Advances in Sustainable Energies & Environment, 1 (2026) 3, 1 – 13

Advances in Sustainable Energies & Environment

Journal homepage: https://A-SEE.MazUST.ac.ir/

Research Article

Estimated Electricity Generation from Wind Energy Potential in Northern Iran

Nabiollah Ramezani [a*], **Mohsen Shahnazdoost Kilvaei** [b]

[a] *Department of Electrical & Computer Engineering, University of Science and Technology of Mazandaran, Behshahr, Iran*
[b] *Shahid Beheshti Power Plant, Organization, Lowshan, Guilan, Iran*

Article Info

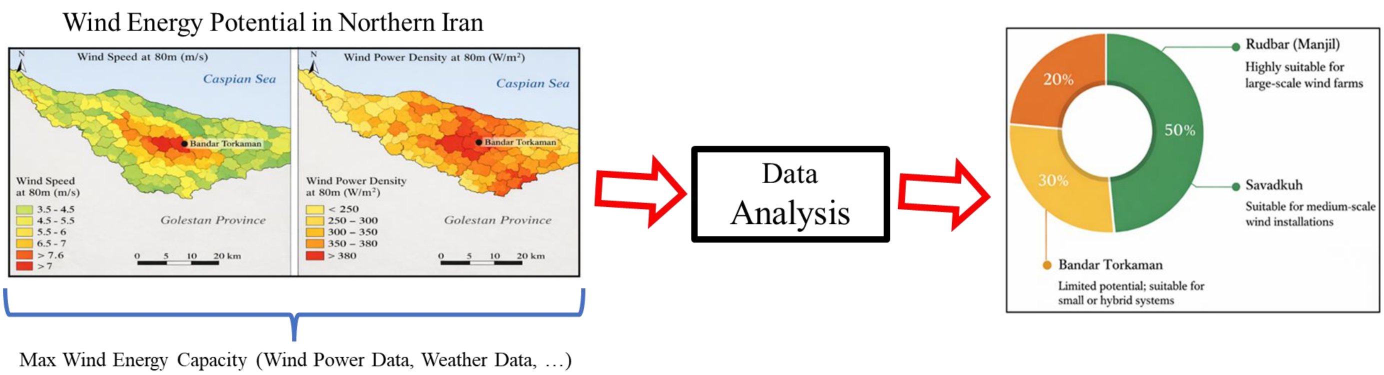
Article history:
Received: 2026-04-30
Revised: 2026-05-31
Accepted: 2026-06-06
Published: 2026-07-01

Keywords:
Clean electricity generation forecasting;
Electricity generation estimation;
Renewable wind energy evaluation;
Wind farm location in northern Iran;
Weibull distribution function;
Maximum estimation method.

Abstract

The increasing demand for sustainable and clean energy sources has positioned wind energy as a critical component of Iran's renewable energy strategy, especially in the northern provinces that enjoy favorable wind conditions. This paper presents a comprehensive assessment of wind energy potential across northern Iran, integrating meteorological data, regional wind patterns, and energy generation models to assess the feasibility of maximizing electricity generation from wind resources, which identifies optimal locations for the development of large-scale wind farms by analyzing spatial and temporal variations in wind speed, along with technological and environmental considerations. The amount of electricity generation assessed from wind potential highlights the significant and untapped potential in the northern regions, especially in coastal and mountainous areas, which can provide clean energy generation. It also contributes to Iran's energy diversification and carbon emission reduction goals. This work provides an essential framework for energy policymakers and planners aiming to implement efficient wind energy projects and support Iran's transition towards sustainable and environmentally friendly electricity generation. In order to predict the amount of electricity generation from the electrical energy potential, a method is presented that can simulate the results using the obtained statistical values, which demonstrates the accuracy of the presented method.

Graphical Abstract



1. Introduction

The global energy sector is experiencing a profound transformation, driven by the dual imperatives of meeting growing electricity demands and addressing the escalating concerns of environmental sustainability and climate change. Fossil fuel-based power generation, long the backbone of global energy supply, is increasingly being challenged due to its significant contribution to greenhouse gas emissions and

*** Corresponding author:**
E-mail address: *ramezani@mazust.ac.ir*

Cite this article as:
Ramezani, N., & Kilvaei, M.Sh. (2026). Estimated Electricity Generation from Wind Energy Potential in Northern Iran. *Advances in Sustainable Energies & Environment 1 (3) 1 - 13*. https://doi.org/10.22034/a-see.2026.2087817.1023

associated climate impacts. Consequently, renewable energy sources, particularly wind energy, have gained prominence as viable, clean, and sustainable alternatives. Over the past two decades, technological advancements, declining costs, and supportive policies have accelerated the deployment of wind power worldwide, making it a critical pillar in the transition toward low-carbon energy systems [1–2].

In recent decades, the global community has increasingly recognized the urgent need to transition from fossil fuel-based energy systems to sustainable and renewable energy sources. Among these alternatives, wind energy has emerged as a leading technology due to its abundance, environmental friendlyness, and cost effectiveness. The continuous advancement in wind turbine technology and the global drive towards reducing greenhouse gas emissions have accelerated the adoption of wind power worldwide. This trend is particularly significant for countries like Iran, where growing energy demand and environmental concerns call for the diversification of the energy portfolio. Despite the promising wind resource, successful deployment requires thorough assessment of the wind potential, integration with the existing power infrastructure, and careful consideration of environmental and social factors. The integration of advanced modeling techniques and geographic information systems has facilitated more accurate mapping of wind energy potential, supporting informed decision-making for site selection and project planning [3-4].

Iran, with its vast and diverse geography, presents unique opportunities and challenges in the field of renewable energy. While the country has traditionally relied heavily on oil and gas resources for electricity generation, increasing energy demand, coupled with environmental and economic considerations, has accelerated efforts to diversify the energy mix. Among renewable options, wind energy stands out due to its significant potential, especially in areas with favorable climatic and topographic conditions. The northern provinces of Iran, namely Guilan, Mazandaran, and Golestan, are particularly notable for their wind resources due to their geographical proximity to the Caspian Sea and the complex interplay of regional meteorological factors. Wind patterns in northern Iran are influenced by the Caspian Sea's thermal dynamics and the topographical effects of the Alborz mountain range. These natural phenomena produce consistent wind regimes characterized by seasonal variations that favor wind power generation. Recent wind speed measurements and meteorological data collected from these regions reveal average annual wind speeds ranging from 5 to 9 meters per second (m/s), which are within the operational thresholds for modern wind turbines. Notably, the Rudbar corridor in Guilan province has been identified as one of the most promising wind energy sites, with wind power densities exceeding 300 watts per square meter (W/m^2) and annual energy outputs capable of supporting large scale wind farm installations [5–6]. Beyond the physical potential, the socio economic and environmental context of northern Iran further underscores the importance of wind energy development. The region is home to a growing population and expanding industrial activities, leading to increased electricity demand and heightened concerns about air pollution and ecological degradation. Wind energy deployment can address these issues by providing clean electricity, reducing reliance on fossil fuels, lowering greenhouse gas emissions, and fostering sustainable economic growth. Moreover, wind farms can stimulate local economies through job creation, infrastructure development, and enhanced energy security [7–9].

The assessment of wind energy potential in northern Iran has been the subject of various recent studies, utilizing advanced methodologies to overcome the complexities posed by the region's terrain and climatic variability. Integration of Geographic Information Systems (GIS), remote sensing technologies, and mesoscale atmospheric modeling allows for detailed spatial and temporal analysis of wind resources. These approaches enable the identification of optimal locations for wind turbine installations by accounting for land use patterns, environmental sensitivity, grid accessibility, and social acceptance. Additionally, sophisticated power system simulations help predict the integration impacts of wind energy on the electrical grid, considering intermittency, variability, and load management challenges. Despite these favorable conditions, several barriers to the widespread adoption of wind energy in northern Iran persist. Grid integration remains a significant technical hurdle, requiring investments in transmission infrastructure, energy storage solutions, and smart grid technologies to accommodate variable renewable generation. Financial constraints, such as high upfront capital costs and limited access to affordable financing, inhibit project development. Public perception and acceptance also play a crucial role, where concerns about noise, visual impact, and potential effects on wildlife can delay or obstruct wind farm projects. Policy frameworks, while improving, need further enhancement to provide stable incentives, streamline regulatory processes, and promote research and development. In recent years, the Iranian government has introduced various policies and incentive mechanisms aimed at promoting renewable energy, including feed in tariffs, tax benefits, and international partnerships for technology transfer. These initiatives, coupled with growing environmental awareness and international climate commitments, set a promising backdrop for accelerating wind energy projects. However, to fully exploit the wind energy potential in northern Iran, integrated strategies encompassing technical innovation, economic viability, environmental stewardship, and social engagement are essential [10–12].

This paper presents a comprehensive evaluation of wind energy potential in the northern provinces of Iran, synthesizing the latest meteorological data, satellite observations, and prior research findings. It aims to delineate high potential zones, assess achievable energy yields under diverse operational scenarios, and analyze the techno economic feasibility of wind power deployment. The study also examines environmental impacts, grid integration challenges, and policy implications, offering actionable recommendations for stakeholders. By focusing on the northern region, which holds one of the country's most substantial wind resources, this research contributes to the broader goal of sustainable energy transition in Iran, supporting energy security, economic development, and environmental preservation. Analysis of long term wind speed data collected from several meteorological stations in the provinces of Guilan, Mazandaran and Golestan highlights the seasonal variability of wind, which is closely related to regional climatic conditions. The Caspian Sea breeze, which is influenced by temperature gradients between the sea and land, generates reliable wind flows, especially in spring and autumn, which coincide with periods of peak energy demand. This seasonality increases the viability of wind farms as a complementary energy source in the regional energy grid [13–15]. The presented paper provides a comprehensive investigation of the geopolitical conditions and detailed practical feasibility study for clean wind power generation in three northern provinces of Iran, considering the available technical infrastructure. It also provides numerical results of estimating sustainable annual energy production, as well as reducing fossil fuel consumption for generating energy equal to the estimated amounts from wind, and reducing greenhouse gas emissions in comparative annual intervals.

2. Proposed Method

There are many methods for researching and providing an algorithm for calculating the potential for electricity generation from geographically limited wind resources, each of which can have different measurement parameters. In this part, the methodology of the study is first explained, followed by discussions on the characteristics of the wind in the study area, special parameters and technology of new wind turbines, zoning of wind speed and power density continuity, locating wind power plant deployment zones with methods (AHP). At the end of the second part, an accurate method for estimating the power generation capacity of electricity by wind power is explained in detail.

2-1. Methodology of the study

This paper presents a detailed descriptive and analytical framework with advanced spatial analysis techniques to estimate electricity generation from wind energy potential and identify optimal locations for wind energy development in three northern provinces of Iran (Guilan, Mazandaran, and Golestan).

Wind characteristics are analyzed using long term wind speed and direction data obtained from synoptic meteorological stations distributed throughout the study area. Measurements were recorded at a standard height of 10 m above ground level, and statistical analyses were performed to extract key parameters, including mean wind speed, wind frequency distribution, and wind persistence. To reflect realistic operating conditions of modern wind turbines, wind speed was extrapolated to higher hub heights using a power law wind profile, and wind power density was calculated as the main indicator of technical feasibility.

The criteria influencing wind farm location selection were systematically identified based on the methodological structure of the reference study and an extensive review of the relevant literature. As summarized in Table 1, the selected criteria were classified into four main categories: climatic and technical factors, topographic features, environmental constraints, and socio economic and infrastructure considerations. Given the purpose of this study, the use of four groups of criteria, climatic, topographic, economic, and environmental-social is essential. Selecting a suitable location for the construction of a wind power plant is not limited solely to the presence of high wind speeds. Climatic criteria were considered to assess the amount of energy that can be extracted from the wind; topographic criteria to examine the effect of land height and slope on turbine performance and the feasibility of power plant construction; economic criteria to reduce costs associated with grid connection and transportation infrastructure; and environmental-social criteria to prevent conflicts with residential areas, protected zones, and environmental restrictions.

The simultaneous use of these four groups of criteria allows for a comprehensive and realistic assessment of different areas and makes the selected locations, in addition to having high wind potential, also technically, economically and environmentally suitable for the development of wind power plants.

Table 1. Criteria used for wind energy site selection in the northern provinces of Iran [15-16]

Criterion Category	Criterion	Description and relevance to northern Iran
Climatic / Technical	Mean wind speed	Determines the technical feasibility of wind energy generation; influenced by coastal and mountainous wind regimes
Climatic / Technical	Wind power density	Quantifies available wind energy at turbine hub heights
Climatic / Technical	Wind persistence	Indicates wind continuity and stability throughout the year
Topographic	Elevation	Affects wind exposure and accessibility in mountainous and foothill areas
Topographic	Slope	Influences construction feasibility and installation costs
Environmental	Distance from protected areas	Ensures conservation of forests, wetlands, and biodiversity-rich zones
Environmental	Distance from rivers and wetlands	Reduces ecological disturbance and flood risk
Environmental	Distance from fault lines	Minimizes seismic risk in tectonically active regions
Socio-economic	Distance from residential areas	Reduces noise, visual impact, and social conflicts
Socio-economic	Distance from roads	Ensures construction and maintenance accessibility
Socio-economic	Distance from power transmission lines	Reduces infrastructure and connection costs
Socio-economic	Distance from airports	Prevents interference with aviation safety

2-2. Characteristics of the study areas

The study area encompasses the three northern provinces of Iran, namely Guilan, Mazandaran, and Golestan, located along the southern coast of the Caspian Sea and on the northern slopes of the Alborz mountain range. Owing to their distinctive geographical position, pronounced topographic gradients, and diverse climatic conditions influenced by both marine and mountainous atmospheric systems, these provinces represent one of the most complex wind regimes in the country [17].

Guilan Province, covering approximately 14,044 km², is situated between latitudes (36°34′–38°27′ N) and longitudes (48°53′–50°34′ E). The province is bordered by the Caspian Sea to the north and the Talesh Mountains to the west and southwest, resulting in marked climatic and topographic variability. Among the various areas of Guilan Province, the Rudbar region is widely recognized as one of the most wind prone areas in Iran. Rudbar is located at the intersection of the Sefidrud Valley and the southern slopes of the western Alborz Mountains, where the topographic configuration facilitates the channeling and acceleration of airflow. This geomorphological setting leads to relatively high wind speeds and notable wind persistence throughout much of the year. The wind in Rudbar is characterized by both sufficient intensity and temporal continuity, which are essential technical requirements for wind power development. Previous climatological and energy-related studies consistently highlight the high wind power density of this area, confirming its strategic importance for wind energy exploitation in northern Iran [18].

Mazandaran Province, with an area of approximately 53,721 km², constitutes the central part of the study area. It is bounded by the Caspian Sea to the north and the central Alborz Mountains to the south. The sharp elevation gradient from coastal plains to high mountainous terrain results in substantial spatial variation in climatic conditions and wind flow patterns. Within Mazandaran Province, the Savadkuh region represents one of the most significant wind prone zones. Located along major mountain corridors of the central Alborz range, Savadkuh is influenced by deep valleys and north–south oriented passages that enhance wind acceleration. The interaction of slope winds, mountain plain circulations, and airflow penetration from Iran's central plateau contributes to relatively high wind speeds, particularly in elevated and mid slope areas [19].

Golestan Province covers approximately 20,367 km² and is located in the eastern part of the study area. The province includes coastal zones, extensive plains, and mountainous areas associated with the eastern Alborz range, resulting in diverse climatic and wind conditions. Among the coastal areas of Golestan Province, the Bandar Turkmen region is identified as a major wind prone zone. Situated along the eastern shoreline of the Caspian Sea and adjacent to broad, low-lying plains, the region benefits from favorable conditions for the development of coastal wind systems. Thermal contrasts between land and sea surfaces, particularly during warm seasons, generate relatively persistent sea breezes with considerable wind speeds. The prevailing winds in Bandar Turkmen generally exhibit stable directional patterns and sufficient intensity during large parts of the year, indicating a high potential for wind energy utilization [20]. The presence of distinct wind prone regions such as Rudbar in Guilan Province, Savadkuh in Mazandaran Province and Bandar Turkmen in Golestan Province, combined with pronounced topographic and climatic diversity, justifies the selection of these provinces as the study area. These regions provide representative examples of the interaction between environmental factors and wind energy potential and offer a robust basis for spatial analysis and site suitability assessment of wind power plants in northern Iran.

2-3. Special parameters and technology of wind turbines

Due to its unique geographical and climatic conditions, Iran possesses substantial wind energy potential. Wind atlas assessments indicate that more than 30% of the country's land area experiences an annual mean wind speed exceeding 5 (m/s) at 80 m hub height, which is generally considered the minimum threshold for economically viable wind power generation. The technical wind energy potential of Iran has been estimated to range between 40 and 60 GW, whereas the currently installed capacity remains below 500 MW, highlighting a significant gap between potential resources and actual exploitation [21]. Wind turbines deployed in Iranian wind farms are predominantly three bladed horizontal axis wind turbines (HAWTs), which are widely adopted in utility scale applications due to their superior aerodynamic efficiency and operational stability. The rated power of these turbines typically ranges from 660 kW to 2.5 MW, with rotor diameters between 47 and 100 m. From an operational perspective, the capacity factor of wind turbines in major Iranian wind corridors, such as Rudbar, has been reported in the range of 25–35%, depending on wind speed distribution, turbulence intensity, and turbine availability [22]. Regarding electrical configuration, most wind turbines currently operating in Iran employ doubly fed induction generators (DFIGs) or gearbox coupled synchronous generators; although these configurations offer lower initial investment costs, they are associated with higher mechanical losses, increased maintenance requirements, and greater sensitivity to grid disturbances.

Over the past decade, the global wind energy industry has undergone rapid technological evolution, characterized by the development of wind turbines with higher rated capacities, larger rotor diameters, and advanced control strategies. Modern onshore wind turbines now typically feature rated capacities of 4–6 MW, while offshore turbines have reached capacities of 8–15 MW and beyond. State of the art offshore turbines exhibit rotor diameters exceeding 220 m, corresponding to swept areas of more than 38,000 m², enabling efficient energy capture even under low wind conditions (below 6 m/s). One of the most significant performance improvements in next generation wind turbines is the substantial increase in capacity factor; advanced offshore wind farms now achieve capacity factors in the range of 50–60%, while modern onshore installations commonly reach 35–45%. These improvements are primarily attributed to optimized aerodynamic blade designs, increased hub heights (up to 160 m), and adaptive control systems that dynamically respond to changing wind conditions.

From a drivetrain perspective, the widespread adoption of permanent magnet synchronous generators (PMSGs) and direct drive architectures has significantly reduced mechanical losses by approximately 2–4% while enhancing system reliability and reducing maintenance demands. Furthermore, the use of advanced composite materials, such as carbon fiber reinforced polymers, has enabled blade lengths exceeding (110 m) without substantial increases in structural mass. In addition to hardware innovations, digitalization and intelligent control systems have become integral components of high efficiency wind turbines; the implementation of real time data analytics, machine learning algorithms, and predictive maintenance strategies has reduced turbine downtime and significantly lowered operation and maintenance (O&M) costs. As a result of these technological advancements, the levelized cost of electricity (LCOE) from wind energy has declined markedly, positioning wind power as one of the most cost competitive sources of electricity generation globally [23-24].

2-4. *Locating areas suitable for wind power plant deployment using the AHP-GIS method*

Wind farm site selection is a complex spatial multi criteria decision making problem that requires the simultaneous evaluation of climatic, physiographic, economic, and environmental social factors. In this study, an integrated approach based on the Analytic Hierarchy Process (AHP) and Geographic Information Systems (GIS) was employed to identify suitable areas for wind power plant installation in the Guilan, Mazandaran and Golestan Provinces of northern Iran. The (AHP) method enables systematic weighting of decision criteria according to their relative importance, while (GIS) provides powerful tools for spatial analysis and weighted overlay of georeferenced datasets. Different areas in the three northern provinces of Iran are examined and, using appropriate weighting criteria, the optimal point for installing a wind power plant and its permanent operation is selected. The integration of these two methods establishes an efficient framework for evaluating land suitability for wind energy development across regions with hetero-geneous geographical conditions. The flowchart of wind farm location selection using the integrated (AHP-GIS) approach is shown in Fig. 1.

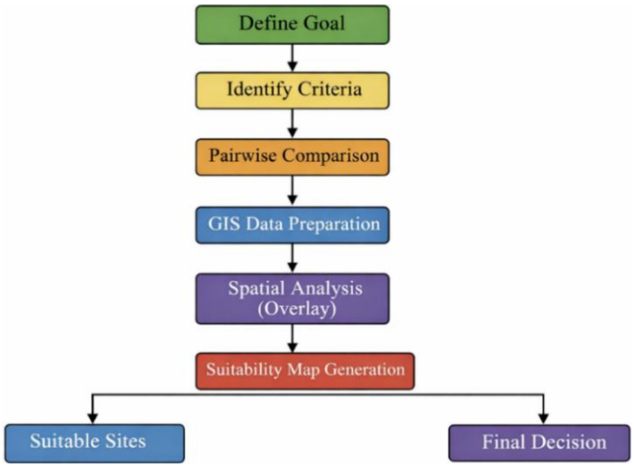


Fig. 1. Flowchart of wind farm site selection using the integrated (AHP–GIS) approach

Considering the technical requirements and environmental impacts of wind farms, the site selection criteria were classified into four main groups: climatic, topographic, economic and socio ecological. Each criterion includes several sub criteria that contribute differently to the assessment of land suitability, which are given in Table 2.

To determine the relative importance of the criteria, the pairwise comparison technique of the (AHP) method was applied. Each criterion was evaluated relative to the others, and final weights were calculated accordingly. Due to the differences in natural conditions, economic characteristics, and environmental constraints in the three northern provinces of Iran that were studied, the weighting process was carried out independently for each province .

The final weighting of the main criteria has been done for the regions of the provinces that, according to the initial data obtained from the research, emphasize the maximum strength and continuity of wind throughout the year. The total number of important primary criteria in the cities of Rudbar and Astara for Guilan Province, Savadkuh and Noor for Mazandaran Province, Bandar Turkman and Gonbad for Golestan Province, which have the maximum strength and continuity of wind throughout the year, is reviewed in Table 3.

In the AHP method, the main criteria were compared pairwise to determine their relative importance in wind farm site selection. Based on expert judgment and findings from previous studies, each criterion was assigned a preference score according to its influence on wind energy development. The pairwise comparison matrix was subsequently normalized, and the final weights were calculated.

Table 2. Criteria and sub-criteria used for wind farm site selection [15-16]

Main Criterion	Sub Criteria
Climatic	Mean wind speed, wind power density, wind persistence
Topographic	Elevation above sea level, slope
Economic	Distance to power transmission lines, distance to roads, distance to industrial centers
Environmental-Social	Distance from residential areas, distance from protected areas, land-use type, distance from fault lines

Table 3. Final weights of the main criteria in the study provinces

Criterion	Rudbar (Guilan)	Astara (Guilan)	Savadkuh (Mazandaran)	Noor (Mazandaran)	Bandar Turkmen (Golestan)	Gonbad (Golestan)
Climatic	0.4	0.35	0.38	0.34	0.35	0.32
Topographic	0.25	0.22	0.3	0.25	0.15	0.14
Economic	0.2	0.23	0.18	0.21	0.25	0.19
Environmental–Social	0.15	0.2	0.14	0.20	0.25	0.17
Total	1	1	1	1	1	1

The resulting priority values for each study region are presented in Table 3. The weighting results show that climatic and topographic criteria play a dominant role in mountainous areas, while environmental and social considerations become more influential in coastal and plain environments. The study cases in the two provinces of Guilan and Mazandaran are both mountainous and coastal, while the study cases in Golestan province are flat and coastal. In Table 4, the percentage of wind frequency, which is an average of the strength and duration of the wind throughout the year, is compared in each province with two different climates. Wind Persistence (%) can be defined as the percentage of hours per year with wind speeds above 4.5 or 5 m/s.

In each province, the optimal point can be selected by considering the average wind speed parameter and the wind persistence parameter. Obviously, each region that has higher values in both parameters has higher investment and power exploitation value. The final results of the regions in question are presented in Table 5.

The comparison presented in Tables 4 and 5 shows that mountainous areas generally show higher wind speeds, more wind continuity, and superior energy efficiency per unit investment compared to coastal areas in the same province. However, coastal areas such as Bandar Turkman benefit from easier access and relatively flat terrain, and the continuity of wind potential in this area is the best point in Golestan province. Therefore, by examining the criteria, it is not necessary to always prioritize mountainous areas over coastal areas, and only by examining a region can the optimal point be selected that has a higher annual wind turbine electricity generation capacity coefficient than the rest of the regions.

The Rudbar region is located within an active wind corridor, where specific topographic conditions enhance wind acceleration through valleys and surrounding elevateons, resulting in a high potential for wind energy generation. From a climatic perspective, wind speed and persistence are particularly significant in elevated areas. In terms of topography, zones with moderate slopes and suitable elevations exhibit the highest potential for turbine installation. Proximity to power transmission lines and transportation networks further improves the economic feasibility of wind energy development in this region. However, environmental constraints and buffer zones around residential areas were incorporated to define the final suitable zones. The wind farm suitability map in the Rudbar region is shown in Fig. 2. The results show that a considerable portion of the elevated areas surrounding valleys falls within the highly suitable class.

Guilan Province, particularly the Rudbar region, is located along the Rudbar topographic corridor and is considered one of the most stable and well-known wind resource areas in Iran. The simultaneous pressure difference between the Caspian lowlands and the central plateau generates relatively uniform and channeled wind flows throughout the year. GIS based wind zoning analysis indicates that Rudbar exhibits distinctly higher wind continuity compared to other northern regions of the country. The continuity of wind speed and wind power density zoning for the Rudbar region is shown in Fig. 3. Analysis of wind frequency distributions and continuity curves shows that over 65% of the hours in a year experience wind speeds exceeding 5 (m/s). This indicates a favorable temporal stability of wind and reduced calm periods, which is critical for increasing the capacity factor of wind turbines.

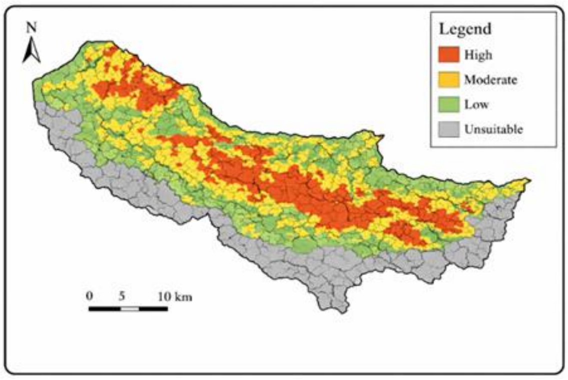


Fig. 2. Wind farm suitability map of the Rudbar region [25]

Table 4. Comparison of wind resource characteristics between mountainous and coastal regions

Province	Mountainous Region	Coastal Region	Mean Wind Speed (m/s)	Wind Persistence (%)	Preferred Area
Guilan	Rudbar	Astara	6.2 vs 5.4	65 vs 52	Rudbar
Mazandaran	Savadkuh	Noor	4.4 vs 3.8	48 vs 40	Savadkuh
Golestan	Bandar Turkmen	Gonbad	4.5 vs 3	50 vs 45	Bandar Turkmen

Table 5. Economic comparison of mountainous and coastal wind farm development

Province	Mountainous Region	Coastal Region	Relative Construction Cost	Energy Yield per Investment	Preferred Area
Guilan	Rudbar	Astara	Medium vs Medium	High vs Moderate	Rudbar
Mazandaran	Savadkuh	Noor	Medium vs Medium	Moderate vs Low	Savadkuh
Golestan	Bandar Turkmen	Gonbad	Medium vs Medium	Moderate vs Moderate-Low	Bandar Turkmen

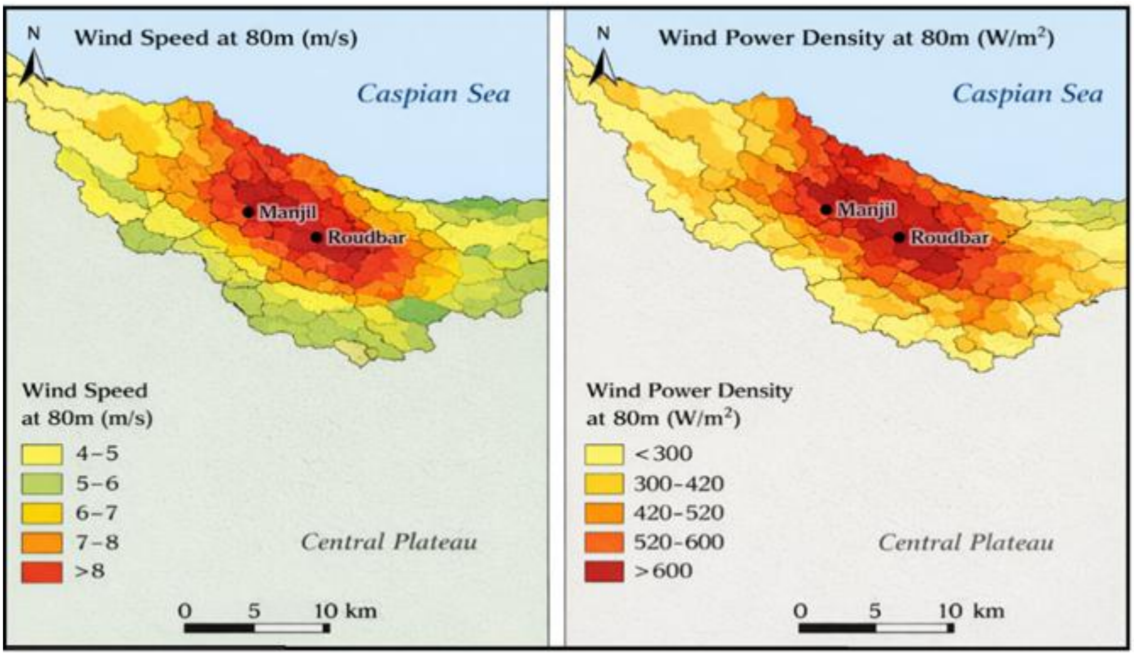


Fig. 3. The wind speed continuity and wind power density zoning for the Roudbar region [25]

The annual mean wind speed in Rudbar is estimated at 6.8–7.5 (m/s) at 50 (m) and 7.8–8.6 (m/s) at 80 (m) above ground. The noticeable increase in wind speed with height reflects a favorable wind shear profile, justifying the use of taller towers.

Wind power density zoning shows that Rudbar predominantly falls within wind power classes 4 and 5. Power density ranges from 420–520 (W/m²) at 50 m and 550–680 (W/m²) at 80 (m), demonstrating the high potential of the region for large scale wind farm development and the use of medium to high rated turbines.

Savadkuh is one of the major mountainous regions in northern Iran, where wind regimes are strongly influenced by elevation differences and terrain roughness. These conditions facilitate the formation of channelized winds along valley axes, leading to relatively stable wind conditions in certain parts of the region. While high elevation enhances wind potential, steep slopes in some areas impose technical limitations on turbine installation. Accessibility to major transportation routes and power transmission infrastructure improves the economic conditions of the region. At the same time, dense forest cover and environmentally sensitive areas were considered as limiting factors in the suitability analysis. The wind farm suitability map in the Savadkuh region is shown in Fig. 4. The central and northern parts of the region are mainly classified as suitable to highly suitable for wind power development.

Unlike the coastal areas of Mazandaran, which are influenced by high surface friction and dense forest cover, Savadkuh experiences entirely different wind conditions due to its mountainous location on the slopes of the Central Alborz range. GIS wind zoning analysis identifies Savadkuh as one of the few areas in Mazandaran with significant technical wind energy potential. The continuity of wind speed and power density zoning for the Savadkuh region is shown in Fig. 5.

Wind speed continuity in Savadkuh is heavily influenced by topography, channeled flows in valleys, and thermal differences between highlands and surrounding plains. Continuity curve analysis indicates that approximately 45–50% of the hours per year experience wind speeds above 4.5 (m/s), and 30–35% of hours exceed 5 (m/s). Although these values are lower than Rudbar, they are favorable compared to the provincial average. The annual mean wind speed ranges from 4.8–5.6 (m/s) at 50 (m) and 6.0–6.8 (m/s) at 80 (m). Weibull k values between 1.7 and 2.0 suggest moderate wind fluctuations, allowing usable wind periods alongside low wind intervals. Wind power density zoning indicates that elevated ridges and peaks in Savadkuh fall into wind power class 3. Power density ranges from 220–300 (W/m²) at 50 (m) and 300–380 (W/m²) at 80 (m), suggesting the need for low cut in speed turbines and designs suitable for mountainous terrain. Overall, Savadkuh is recognized as the most promising wind zone in Mazandaran.

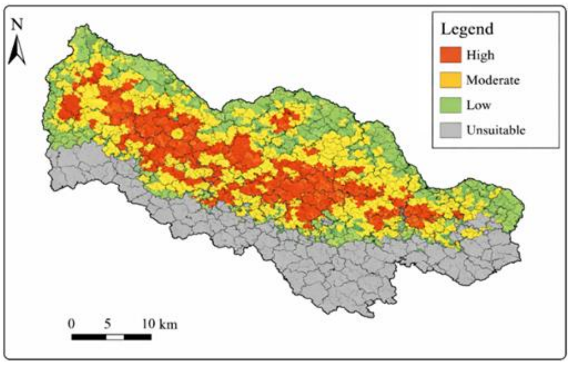


Fig. 4. Wind farm suitability map of the Savadkuh region [26]

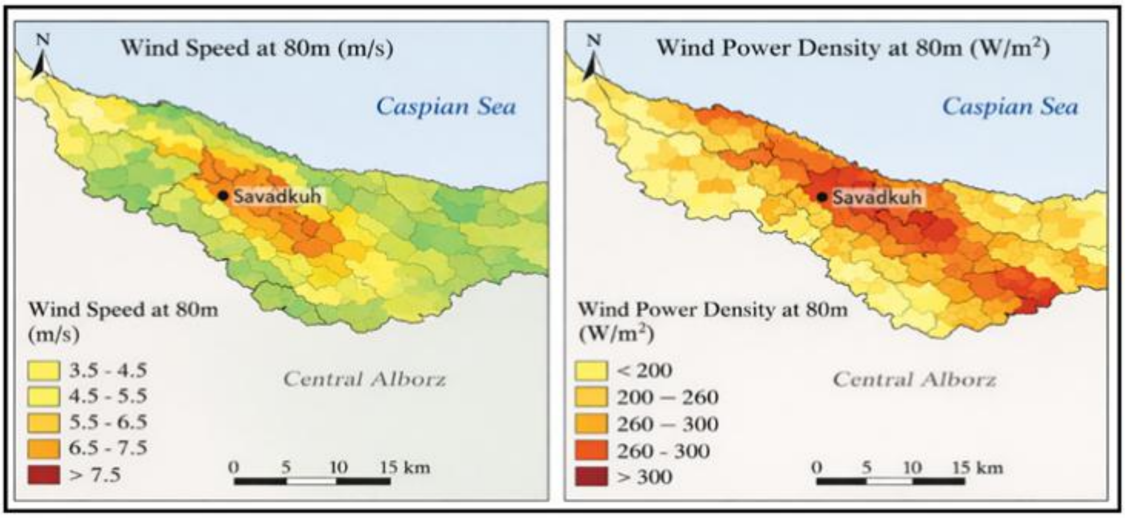


Fig. 5. The wind speed continuity and wind power density zoning for the the Savadkuh region [26]

Bandar Turkmen exhibits a spatial pattern distinct from the mountainous regions, as it is located in a coastal lowland environment. Wind regimes in this area are primarily influenced by coastal circulation and land sea thermal contrasts, resulting in acceptable wind persistence throughout the year. The predominantly flat terrain represents a significant technical advantage for wind turbine installation. Moreover, proximity to power infrastructure and transportation networks enhances economic viability. Nevertheless, the presence of wetlands, ecologically sensitive habitats, and migratory bird pathways imposes strict environmental constraints on site selection. The wind farm suitability map in the Bandar Turkmen region is shown in Fig. 6. Areas located at sufficient distances from environmentally sensitive zones are classified as suitable for wind farm installation.

Golestan Province, bordering the Caspian Sea and located in the Gorgan Plain, experiences relatively stable Caspian wind patterns. Zoning analysis shows that the northern and northeastern regions, particularly Bandar Turkmen, possess more favorable wind conditions than the inland areas. The zonation of wind speed continuity and power density for Bandar Turkman is presented in Fig. 7.

In Gonbad Kavous, wind speed continuity indicates that approximately 40–45% of hours per year exceed 4.5 (m/s). The annual mean wind speed is 5.2–6.1 (m/s) at 50 (m) and 6.3–7.2 (m/s) at 80 (m). Power density at 80 (m) is estimated between 350–450 (W/m²), placing it in wind power class 3. Conversely, Bandar Turkmen, affected directly by Caspian winds, exhibits higher wind continuity, with over 50% of hours per year exceeding 4.5 (m/s).

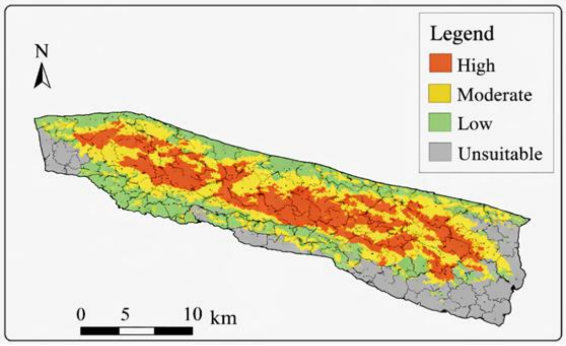


Fig. 6. Wind farm suitability map of the Bandar Turkmen region [27]

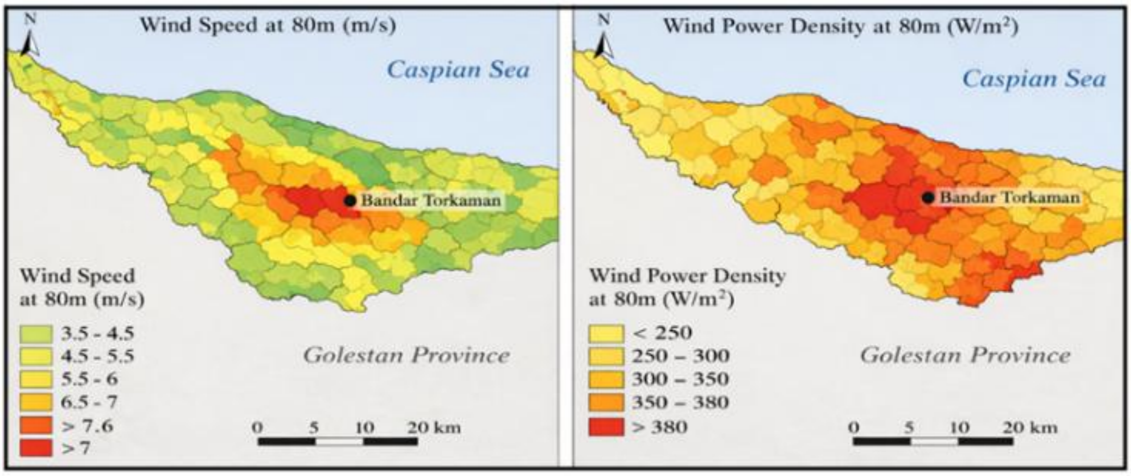


Fig. 7. The wind speed continuity and wind power density zoning for the Bandar Turkmen [27]

Table 6. Comparison of wind farm suitability among the study regions [25-27]

Region	Climatic Type	Topographic Condition	Dominant Suitability Class
Rudbar	Mountainous Valley	Moderate slope	Highly suitable
Savadkuh	Mountainous	Variable slope	Suitable to highly suitable
Bandar Turkmen	Coastal Lowland	Low slope	Suitable

The mean wind speed at 80 (m) ranges from 6.9–7.8 (m/s), and the power density spans 450–560 (W/m²), classifying it mainly in wind power classes 3 and 4. The wind speed continuity and wind power density zoning analysis indicate that among the studied regions, Rudbar exhibits the highest temporal wind stability and power density, making it the most suitable site for large scale wind farm development.

Savadkuh is the main high potential wind area in Mazandaran, while Bandar Turkmen in Golestan shows favorable conditions for medium scale wind projects.

A comparative summary of climatic conditions, topographic characteristics, and dominant suitability classes for the three study areas is provided in Table 6 [25-27]. The results demonstrate that the integrated AHP-GIS approach effectively identifies suitable areas for wind farm development in regions with contrasting geographical characteristics. The main differences among the study areas arise from variations in criterion weighting and environmental constraints, while the methodological framework remains robust and transferable across different spatial contexts.

2-5. Characteristics of the study points

The analysis of wind characteristics of the northern regions of Iran, presented in Table 7, shows that the effective potential of wind energy in Iran is strongly influenced by the stability of wind speed, prevailing wind direction, and seasonal wind regimes. According to the temporal directional classification, productive wind conditions generally occur during the warmer months (April to August), with peak wind activity concentrated in afternoon and early evening hours, which coincides with maximum electricity demand.

Extending these findings to the northern regions of Iran reveals distinct wind regimes influenced by topography, proximity to the Caspian Sea, and regional pressure gradients. In Rudbar (Guilan), the well known Rudbar wind corridor benefits from channeling effects within narrow valleys, resulting in persistent north northwesterly winds with relatively high annual mean wind speeds, making the area highly suitable for large scale wind power generation. In Savadkuh (Mazandaran), wind characteristics are primarily controlled by elevation and orographic effects. Although average wind speeds are lower than Rudbar, seasonal enhancement during spring and summer, combined with afternoon wind maxima, supports medium scale wind energy applications, particularly along ridgelines and mountain passes. Conversely, Bandar Turkmen (Golestan) exhibits a coastal wind regime dominated by land sea breeze circulation and synoptic northerly winds from the Caspian Sea. While wind speeds are moderate, the high frequency of winds above the cut in speed (≈ 4 ms^{-1}) during warm months indicates favorable conditions for distributed and hybrid wind energy systems. Overall, the temporal consistency and directional stability of winds in these three regions align well with the national wind characteristics summarized in Table 2, confirming their strategic importance for wind energy development in northern Iran.

2-6. Wind Speed Frequency Analysis in Windy Northern Stations of Iran

Analysis of wind speed frequency is a key factor in assessing wind energy potential. Based on the statistical interpretation of synoptic wind data presented in the reference material, the northern regions of Iran show notable spatial variability in wind regimes. Windy stations such as Rudbar (Manjil) in Guilan Province, mountainous areas of Savadkuh in Mazandaran Province, and Bandar Turkmen in Golestan Province exhibit different wind speed frequency characteristics due to topography and regional circulation patterns, which is presented in Fig. 8.

The results indicate that Rudbar (Manjil) has the highest frequency of wind speeds exceeding the operational threshold of 3 m/s, making it one of the most suitable locations for wind power generation in northern Iran. In contrast, Savadkuh, despite its mountainous terrain, shows a moderate frequency of effective wind speeds, while Bandar Turkmen, influenced by coastal and Caspian Sea climatic conditions, demonstrates a lower but still usable wind speed frequency. Overall, the comparative analysis confirms that wind energy potential in northern Iran is highly site dependent, and localized assessments are essential for sustainable wind farm development.

2-7. Presenting a method for accurate estimation of electricity production capacity from wind potential

This paper presents an in-depth assessment of wind energy potential in three windy regions of northern Iran using Weibull probability distribution. Wind speed data from Manjil, Savadkuh, and Bandar Turkman meteorological stations are analyzed using two parameter Weibull models. Accurate wind resource assessment is crucial for the design and financial feasibility of wind power plants.

Table 7. Summary of wind characteristics for selected regions in northern Iran [28-29]

Region	Dominant Wind Direction	Windy Months	Peak Wind Hours	Typical Mean Wind Speed	Wind Energy Suitability
Rudbar	NW-N	April-September	12:00–18:00	6.0–7.5 ($m\ s^{-1}$)	High (Utility-scale)
Savadkuh	N-NE	May-August	13:00–18:00	4.5–5.5 ($m\ s^{-1}$)	Moderate (Medium scale)
Bandar Turkmen	N–NE	April-August	14:00–19:00	4.0–5.0 ($m\ s^{-1}$)	Moderate (Distributed/Hybrid)

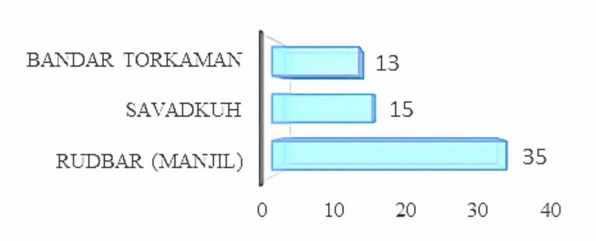


Fig. 8. Frequency of wind speed > 3 m/s (%) [30-31]

Weibull probability distribution provides a robust statistical framework for representing wind speed frequency and calculating expected energy yield. This study focuses on using real meteorological data from three windy regions in northern Iran to model wind speed distribution and estimate theoretical energy efficiency.

The Weibull distribution is one of the most widely used statistical models for describing wind speed behavior and is defined by two main parameters: the shape parameter (k) and the scale parameter (c). These parameters enable accurate modeling of wind speed variability and form the basis for estimating the amount of extractable wind energy [32]. The shape parameter (k) represents the degree of dispersion and variability of wind speeds within a given region. Lower values of k indicate highly variable and unstable wind regimes, whereas higher values correspond to more uniform and steady wind conditions. This parameter plays a crucial role in characterizing wind regime stability and directly influences the operational performance of wind turbines. The scale parameter (c) reflects the overall wind energy level of a region and is closely associated with the dominant wind speed magnitude. Higher values of c indicate stronger wind conditions and, consequently, greater wind energy potential. Therefore, the scale parameter is considered one of the most important indicators in the technical and economic evaluation of wind power plants and is commonly used as a primary criterion for comparing different regions in terms of energy production capacity. Maximum likelihood estimation (MLE) and Monte Carlo simulation methods are used to calculate power density, and estimate annual energy production. The basic Weibull probability density function is expressed in Eq. (1):

$$\mathrm{f}(v) = (\frac{k}{c}) \times (\frac{v}{c})^{(k-1)} \times e^{-(\frac{v}{c})^k} \tag{1}$$

Where v is wind speed (m/s), k is the shape parameter, and c is the scale parameter. Also, the cumulative distribution function is expressed according to Eq. (2):

$$F(v) = 1 - \mathrm{e}\text{^}(-(v \,/\, c)\text{^}k\ ) \tag{2}$$

To derive key statistical and physical quantities such as mean wind speed and wind power density from the Weibull distribution, the gamma function (δ) is employed. The gamma function (δ) facilitates the calculation of statistical moments of the distribution and plays a fundamental role in linking the statistical parameters of the Weibull model to the physical characteristics of wind flow. In particular, for wind power density estimation, which is proportional to the cube of wind speed, the inclusion of the gamma function (δ) allows the combined effects of the shape and scale parameters to be accurately captured. Consequently, the integration of Weibull parameters with the gamma function (δ) provides a robust and coherent framework for wind energy potential assessment and annual energy production estimation.

To use the proposed method for estimation, the average wind speed (*Vm*) and the average power density (*P*) must be calculated as equations Eq. (3) and Eq. (4):

$$V_m = \mathrm{c} \times \delta\left(1 + \frac{3}{k}\right) \tag{3}$$

$$P = 0.5 \times \rho \times \mathrm{c}^3 \times \delta\left(1 + \frac{3}{k}\right) \tag{4}$$

Where (ρ) is the air density (1.225 kg/m³). Wind speed data for the Rudbar region (Guilan), Savadkuh (Mazandaran), and Bandar Turkman (Golestan) are obtained continuously from published meteorological records and reliable sources. In cases where hourly data were available, Weibull parameters were estimated using maximum likelihood estimation (MLE). In cases where partial data are missing, mean values can be used to approximate c. *k* is selected based on the environmental conditions and the turbine in question, which is assumed to be 2 in this study, assuming the most widely used turbine in Iran. At least 1000 simulations can be used for more accurate interpolation to generate artificial hourly wind speeds and calculate the total annual electrical energy produced by a wind turbine (AEP). Equation (5) is used to convert wind statistical information into the actual amount of electrical energy that can be produced in a year and is considered the most important relationship in the article for estimating the electricity generation capacity from wind potential. The total amount of electrical energy produced by a wind turbine during a year (AEP) can be calculated in MWh/year according to Eq. (5):

$$AEP = 8760 \times \int_0^\infty \mathrm{P(v)} \times \mathrm{f(v)} \tag{5}$$

3. Case Studied

In this section, according to the theoretical method presented, a numerical discussion is presented to investigate the maximum amount of electricity generated from wind potential in the windy areas of northern Iran, which include three large areas.

Table 8. Wind data of selected northern Iranian sites [30-31]

Region (Station)	Province	Mean Wind Speed (m/s)	Wind Speed Range (m/s)	Remarks
Rudbar (Manjil)	Guilan	6.2	6.0 – 6.5	Iran’s most productive wind corridor; persistent mountain valley winds
Savadkuh	Mazandaran	4.4	4.0 – 4.8	Moderate winds; strongly influenced by Alborz mountainous topography
Bandar Turkmen	Golestan	3.8	3.5 – 4.2	Coastal winds affected by Caspian Sea circulation; lower persistence

In the first step, the average wind speed values with stability characteristics should be given in the three areas of Rudbar (Guilan), Savadkuh (Mazandaran), and Bandar Turkman (Golestan) in Table 8. The continuity of the average wind speed at heights of 10, 30, and 50 meters above the ground surface has been prepared.

Matlab software was used for coding and final calculations of the equations of the presented method, and Windographer software was used to analyze wind energy and its continuity in different areas. The proposed method calculates the power density using Eq. (4). For estimating the annual energy production (AEP), a rotor swept area of 1000 m² was assumed, corresponding to a medium scale wind turbine. An overall system efficiency of 30% was considered to account for aerodynamic, mechanical, and electrical losses. The final results are shown in Fig. 9 and Fig. 10 for comparison.

The simulation results clearly indicate that Rudbar (Guilan) exhibits the highest wind power density and annual energy production among the sites studied. This is primarily attributed to its unique mountain valley wind corridor, which enhances wind speed persistence and intensity throughout the year. Consequently, Rudbar remains the most promising location for large scale wind energy development in northern Iran. Savadkuh (Mazandaran) demonstrates moderate wind energy potential, with power density and (AEP) values significantly lower than those of Rudbar but still within a viable range for medium scale wind power projects.

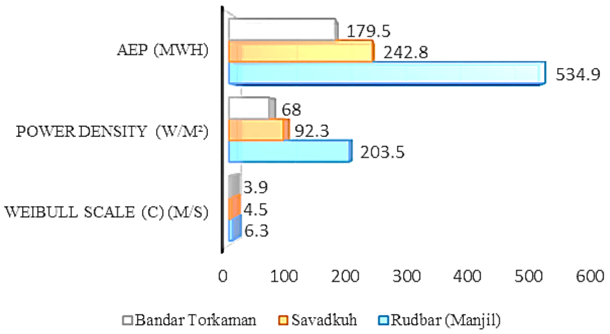


Fig. 9. Simulated wind power density and annual energy production for selected northern Iranian sites

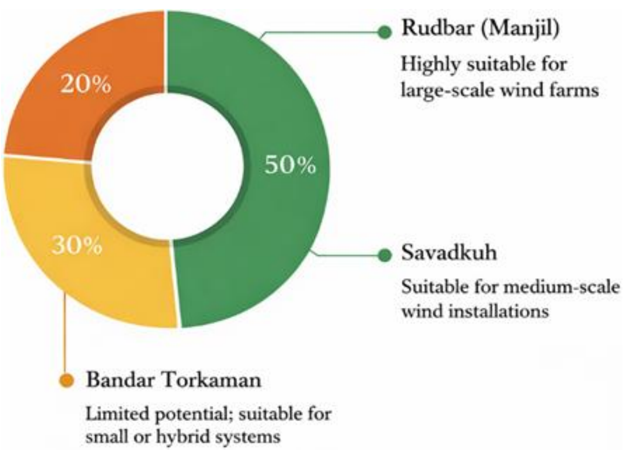


Fig. 10. Wind Energy Assessment

The mountainous terrain and elevation driven airflow patterns contribute to a relatively stable wind regime, particularly in exposed ridge and high altitude areas. Bandar Turkmen (Golestan) shows the lowest wind power density among the three locations, mainly due to its coastal setting and weaker large scale pressure gradients. However, the presence of regular land sea breeze circulation results in non-negligible energy production, suggesting that small scale wind turbines or hybrid wind solar systems could be technically feasible in this region. Overall, the findings emphasize that while high wind corridors such as Rudbar maximize energy yield, regions with moderate or even relatively low wind speeds can still contribute to regional renewable energy portfolios when turbine size and system design are optimized for local wind conditions.

4. Comparison of the amount of electricity generated from wind energy compared to fossil fuel

Wind energy assessment in northern Iran demonstrates a significant potential for electricity generation, particularly in regions with favorable topographical and meteorological conditions. Among the three studied sites, Rudbar (Guilan) exhibits the highest wind power density and annual energy production, owing to its persistent mountain valley wind corridors. Savadkuh (Mazandaran) shows moderate wind potential, while Bandar Turkmen (Golestan) demonstrates limited but technically feasible energy yield. The annual energy production (AEP) values for these regions are 534.9 (MWh), 242.8 (MWh), and 179.5 (MWh), respectively. These results indicate that even areas with moderate or relatively low wind speeds can contribute meaningfully to the regional renewable energy portfolio when turbine specifications and system design are optimized. For comparison with conventional fossil fuel based electricity generation, the equivalent energy input required for thermal power plants has been estimated assuming an average conversion efficiency of 40%. The analysis shows that to generate the same amount of electricity as produced by wind turbines, a fossil-fuel plant would need substantially higher energy input, resulting in increased fuel consumption and associated greenhouse gas emissions. Table 9 presents the calculated fossil fuel requirements in terms of energy and natural gas volume equivalents for the three studied regions. The deployment of wind power instead of conventional thermal power plants can lead to significant fossil fuel savings. For instance, in Rudbar, the 534.9 (MWh) of electricity generated by wind turbines avoids the consumption of approximately 1337 (MWh) of fossil fuel energy, corresponding to around 134,000 (m^3) of natural gas. Similarly, Savadkuh and Bandar Turkmen avoid the use of 60,700 (m^3) and 44,880 (m^3) of natural gas, respectively. These figures demonstrate that integrating wind energy into the regional grid can substantially reduce fossil fuel demand and associated environmental impacts, highlighting the economic and ecological benefits of wind power deployment [33-34].

Table 9. Equivalent fossil fuel consumption avoided by wind electricity generation [33-34].

Region	Annual Energy Production (MWh/year)	Equivalent Fossil Fuel Energy Input (MWh/year)	Equivalent Natural Gas Saving (m^3/year)
Rudbar (Guilan)	534.9	1337.3	134,000
Savadkuh (Mazandaran)	242.8	607.0	60,700
Bandar Torkaman (Golestan)	179.5	448.8	44,880
Total	957.2	2393.1	239,580

5. Improving the environment by replacing electricity generation from wind energy with fossil fuels

Environmental benefits, primarily due to the reduction in greenhouse gas emissions. Fossil fuel combustion in thermal power plants emits large quantities of carbon dioxide (CO_2), a major contributor to global warming and climate change. By generating the same amount of electricity using wind turbines, the consumption of natural gas or other fossil fuels is avoided, directly reducing the (CO_2) emissions associated with electricity production. If the mechanism of generating electricity from the wind energy potential in the northern regions of Iran is not used, as presented in the article, a large amount of fossil fuel will be needed to the thermal power electric mechanism [35].

By comparing the amount of electricity generated using the wind potential presented in the proposed method with the equivalent amount of thermal electricity generation, it is determined that if an emission factor of approximately 0.2 tons of (CO_2) per (MWh) of electricity generation with natural gas is used, the avoided (CO_2) emissions for Rudbar (Guilan) will be about 267.5 tons, for Savadkuh about 121.4 tons, and for Bandar Turkman about 89.8 tons per year, which are graphically presented in Fig. 11 for visual comparison.

These values indicate that even medium and small-scale wind energy projects can significantly contribute to improving local air quality and climate change mitigation efforts. Beyond (CO_2) reduction, substituting wind energy for thermal generation also decreases emissions of other pollutants, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter, which are associated with respiratory and cardiovascular health issues. The integration of wind power into the regional energy mix therefore not only reduces greenhouse gas emissions but also alleviates local environmental pollution, supporting sustainable development and public health improvements [35].

The findings confirm that expanding wind energy deployment in northern Iran can play a critical role in reducing reliance on fossil fuels, mitigating environmental pollution, and supporting national energy diversification goals. Even regions with moderate wind potential can make meaningful contributions to clean electricity generation when site selection, turbine design, and system efficiency are optimized.

6. Conclusion

This paper provided a comprehensive assessment of wind energy potential in the northern provinces of Iran, focusing on the Rudbar (Guilan), Savadkuh (Mazandaran), and Bandar Turkmen (Golestan) regions. By integrating long-term meteorological data, Weibull statistical modeling, (GIS) based spatial analysis, and (AHP) multi criteria decision making, the results demonstrate that northern Iran possesses considerable yet underutilized wind resources. Among the investigated sites, Rudbar exhibits the highest wind power density and annual energy production, confirming its suitability for large scale wind farm development, while Savadkuh and Bandar Turkmen show viable potential for medium scale and distributed wind energy systems when appropriate turbine technologies are employed. The substitution of wind generated electricity for fossil fuel based power plants yields substantial benefits. The results indicate that annual wind electricity production of 534.9 (MWh) in Rudbar, 242.8 (MWh) in Savadkuh, and 179.5 (MWh) in Bandar Turkmen can collectively avoid the consumption of approximately 239,000 (m^3) of natural gas per year. This reduction in fossil fuel use translates into significant greenhouse gas mitigation, with avoided (CO_2) emissions estimated at about 267.5 tons, 121.4 tons, and 89.8 tons per year for Rudbar, Savadkuh, and Bandar Turkmen, respectively. In addition to (CO_2) reduction, replacing thermal power generation with wind energy decreases emissions of air pollutants such as (NO_x), (SO_2), and particulate matter, thereby contributing to improved air quality and public health in these regions. The proposed assessment framework and quantitative results provide a reliable basis for policymakers, energy planners, and investors to accelerate wind energy development, promoting a more sustainable and environmentally resilient energy system in Iran.

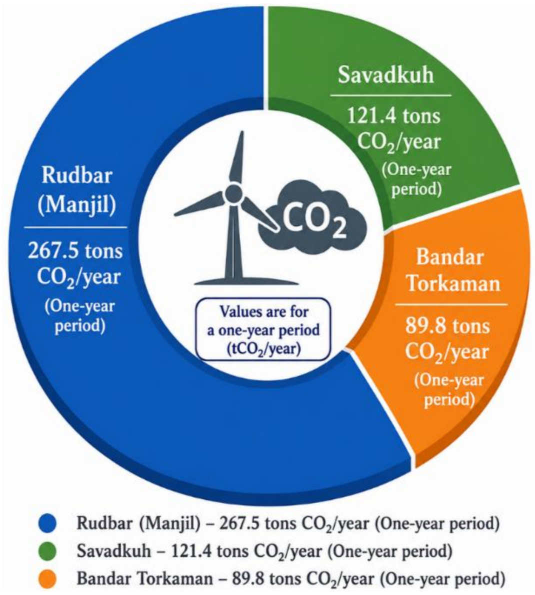


Fig. 11. Annual (CO_2) emissions from generating electricity with fossil fuels instead of using wind energy potential

7. References

[1] Shorabeh SN, Firozjaei HK, Firozjaei MK, Jelokhani Niaraki M, Homaee M, Nematollahi O. The site selection of wind energy power plant using GIS multi criteria evaluation from economic perspectives. Renewable and Sustainable Energy Reviews. 2022 Oct 1; 168:112778.

[2] Mohamadi H, Saeedi A, Firoozi Z, Zangabadi SS, Veisi S. Assessment of wind energy potential and economic evaluation of four wind turbine models for the east of Iran, Heliyon 7 (6)(2021) e07234.

[3] Mohammadpour M, Bevrani H. Comparative analysis of two new wind speed TX models using Weibull and log logistic distributions for wind energy potential estimation in Tabriz, Iran. 2024 Feb 2.

[4] Spiru P, Simona PL. Wind energy resource assessment and wind turbine selection analysis for sustainable energy production. Scientific Reports. 2024 May 10;14(1):10708.

[5] Roshan GR, Saman AA, Sarli R, Martinez A, Iglesias G. Projected shifts in wind energy availability in response to climate change in southwestern Iran. Sustainable Energy Technologies and Assessments. 2025 Nov 1;83:104655.

[6] Nassar AK, Al Dulaimi O, Fakhruldeen HF, Sapaev IB, Jabbar FI, Dawood II, Khalaf DH, Algburi S. Multi criteria GIS based approach for optimal site selection of solar and wind energy. Unconventional Resources. 2025 Jul 1;7:100192.

[7] Demir A, Dincer AE, Ciftci C, Gulcimen S, Uzal N, Yılmaz K. Wind farm site selection using GIS based multi criteria analysis with Life cycle assessment integration. Earth Science Informatics. 2024 Apr;17(2):1591-608.

[8] Can G, Kocabaldır C, Yucel MA. Spatial multi criteria decision analysis for site selection of wind power plants: a case study. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2024 Dec 31;46(1):4012-28.

[9] Wind atlas and resource prediction tools for wind farm planning, Journal of Wind Engineering (2023).

[10] Wind power integration and grid challenges in renewable energy systems, IEEE Trans. on Sustainable Energy (2023).

[11] Renewable energy transition in fossil fuel dominated economies, Energy Strategy Reviews (2022).

[12] Multi criteria approach for wind turbine optimization under climatic constraints, Renewable & Sustainable Energy Reviews (2021).

[13] Economic and environmental assessment of wind power integration, Energy Economics (2022).

[14] Wind speed statistical modeling for energy potential assessment, Journal of Renewable and Sustainable Energy (2023).

[15] Yildiz SS, Yalcin EY, Demircioglu Z, Balkaya C. Spatial multi criteria decision making approach for wind farm site selection: A case study in Balıkesir, Turkey. Renew Sustain Energy Rev. 2024; 192:113780.

[16] Optimal site selection for wind power plant using multi criteria decision making methods: A case study in eastern Iran. Int J Low Carbon Technol. 2025.

[17] Mirrashid N, Rakhtala SM. Feasibility Study of a Zero Energy Building Based on Photovoltaic Low Speed Wind Battery Hybrid System: A Case Study in Golestan North of Iran. Iranica Journal of Energy & Environment. 2024 Jul 1;15(3):235-47.

[18] Yeganeh M. An Assessment of Wind Energy Potential as an Electricity Generation Source in Iran. InAlternative Energy Resources in the MENA Region 2024 Apr 18 (pp. 117-143).

[19] International Journal of Sustainable Energy and Environmental Research. Wind energy in Iran: analysis of installed capacities and wind characteristics in different regions. Int J Sustain Energy Environ Res. 2022;11(1):1–22.

[20] Khanali M, et al. Wind Energy Potential Ranking of Meteorological Stations of Iran and Its Energy Extraction by Piezoelectric Element. MDPI Knowledge. 2025;2(3):508.

[21] Mohseni Cheraghlou A. Wind Power in Iran: Technical, Policy, and Financial Aspects for Better Energy Resource Management. Energies, 15(9):3230, 2022.

[22] Khazaee M, Zahedi R, Faryadras R, Ahmadi A. Potential assessment of renewable energy resources and their power plant capacities in Iran. Glob J Ecol. 2022;7(2):60–71.

[23] Filom S, Radfar S, Panahi R, Amini E, Neshat M. Exploring Wind Energy Potential as a Driver of Sustainable Development in the Southern Coasts of Iran: The Importance of Wind Speed Statistical Distribution Model. Sustainability. 2021;13(14):7702.

[24] Beyond 15 MW: A cost of energy perspective on the next generation of drivetrain technologies for offshore wind turbines. Appl Energy. 2023;344:121272.

[25] Sobhani B, Safarian VZ, Kianian MK. Potentiometric mapping for wind turbine power plant installation in Guilan Province, Iran. Potentiometric Mapping for Wind Turbine Power Plant Installation Guilan Province in Iran. 2019.

[26] Derafshi K, Motevalli S, Bairamvand R, Janbaz Ghobadi GR. Analysis of wind power characteristics and the influence of topography with a renewable energy generation approach: Case study of Mazandaran Province, Iran. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2024.

[27] Babayani D, Khaleghi M, Hashemi Tilehnoee M. Statistical evaluation of wind speed frequency and wind power potential in Golestan Province, Iran. Int J Renew Energy Dev. 2016;5(1):25–31.

[28] Gandomkar A. Assessment of wind energy potential across Iran using statistical wind analysis. J Geogr Plan Environ. 2009;20(2):45–60.

[29] Ghabbadi J. Wind energy potential assessment for optimal wind turbine site selection in Mazandaran Province, Iran. Amayesh J Geogr Space. 2019;11(4):123–138.

[30] Noorollahi Y, Yousefi H, Mohammadi M. Statistical analysis of wind speed data and assessment of wind energy potential in northern Iran using synoptic stations. Energy Convers Manag. 2016;122:451–463.

[31] Mostafaeipour A, Sedaghat A, Dehghan-Niri AA, Kalantar V. Wind energy feasibility study using Weibull distribution for selected sites in northern Iran. Renew Sustain Energy Rev. 2011;15(8):3881–3891.

[32] Zhang J, Wu Y, Lu X. Application of Weibull distribution for wind energy assessment: Definitions and parameter interpretation. Sustain Energy Res. 2023;10(1):15–28.

[33] Komanoff C. Wind Power's Displacement of Fossil Fuels. Accessed 31 Dec 2025.

[34] U.S. Energy Information Administration (EIA). Fossil fuel equivalency approach to convert renewable electricity generation to primary energy consumption. Monthly Energy Review. 2025; Section 12, p. 255.

[35] Bertolini M, Duttilo P, Lisi F. Accounting carbon emissions from electricity generation: a review and comparison of emission factor based methods. Appl Energy. 2025.