significant amount of polluting gases, 34 % of which are carbon dioxide, are emitted into the atmosphere every year. However, if RES is used efficiently, 427 tons of carbon dioxide emitted into the atmosphere in each million kWh of energy production will be prevented. Also, since renewable energy stations do not require any costs other than annual maintenance, they will pay back the investment amount within an average of 8 years. This makes wind turbines economically viable as a future electricity investment. It will also ensure the return of the investment in the plant and additional profit over the 25-year operation period.

The capital cost of one MW of a wind turbine in Azerbaijan is 3 million US dollars. The wind energy was calculated based on the average annual wind speed and the area of optimal areas, and it was determined that there are many suitable areas in the country for building stations with a capacity of 400 MW. These stations can generate 1.5 billion kWh of electricity per year, as well as save 365 million m³ of natural gas. The following table was prepared based on data from the Geographic Atlas of the Republic of Azerbaijan (2018) and the Global Wind Atlas (2021) (table 2).

Table 2
Таблица 2

Area of potential areas suitable for wind power generation in Azerbaijan
Площадь потенциальных территорий, пригодных для ветрогенерации в Азербайджане

Regions	Wind power	Average annual wind speed (m/s)	Occupied area (thousand km^2)	Usable areas (thousand km^2)
Absheron Peninsula	High	5–6	3.9	0.34
Caspian Coastal Areas	High	6–7.5	2.3	0.2
Gobustan	Medium	3.5–5	2.5	0,5
Samur-Shabran	Medium	4.5–5	1.7	0.3
Ganja-Gazakh	Weak	2.6–4.2	2.8	0.46
Nakhchivan AR	Weak	2.5–3.1	5.5	0.275

With the development of wind turbine manufacturing technologies and the competitiveness of new manufacturing facilities, the cost of offshore wind energy production will decrease by 35 % and onshore by 26 % by 2025, to US $0.07 per kWh.

The analyses conducted in this study clearly demonstrate that Azerbaijan possesses significant wind energy resources, particularly along the Caspian coastal regions and the Absheron Peninsula. The integration of meteorological data, GIS-based spatial analysis, and energy modelling provides a scientific basis for identifying optimal locations for wind turbine deployment. Despite the current underutilization of this renewable energy source, the technical, environmental, and economic indicators all point to a strong potential for future development.

Practical Significance and Novelty

In this research, Azerbaijan's wind energy potential was evaluated in detail through a combination of long-term meteorological records (1981–2020) and MERRA-2 satellite data, interpreted within a GIS environment. The work has direct practical value as it offers a location-based assessment of where wind power plants could be most effective, taking into account both wind speed and terrain conditions. These results can be used by energy planners, engineers, and investors to select suitable sites, choose appropriate turbine heights, and estimate production capacity with greater accuracy. The findings show that 10.7 % of the national territory – primarily along the Caspian Sea coast and the Absheron Peninsula – has the potential to produce around 2.4 billion kWh of electricity each year, significantly reducing fossil fuel demand and preventing thousands of tons of carbon emissions.

Comparative Analysis with Previous Studies

Compared to earlier works [Salmanov, 2009; Khammadov, 2012], this study offers:

1. Higher spatial resolution in wind mapping (250 m grid from GWA data).
2. Altitude-specific wind potential mapping (10, 50, 100 m).
3. Integrated turbine performance modelling for site-specific yield estimation.

The methodology replicability allows for application in other Caspian Basin countries with similar climatic and topographic conditions. What sets this study apart is its integrated approach: satellite observations, ground measurements, and cartographic sources were combined to generate detailed wind maps for different altitudes (10, 50 and 100 m). The analysis also links wind speed patterns with technical capacity factors for different turbine models, offering insights not covered in earlier studies. This makes the methodology transferable to other regions with similar physical and climatic characteristics.

Conclusion

The primary aim of this study was to identify the most suitable territories for wind power plant deployment in Azerbaijan, fully aligned with the country's renewable energy transition long-term goals. By integrating long-term meteorological records (1981–2020) from 84 stations with MERRA-2 satellite data, Global Wind Atlas information, and field measurements into a GIS-based spatial analysis and wind turbine performance modelling framework, the research successfully achieved all stated objectives. The results showed that 10.7 % of the national territory (9.2 thousand km²), concentrated mainly along the Caspian coastline and the Absheron Peninsula, offers optimal technical and environmental conditions for wind turbine installation. These areas exhibit average annual wind speeds of 5.6–8.5 m/s and power densities of 390–975 W/m² at 50 m hub height. The technical potential is estimated at 800 MW, which is approximately 2.4 billion kWh per year. This is equivalent to 8.6% of Azerbaijan's electricity production in 2022. Performance modelling of 2 MW and 3.45 MW turbines indicated annual generation capacities of 3.4–4.96 million kWh per unit, while increasing hub height to 100 m improve yields by up to 38.5 %. Pirallahi Island alone could host 118 turbines generating 260 million kWh/year, or 1.3 billion kWh/year with 9.5 MW units.

Despite this significant resource base, only 2.2 % (64 MW) of the technically exploitable 3000 MW potential is currently utilized. Large-scale deployment is projected to raise this share to 20 % within the next decade, offering substantial environmental and economic benefits. Each 1 MW of installed capacity could save 14,500 tonnes of coal and 46,000 barrels of oil, while preventing 20,000 tonnes of CO_2 emissions over a 10-year period.

The integrated methodology applied here – combining multi-source datasets, altitude-specific wind mapping, and turbine performance modelling – offers a transferable decision-support tool for policymakers, engineers, and investors. Its application can guide strategic renewable energy planning not only in Azerbaijan but also in other regions with similar climatic and topographic conditions.

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INFORMATION ABOUT THE AUTHOR

Nijat Imamverdiyev, Senior Researcher at the Department of Azerbaijan Economic and Political Geography, Institute of Geography, Ministry of Science and Education of Azerbaijan, Baku, Azerbaijan

ИНФОРМАЦИЯ ОБ АВТОРЕ

Имамвердиев Нижат, старший научный сотрудник отдела политической и политической географии Азербайджана, Институт географии, Министерства образования и науки Азербайджана, Баку, Азербайджан