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Research Article

Analysis of wind power characteristics and the influence of topography, with a renewable energy generation approach (Case study: Mazandaran province)

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Abstract

In this study, a statistical analysis of daily wind speed and direction at a height of 10 m in 15 synoptic meteorological stations of Mazandaran Province over a 12-year period (2006 to 2017) was conducted to provide a preliminary estimate of the extractable energy and spatial capacity of wind flow. In addition, the characteristics of wind speed and direction, Weibull probability distribution parameters and wind power potential and density of the stations were also determined. ArcGIS interpolation method (IDW) was used to prepare the calculated layers of the average speed, speed continuity, and power density of the wind at 10, 30, and 50 m heights. Furthermore, to examine the influence of topography on the wind variables, the Pearson correlation coefficient was used to evaluate the relationship between altitude, hillslope aspect, and slope indicators with each of the wind variables. There is only Baladeh station that has a limited possibility of extracting wind power at different heights. A map of wind speed zones at 50 m height reveals that Baladeh station has a maximum wind speed in July. The correlation coefficient between wind speed and altitude above sea level was 0.677. As the altitude of the meteorological stations in the province above sea level increases, the wind speed increases at a height of 10 meters above the ground. Wind energy is one of the most cost-benefit renewable energy sources for power generation, which is not only polluting the environment and being abundant and permanent, but also has the lowest price fluctuations. With the increase of altitude of meteorological stations of the province, the wind speed and power density of the station increases at a height of 10 meters above the ground.

Keywords: Renewable energy, Topography, Wind power density, Wind turbine, Mazandaran Province.

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Introduction

Energy sources, primarily fossil fuels and uranium, based fission systems, that currently meet approximately 70% of global demand are projected to be depleted by the end of this century, posing significant challenges for humanity. (Yue and Wang, 2006; Strantzali and Aravosis, 2016). The depletion of fossil and nuclear energy sources has long attracted the attention of scientists and researchers. Consequently, extensive studies are being conducted worldide to develop and implement alternative clean energy sources (Baban and Parry, 2001; Kenisarin, 2007; Caralis et al, 2008; Ajayi et al, 2011; Chong et al, 2016; Gandomkar, 2010; Heydari et al, 2009; Esfandiari et al, 2011; Entezari et al, 2012). Rising concentration of carbon dioxide and other greenhouse gases resulting from the combustion of fossil fuels have critically contributed to unprecedented shifts in the Earth’s climate system (IPCC 2013). Accordingly, there is a board scientific and policy-level consensus for long-term objective of net-zero carbon emissions. Despite technological advancements, more than a billion individuals, approximately 15% of the global population, still lack access to electricity (REN21, 2015). Furthermore, global population of figures are anticipated to nearly double by the end of the twenty-first century, which may lead to a two-to-fourfold increase in energy demand. The urgent challenge remains to satisfy this growing energy need using sources that are clean, secure, and environmentally sustainable. Governments worldwide continue to allocate substantial resources to the generation of electricity, often for minimal energy output. Thus, a pressing issue is how to both optimize energy consumption and reduce production costs. Although emerging energy technologies are largely carbon-neutral and generally more sustainable than conventional fossil and nuclear fuels, the maturation of these technologies remains uneven, and in some cases, prohibitively expensive (Partovi, 2012; Entezari et al, 2012; Rezaei Banafsheh et al, 2014; Ahmadi and Dadashi Roudbari, 2015; Maryanaji et al, 2016). Renewable energy systems are instrumental in advancing climate change adaptation strategies. They enhance the resilience of current energy infrastructures and help maintain energy service continuity amid shifting climatic regimes(Ajayi et al, 2011; Ilkilic and Aydin, 2015; Allouhi et al, 2017; Kruyt et al, 2018; Chen et al, 2018; Salam et al, 2018). Among these, wind energy stands out as one of the most economically viable solutions due to its low market volatility, minimal environmental footprint, abundance, and consistency. A key prerequisite for expanding wind power utilization is the identification of optimal geographical zones that satisfy the technical and environmental requiements for wind wind farm development (Allouhi et al, 2017; Kim and Lim, 2017; Baker and Sovacool, 2017; Shahriari and Blumsack, 2017; Bryne et al, 2020; Chen et al, 2018; Salam et al, 2018). Assessnig the aerodynamic and environmental parameters influeing wind flow is critical in this context (Promsen et al, 2014; Aien et al, 2014; Ilkilic and Aydin, 2015; Bairamvand et al, 2022c). However, the complex behavior of meteorological phenomena under environmental constraints, particularly in mountains terrains, has received limited attention in Iranian climatological research. Topographical factors such as elevation, slope, and hillslope aspect significantly influence local atmospheric dynamics. Wind, as the most dynamic meteorological element, exhibits diverse intarctions with terrain morphology, especially in orographically complex systems. The role of mountainous topography in generation distinictive wind types underscores the importance of micro-climate analysis in wind energy assessment (Whiteman, 2000; Azizi et al, 2017). Quantitave indicators such as annual average net energy output and capacity factor, both sensitive to variations in wind speed distribution, are essential for evaluating wind energy potential in specific regions (Azizi et al, 2017; Janbaz Ghobadi, 2019; Kruyt et al, 2018; Negash, 2020; Rehman et al, 2020). Despite considerable economic growth improvements in public welfare across Iran, current patterns of energy utilization continue to raise environmental concerns due to high consumption rates and greenhouse gas emissions. Promoting renewable energy development is therefor a strategic imperative for sustainable progress. Among the available options, wind energy holds strategic relevance for Iran given its abundant wind resources and favorable topographic conditions. This study focuses on assessning the spatial distribution of wind power capacity in Mazandaran Province.

The objective is to evaluate wind energy potential and develop zoning maps based on with speed and energy production indicators, thereby identifying suitable locations for wind farm implementation in the Province's high-wind regions. The main research questions are as follows:

1) What is the spatial distribution of wind energy potential across Mazandaran Province, and which regions exhibit optimal conditions for wind farm development?

2) How do topographic factors such as elevation, slope, and aspect influence wind behavior and energy generation efficiency in mountainous terrains?

3) To what extent can wind energy contribute to Iran's transition toward clean and sustainable energy under climate change pressures and growing energy demands?

4) What are the key indicators, such as wind speed variability, capacity factor, and net annual energy output, that define the suitability of a location for wind power exploitation?

5) How does the intraction between local meteorological dynamics and topography affect wind flow modeling and renewable energy zoning in synoptic stations?

Materials and Methods

Regional setting

Mazandaran Province, with an area of 23,756 km2, occupies about 1.46% of Iran, ranking 18th in land area. It lies between latitudes 35̊ 47′ to 36̊ 54′ N and longitudes 50̊ 34′ to 54̊ 10′ E (Figure 1). Mazandaran Province has a high potential for extractable energy and spatial capacity of wind flow. This province is characterized by a particular topography (from -26 to over 2500 m altitude), a northern hillslope aspects and prevailing winds from west to northwest to north, all of which provide the conditions for wind energy evaluation and spatial capacity. The increase of population in Mazandaran Province as well as its development as the first tourism hub in Iran have drastically reduced the capacity of the province in terms of environmental resources utilization. Therefore, it is necessary to zone different regions of the province, focus on topographical conditions and identify areas suitable for wind turbine construction in order to exploit the wind power potential and meet the replacement demand for cheap renewable energy instead of expensive fossil fuels.

Methodology

A descriptive, analytical and field approach is used in this study. The spatial capability of wind energy in Mazandaran Province was evaluated using spatial and quantitative data. Wind speed and direction data from 15 synoptic meteorological stations in the province were examined to determine the spatial capability of wind energy. These stations (Table 1, Figure 2) include Ramsar, Nowshahr, Siahbisheh, Kojoor, Baladeh, Amol, Babolsar, Gharakhil-e Ghaemshahr, Pol-e Sefid, Alasht, Firoozkooh, Sari, Kiasar, and Bandar-e Amirabad. Due to vector variable behavior of wind and the influence of local and atmospheric parameters on its direction and speed, reconstruction of wind data is either impossible or fraught with uncertainty. A comprehensive flowchart illustrating the research methodology has been presented in Figure 3. Since the windy statistical periods were not the same at all stations, the range of years with a common statistical period was considered over the 12 years (2006 to 2017). The wind speed and direction characteristics and Weibull probability distribution function parameters, were evaluated after quantitative and qualitative data control. Then, the wind power potential and density of the studied stations in the province were calculated at different heights.

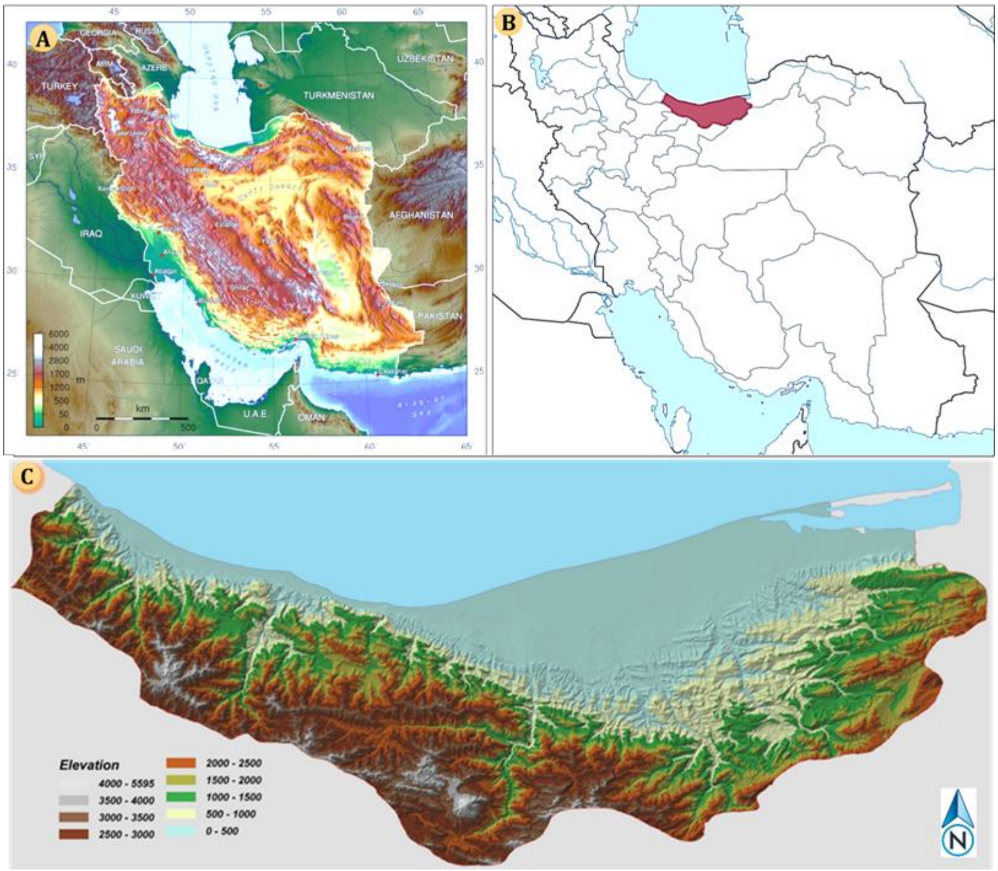

Fig. 1: Geographical location of Mazandaran Province; A: Topographic map of Iran shows various physiographic regions (www.worldofmaps.net). B: Map of Iran with boundaries of provinces. C: Triangulated Irregular Network (TIN) of Mazandaran Province.

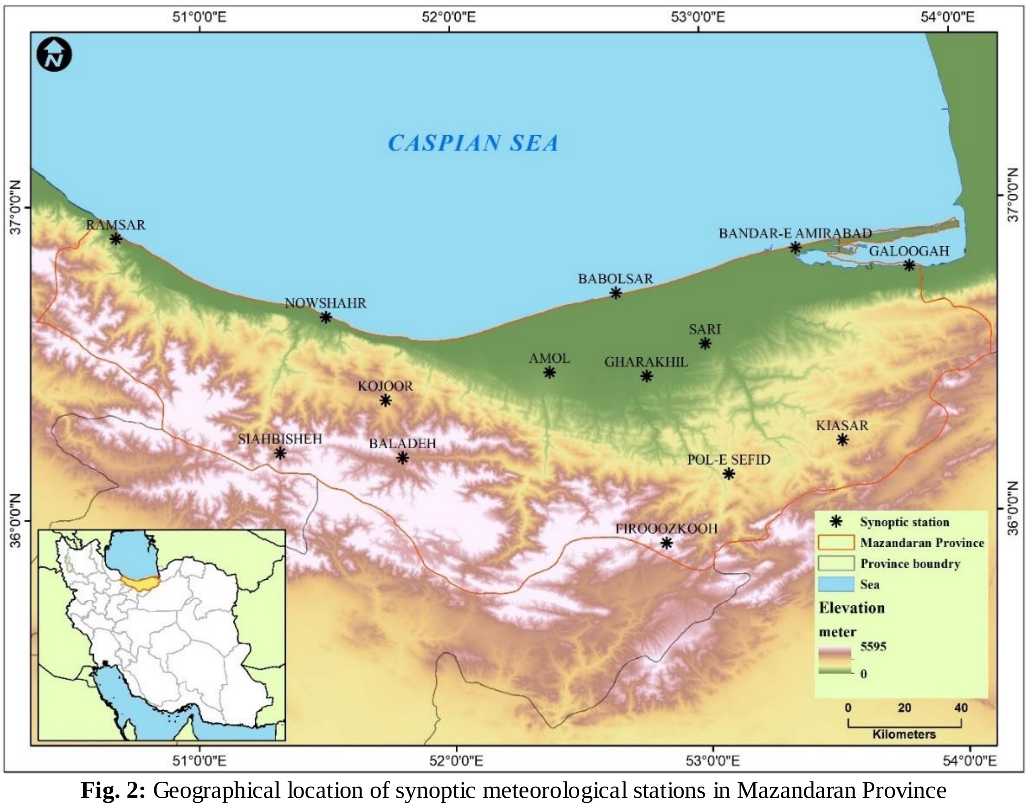

Fig. 2: Geographical location of synoptic meteorological stations in Mazandaran Province

Table 1: Location and characteristics of synoptic meteorological stations in Mazandaran Province (Bairamvand et al, 2022a)

No.	Station	Longitude (E)	Latitude (N)	Altitude (m)	Statistical period (year)
1	Ramsar	50° 40´	36° 54´	-20	1955-2017
2	Nowshahr	51° 30´	36° 39´	-20.9	1977-2017
3	Siahbisheh	51° 19´	36° 13´	2165	1999-2017
4	Kojoor	51° 44´	36° 23´	1550	2006-2017
5	Baladeh	51° 48´	36° 12´	2120	2006-2017
6	Amol	52° 23´	36° 28´	23.7	2001-2017
7	Babolsar	52° 39´	36° 43´	-21	1951-2017
8	Gharakhil	52° 46´	36° 27´	14.7	1984-2017
9	Alasht	52° 51´	36° 05´	190	2003-2017
10	Firoozkooh	52° 50´	35° 55´	1975.6	1993-2017
11	Pol-e Sefid	53° 05´	36° 08´	610	2003-2017
12	Sari	53°	36° 33´	23	1999-2017
13	Kiasar	53° 32´	36° 14´	1294.3	2002-2017
14	Amirabad	53° 22´	36° 51´	-20	2005-2017
15	Galoogah	53° 49´	36° 47´	-10	2005-2017

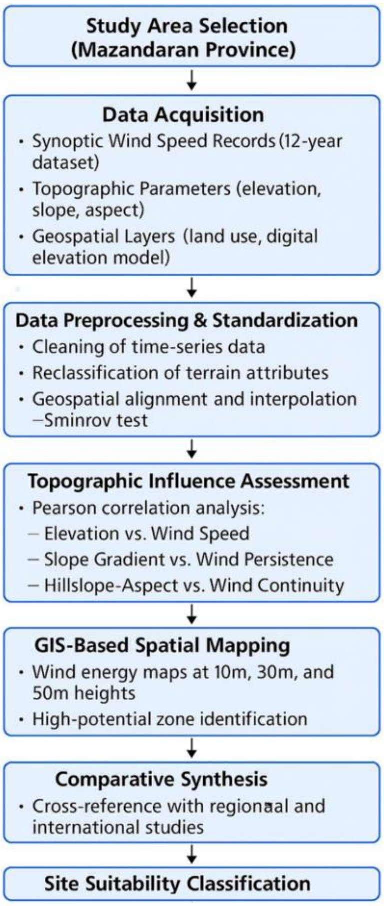

Fig. 3: Structured Workflow for Topography-Based Wind Power Evaluation

The Weibull probability distribution function: this function is generally used to represent the frequencies of the wind speed. It also represents the most frequent starting point of stochastic analysis, simulation, and forecasting of wind speed. Its general formulation is given as follows (Equation 1, Kruyt et al, 2018):

Eq. 1)

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)\right)^{k}, (k > 0, v > 0, c > 1)$$

Where the parameters f(v) probability of occurrence of wind speed (m/s) v is the wind speed (m/s), and c and k are the scale (m/s) and shape (unitless), respectively. As the names imply, the k changes the shape of the curve and not the dimensions, whereas c shifts the curve toward high or low wind speeds. These two parameters must be identified for each given location. Their identification can be performed with use of some classic techniques such as the minimum square error, the least squares method, and the standard deviation method that were calculated here using the maximum likelihood method (Equations 2 and 3, Akpinar et al, 2005).

Eq. 2)

$$k = \left(\frac{\sigma}{v}\right)^{-1.086} \quad (1 \le k \le 10)$$

Eq. 3)

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

Where k is the Weibull shape factor (unitless), v is the wind speed (m/s) and σ is the standard deviation and $\bar{v}$ is the mean wind speed (in meter per second) and Γ is the Gamma function. The mean wind speed ($\bar{v}$) is (equation 4). It is based on the numerical iteration of mean wind speed ($\bar{v}$) andstandard deviations (σ) of wind speeds are expressed, where:

Eq. 4)

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

Calculation of wind power potential: the power of wind energy is directly related to the cube of wind speed (Equation 5, Kruyt et al, 2018).

Eq. 5)

$$p(v) = \frac{1}{2}\rho\backslash rhoAv^3$$

Where ρ\rho is the standard air density (kg/m^3) at sea level with an average temperature of 15 °C and a pressure of one atmosphere ($1.225\frac{kg}{m\hat{}3}$), and Av is the average wind speed (Selic, 2003). According to the International Standard Atmosphere (ISA) values (15° C at sea level) the density of dry air is 1.225 kg/m^3 at 15.55°C and 101,325 Pa. Since the air density is a function of the altitude (and temperature), the temperature deviation from the ISA value at that pressure altitude needs to be corrected, with lower temperatures than standard lowering the density altitude and higher temperatures raising the density altitude which considered in the calculations. Accordingly, the ρ\rho of the synoptic stations was found as the following table (Table 2). This table illustrates ρ\rho of the stations calculated using the measured data (average annual of air temperature, air humidity, biometric pressure and altitude) and following equations (Equations 6 and 7, Kruyt et al, 2018):

Eq. 6)

$$p = p_0 \,.\, (1 - \frac{L\,.\,h}{T_0})^{\frac{g.M}{R.L}}$$

Eq. 7)

$$\rho\backslash rho = \frac{p.M}{R.T}$$

Where p (Pa) is the pressure at altitude, p_0 (Pa) is the sea level standard atmospheric pressure, T_0 (k) is the sea level standard temperature, g (m/s2) is the Earth-surface gravitational acceleration, L (K/m) is the temperature lapse rate, R (J/(mol.K) is the universal gas constant, M (kg/mol) is the molar mass of dry air and ρ\rho (kg/m^3) is the air density at altitude.

Table 2: Altitude, temperature, humidity and barometric pressure and their impact on local atmospheric air density on the synoptic stations

No.	Station	Altitude (m)	Air temperature (C)	Air humidity (%)	Biometric pressure (hPa)	ρ\rho (kg/m^3)
1	Ramsar	-20	16.5	81	1015.64	1.215
2	Nowshahr	-20.9	16.5	81	1015.75	1.215
3	Siahbisheh	2165	11	60	775.85	1.239
4	Kojoor	1550	11.8	61	838.59	0.948
5	Baladeh	2120	9.6	55	779.24	0.957
6	Amol	23.7	17.6	78	1010.43	1.204
7	Babolsar	-21	17.6	80	1015.75	1.210
8	Gharakhil	14.7	17.1	79	1011.50	1.207
9	Alasht	190	11.2	67	990.33	1.209
10	Firoozkooh	1975.6	8.3	71	792.72	0.978
11	Pol-e Sefid	610	15.4	69	942.18	1.132
12	Sari	23	18.2	76	1010.52	1.201
13	Kiasar	1294.3	13.3	68	866.31	1.049
14	Amirabad	-20	17.2	80	1015.64	1.211
15	Galoogah	-10	17.7	75	1014.44	1.208

Equation 8 provides the calculated wind energy power at a height of 10 m.

Eq. 8)

$$p_{10} = \frac{1}{2}\overline{pv^3}(\frac{w}{m^2})$$

Wind speeds at upper hights are estimated using equations 9 and 10 (a height of 40 m is suitable for building wind turbines, for example).

Eq. 9)

$$\frac{v}{v_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\alpha}$$

Eq. 10)

$$v = v_0\left(\frac{z}{z_0}\right)^{\alpha}$$

Where v nad v_{ref} are the wind speed at height z above the ground (wind speed at the desired height), the wind reference speed measured at height z_{ref} (wind speed at a height of 10 m), respectively, and α is as a function of the degree of unevenness of the earth's surface (calculated using equation 11).

Eq. 11)

$$\alpha = \frac{[0.37 - 0.088\ln v_{10}]}{[1 - 0.088\ln(z_{10}/10)]}$$

Average wind power potential: is calculated with equation 12 during the windy period.

Eq. 12)

$$WPD = \frac{\sum_{i=1}^{n} 1/2\rho\backslash rhov_i^3}{N}$$

Where i is the measured 3 hours wind speed, ρ\rho is the standard air density ($1.225\frac{kg}{m^{\wedge}3}$), v is the wind speed (m/s), W is the amount of energy in joules and N is the total data per year, respectively. In addition, based on the measured wind speed, the wind power or energy potential can be calculated by analyzing the Weibull distribution and equation 13.

Eq. 13)

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

Where Pw refers to the energy obtained, ρv refers to the power curve of wind turbine.

Wind power density: the amount of it can be calculated using equation 14 for a given site.

Eq. 14)

$$\frac{E}{A} = \frac{1}{2}\rho c^3 \Gamma\left(1 + \frac{3}{k}\right) T$$

Extractable energy estimation: given the threshold of the 660 kW, (4 m/s) turbines and considering the threshold of wind speed at a height upper than 40 m, the amount of extractable energy and its confidence percentage are calculated and estimated.

Wind variability: since the continuity and stability of wind crucial for electricity power generation, the wind variability is calculated using equation 15.

Eq. 15)

$$CV = \frac{\sigma}{\bar{x}} \times 100$$

In this equation, CV, $\bar{x}$, and σ are the percentage of variability, data average and standard deviation of the data obtained from equation 16, respectively.

Eq. 16)

$$\sigma = \sqrt{\frac{1}{n}\sum (x_i - \bar{x})^2}$$

Where, σ, x_i, $\bar{x}$ and n are the standard deviation, individual data, data average and the number of data, respectively (Kruyt et al, 2018; Negash et al, 2020).

Results and Discussion

Frequency and continuity of the wind speed values

The average hourly continuity values of monthly and annual winds in different speed categories were calculated. It is obvious that the total hours of wind continuity in different speed categories in each year also as an average in each statistical period will be equal to 24×365=8760 hours. The curves and histograms of wind frequency distribution refer to a height of 10 meters above the ground. The frequency histogram and plot of Weibull distribution curve with the k and c parameters of wind speed mean values in Mazandaran Province synoptic meteorological stations from 2006 to 2017 have been presented in Bairamvand et al, 2022a, b (Figure 4). Frequency -speed histograms are primarily characterized by their positive skewness. A positive skewness indicates a low frequency of high-speed winds, which is unfavorable for the exploitation of wind energy. Values of skewness that are close to zero or negative indicate a higher frequency of high-speed winds, which can be considered more suitable for wind energy exploitation. Therefore, the highest skewness is calculated for Ramsar, Nowshahr, Kiasar, Amol, and Babolsar stations, and the lowest for Baladeh and Kojoor stations. Baladeh station has the highest frequency of wind values with speeds above 3 m/s and the highest values of parameters k and c among the 15 stations studied in Mazandaran Province. The conditions at Baladeh station are favorable for turbine installation, which makes it an ideal site for the construction of a wind power plant. Accordingly, Kojoor, Pol-e Sefid, Sari, Amirabad, Siahbisheh, and Firoozkooh stations with the abundance of wind speed values in the categories more than 3 m/s are considered as other suitable locations for the construction of small wind turbines that could be used for special activities. However, due to the abundance of low winds and lack of suitable wind conditions, other stations such as Alasht, Amol, Babolsar, Galoogah, Kiasar, Nowshahr, and Ramsar cannot be considered for the construction of a power plant on a priority basis. Base on the total continuous wind hours map at a speed of 3 m/s or more, an optimal condition for wind turbine construction was observed at Baladeh station with wind continuity at a height of 10 m above the ground (5548 hours and a frequency of 63.3%) and a speed equal to or greater than the mentioned threshold. Kojoor, Pol-e Sefid, Sari, and Amirabad stations also have relatively favorable conditions for the construction of some wind turbines, with duration of 4048, 3932, 3868 and 3640 hours, and frequency of 46.2, 44.9, 44.2, and 41.6 %, respectively. On the other hand, Alasht, Gharakhil-e Ghaemshahr, Amol, Babolsar, Firoozkooh, Galoogah, Kiasar, Nowshahr and Ramsar stations have low abundance values of winds continuity of more than 3 m/s, which makes them unsuitable for wind turbine installation and power plant construction (Bairamvand et al, 2022a, b).

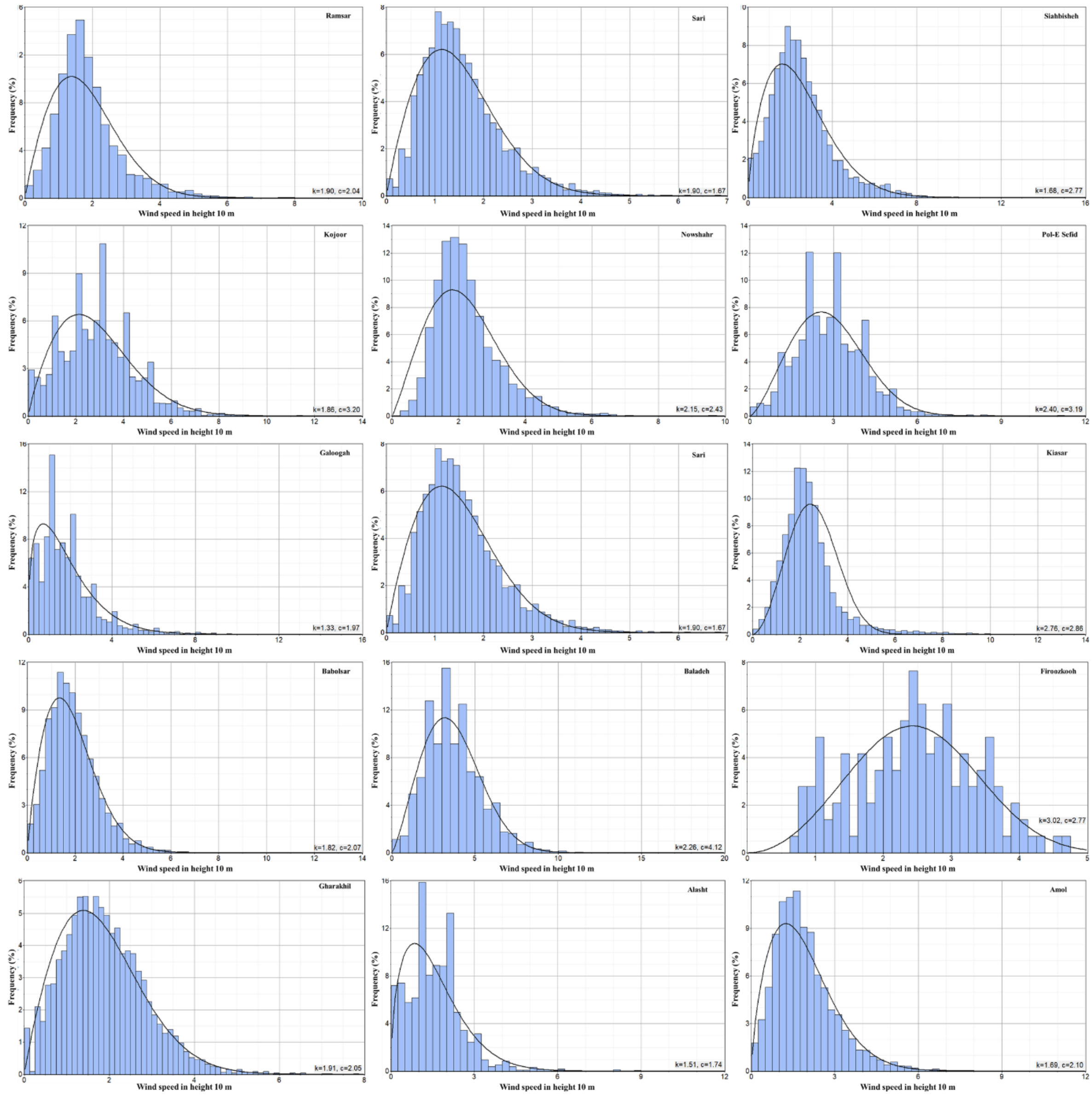

Fig. 4: Frequency histogram and plot of Weibull distribution curve, where the parameters k and c are the mean values of wind speed in Mazandaran Province synoptic meteorological stations based on wind data 2006 to 2017.

Generally, Mazandaran Province can be spatially divided into two parts in terms of suitable conditions for the use of wind energy. One is unsuitable area for wind turbine installation due to constant winds with a minimum threshold, include: the western parts of the province such as Ramsar, Tonekabon, and Chaloos Townships, the east of Behshahr, Neka, and Sari Townships, the coastline strip of the province in the townships of Nowshahr, Noor, Mahmoudabad, Babolsar, and Jooybar and the plain parts of the province in townships of Ghaemshahr, Babol, and Amol. On the other hand, the foothills and highlands of Nowshahr, Noor, and Amol Townships, as well as the nearby areas of Ghaemshahr and Savadkooh and the western parts of Sari, Neka, and Behshahr Townships are in a relatively favorable condition in terms of sustained winds of 3 m/s and more. According to these results, the optimal conditions for installing wind turbines are in the mountainous and highland areas of Noor Townships (especially Baladeh region).

Changing monthly and annually trend of wind speed average with increasing height

The trend of the increase in wind speed changes with increasing altitude as a function of surface roughness; thus, it is more pronounced on rough surfaces than on smooth ones. Equations 7 and 8 are used to calculate wind speed at heights greater than 10 meters above the ground. Various heights for wind turbine masts are given in scientific publications. Most commercial wind turbines have an axis height of 30 to 80 meters (Mohammadi et al, 2012; Mojarrad and Hemati, 2013), and are often 50 meters above the ground. However, heights of 120, 150, and sometimes even 200 meters have also been reported. The average monthly and annual speed values of synoptic meteorological stations in the province up to a height of 100 meters above the ground were calculated using wind speed calculations at different heights. These calculations more accurately identified areas with high and low potential for wind power generation. Table 3 shows the average monthly wind speed of the stations at a height of 10 meters above the ground.

Table 3: Average monthly wind speeds (m/s) of Mazandaran Province meteorological synoptic stations at a height 10 m above the ground

Month/ Station	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
Baladeh	2.42	2.72	3.57	4.10	4.14	4.50	4.73	4.42	4.09	3.80	2.84	2.24
Kojoor	1.83	2.57	3.21	3.59	3.62	3.50	3.46	3.45	2.84	2.47	2.02	1.53
Pol-e Sefied	2.55	2.83	3.17	3.02	2.95	3.18	3.23	3.22	2.88	2.48	2.17	2.36
Amirabad	2.32	2.77	2.93	2.88	2.96	3.30	3.54	3.00	2.85	2.47	2.34	2.41
Siahbisheh	3.06	2.97	2.94	2.86	2.38	2.05	1.76	2.10	1.99	2.23	2.44	2.95
Firoozkooh	1.18	1.80	2.31	3.04	3.09	3.81	3.45	2.88	2.73	2.31	1.75	1.18
Kiasar	2.49	2.63	2.56	2.31	2.08	2.35	2.36	2.38	2.18	1.91	1.99	2.32
Nowshahr	2.01	2.34	2.51	2.40	2.36	2.21	2.25	2.20	2.02	2.03	1.92	1.94
Amol	1.72	2.13	2.38	2.32	2.07	1.71	1.68	1.92	1.83	1.57	1.50	1.62
Babolsar	1.52	1.94	2.12	2.19	2.20	2.17	2.19	1.91	1.75	1.49	1.27	1.39
Gharaakhil	1.65	1.91	2.13	2.12	2.13	1.98	1.76	1.73	1.87	1.56	1.46	1.58
Gagloogah	1.37	1.93	2.19	2.21	2.06	2.47	2.35	1.79	1.63	1.25	1.17	1.28
Ramsar	1.61	1.77	2.08	2.00	1.82	1.95	2.08	1.87	1.78	1.62	1.55	1.53
Alasht	1.08	2.79	2.08	2.29	1.32	1.79	1.23	2.02	1.71	1.94	1.35	0.52
Sari	1.30	1.60	1.79	1.74	1.75	1.64	1.59	1.42	1.40	1.31	1.15	1.11

In most months of the year, the stations studied clearly do not have the wind speeds required for the installation of wind turbines. At the stations of Firoozkooh, Siahbisheh, Kojoor, Baladeh, Amirabad, and Pol-e Sefid, wind speeds of more than 3 m/s as the minimum threshold for turbine movement were measured only in some months of the year. The months number with an average wind speed of 3 m/s or more at the stations of Baladeh Kojoor, Pol-e Sefid, Firoozkooh, Amirabad and Siahbisheh is 8, 6, 5, 4, 3 and 1, respectively. Therefore, Baladeh station has the highest monthly wind speeds. Moreover, the months of March, April, May, June, July, and August have the highest average wind speeds in the study area. In the following, the variations in wind speed are calculated by increasing the height above the ground level to 100 meters as shown in Table 4. The minimum wind speed to start small turbines, which is usually between 3 and 4 m/s, varies depending on the type and design of turbine. Accordingly, there is only Baladeh station that has a limited possibility of extracting wind power at different heights. Firoozkooh, Siahbisheh, Kojoor, Amirabad and Pol-e Sefid stations from 20 meters above, Nowshahr and Kiasar stations from 30 meters above and Amol, Babolsar and Gharakhil-e Ghaemshahr stations from 40 meters above have limited conditions for using wind energy. Moreover, a minimum wind speed of 6 m/s, corresponding to the category IV in the classification of wind turbines based on the international standard IEC61400-1, should be considered to determine the minimum wind speed. From this point of view, only in Baladeh station, from a height of about 40 meters onwards, there is suitable conditions for the use of wind energy, and in all months of the year, the average wind speed is equal to or greater than the required threshold (Bairamvand et al, 2022a, b).

Table 4: Average monthly wind speeds (m/s) of Mazandaran Province meteorological synoptic stations at height above the ground level to 100 m

Height/ Station	10	20	30	40	50	60	70	80	90	100	Station height (m)
Alasht	1.57	1.94	2.20	2.41	2.58	2.73	2.86	2.98	3.09	3.20	190
Amirabad	2.81	3.49	3.96	4.33	4.64	4.91	5.15	5.36	5.56	5.75	-20
Amol	1.87	2.32	2.63	2.87	3.08	3.26	3.41	3.56	3.69	3.81	23.7
Babolsar	1.84	2.29	2.59	2.83	3.04	3.21	3.37	3.51	3.64	3.76	-21
Baladeh	3.65	4.52	5.13	5.60	6.01	6.35	6.67	6.95	7.21	7.45	2120
Firoozkooh	2.47	3.07	3.48	3.80	4.07	4.31	4.52	4.71	4.89	5.05	1975.6
Gagloogah	1.81	2.24	2.54	2.78	2.98	3.15	3.31	3.44	3.57	3.69	-10
Gharaakhil	1.82	2.26	2.56	2.80	3.00	3.18	3.33	3.47	3.60	3.72	14.7
Kiasar	2.29	2.84	3.22	3.52	3.78	4.00	4.19	4.37	4.53	4.68	1294.3
Kojoor	2.86	3.54	4.02	4.39	4.71	4.98	5.23	5.45	5.65	5.84	1550
Nowshahr	2.18	2.71	3.07	3.35	3.59	3.80	3.99	4.16	4.31	4.46	-20.9
Pol-e Sefied	2.84	3.52	3.99	4.36	4.67	4.94	5.19	5.40	5.61	5.79	610
Ramsar	1.81	2.24	2.54	2.77	2.97	3.15	3.30	3.44	3.57	3.69	-20
Sari	1.48	1.84	2.08	2.28	2.44	2.58	2.71	2.82	2.93	3.02	23
Siahbisheh	2.48	3.07	3.48	3.80	4.08	4.31	4.52	4.72	4.89	5.05	2165

Figures 5, 6 and 7 show maps of average annual wind speed for the study area at heights of 10, 30 and 50 meters. According to the prepared maps, the maximum wind speed at different heights corresponds to the southern and mountainous parts of Noor, Amol, Nowshahr, Savadkooh and to some extent of Chaloos, which the highest amount is in the southern parts of Noor Township. The average annual wind speed is the lowest in the plain and coastal areas of Mazandaran Province, especially in Jooybar, Babolsar, Mahmoudabad, Sari, Gharakhil-e Ghaemshahr Townships, the northern parts of Savadkoohand, Babol and Amol, also the western parts of the province (Ramsar and Tonekabon) as well as the eastern parts of Behshahr and Neka Townships. Based on the map of wind speed zones at a height of 10 m in Mazandaran Province, Baladeh station has the highest wind speed compared to other stations in the province, with an average annual wind speed of 3.65 m/s and an average monthly maximum wind speed of 4.43 m/s in July. Therefore, the wind speed at a height of 10 meters is greater than 4 m/s for about 6 months of the year, indicating a favorable location wind turbine installation. Meanwhile, Firoozkooh and Kojoor stations are in the next phase in June and May with maximum monthly average wind speeds of 3.81 and 3.62 m/s, respectively. In terms of average monthly wind speed, Kojoor, Pol-e Sefid and Amirabad stations are in more favorable situation than other stations in the province after Baladeh station with 2.84, 2.84, and 2.81 m/s, respectively. Sari, Alasht, Ramsar, Galoogah, Gharakhil, Babolsar and Amol stations have the lowest average monthly wind speeds. The lowest average monthly wind speeds were recorded at Alasht station in December with 0.52 m/s and in June with 1.08 m/s. Accordingly, Sari station with 1.11 m/s in December and Galoogah station with 1.17 m/s in November have the lowest average monthly wind speeds (Figure 5).

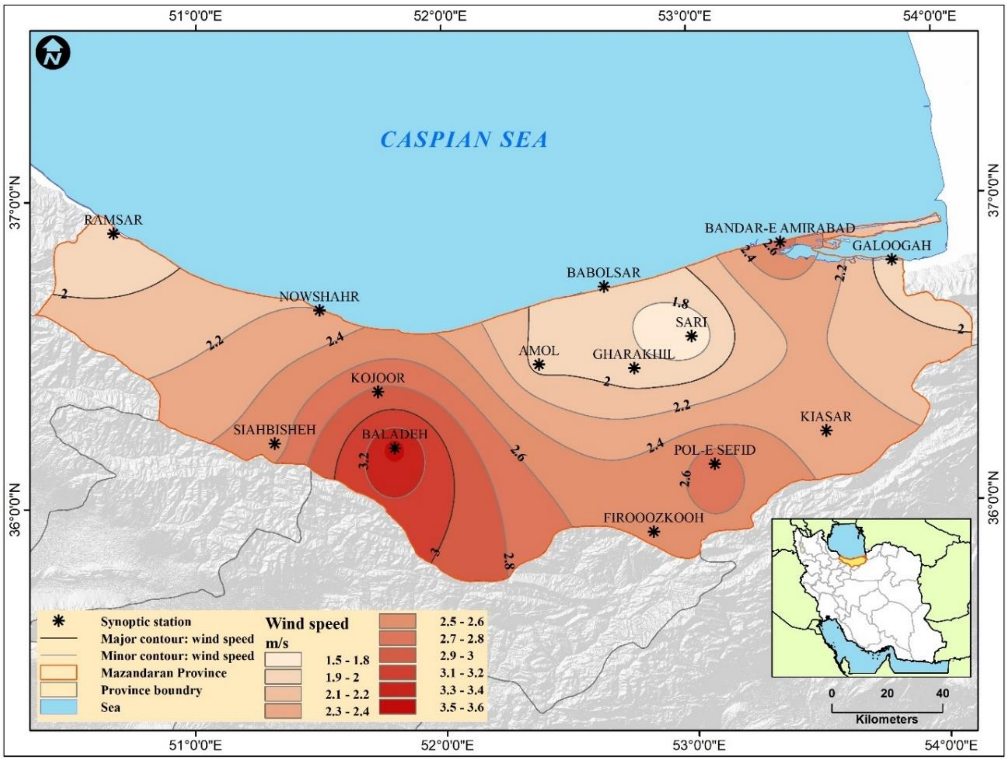

Fig. 5: Map of the average annual wind speed of Mazandaran Province at a height of 10 meters above the ground (Bairamvand et al, 2022a).

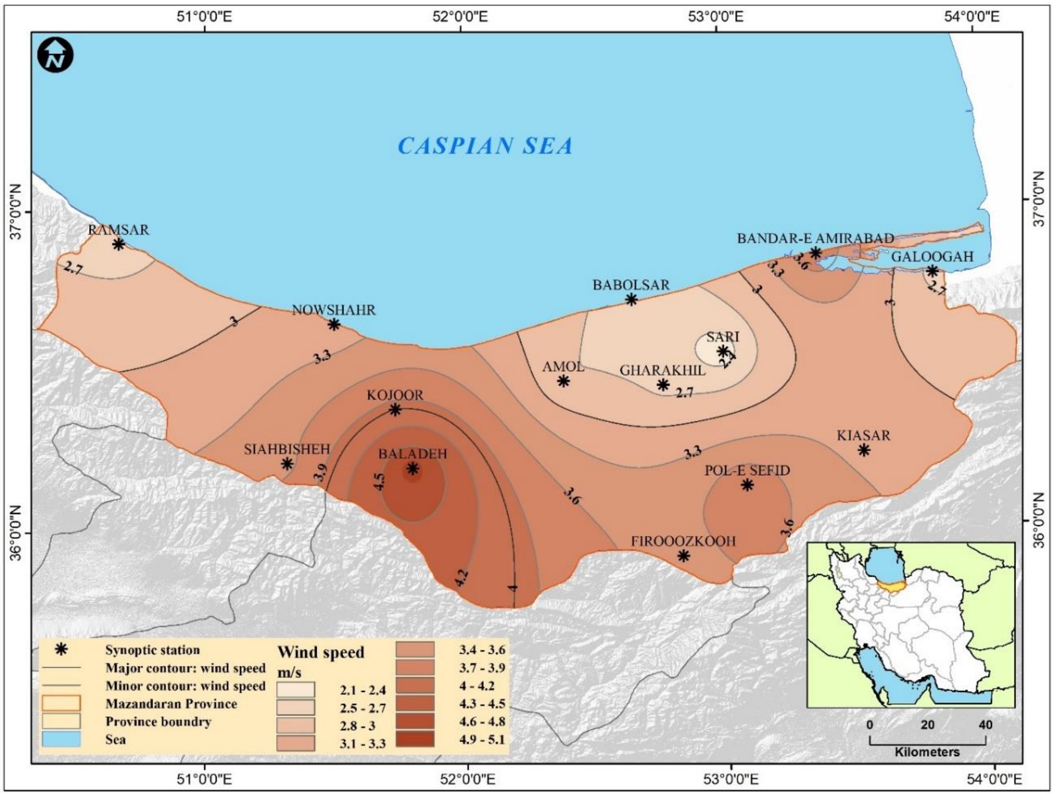

Fig. 6: Map of the average annual wind speed of Mazandaran Province at a height of 30 meters above the ground

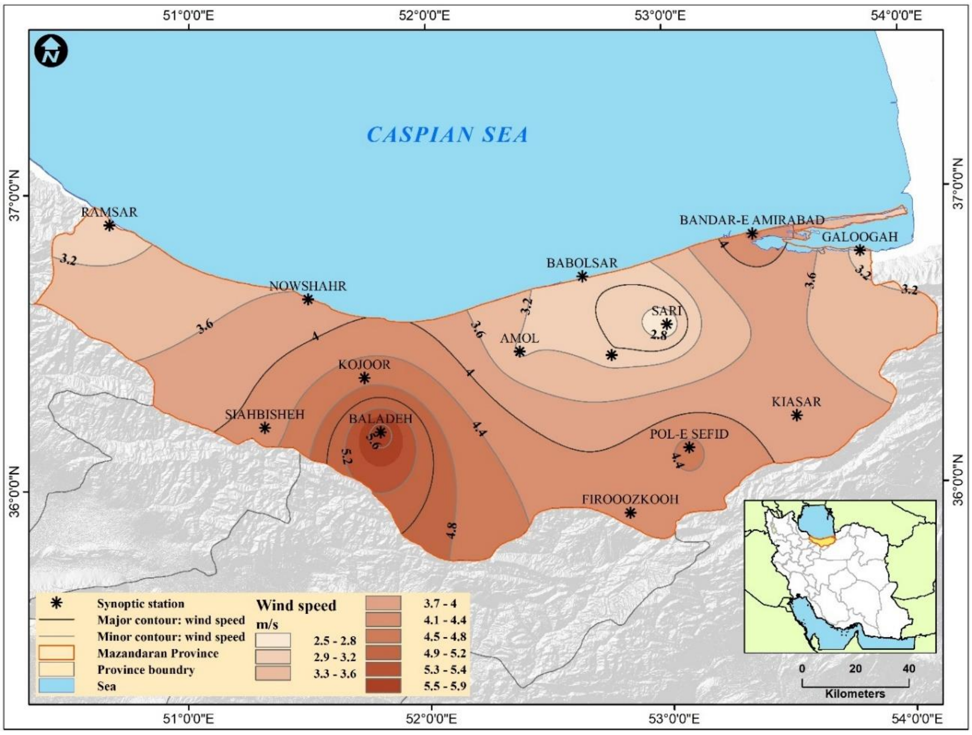

Fig. 7: Map of the average annual wind speed of Mazandaran Province at a height of 50 meters above the ground (Bairamvand et al, 2022a).

Zoning of wind speed in Mazandaran Province at height of 30 meters above the ground shows that Baladeh station with an average wind speed 5.13 m/s has the highest average wind speed (6.64 m/s) in July, which is a good reason for windy conditions and turbine site installation. During about 8 months of the year, wind speeds of more than 5 m/s at 30 m are recorded at Baladeh station, especially during the warmer months (June to September). Winds with speeds greater than 4 m/s are measured at Pol-e Sefid and Amirabad stations for about 7 months (March to September), at Kojoor station for about 6 months (March to August), and at Siahbisheh station for about 5 months (January to April and December). During most months of the year, the average wind speed at height of 30 meters is less than 3 m/s in Sari, Alasht, Ramsar, Galoogah, Gharakhil, Babolsar and Amol stations (Figure 6). The zoning map of wind speed at a height of 50 meters in Mazandaran Province indicates that Baladeh station has a maximum wind speed of 7.78 m/s and an average monthly wind speed of 5.98 m/s in July. Wind speeds of more than 6 m/s are recorded at the station in about 7 months of the year (April to October), especially in the warmer months. Consequently, year-round wind speeds of more than 3 m/s at a height of 50 meters above the ground at Baladeh station could indicate the presence of suitable conditions for power plant installation and power extraction. These results are consistent with previous studies by Janbaz Ghobadi (2017), that Baladeh station has the highest wind power density in Mazandaran Province. After Baladeh, Kojoor, Pol-e Sefid, Amirabad, Siahbisheh, and Firoozkooh stations have better conditions for exploiting wind power potential than other stations with average monthly wind speed of more than 4 m/s. Especially, Kojoor, Pol-e Sefid, and Amirabad have wind speeds of more than 4 m/s in about 9 months of the year (February to October). Siahbisheh and Firoozkooh stations have wind speeds greater than 4 m/s in 6 and 5 months, respectively. The frequency of wind speeds of more than 4 m/s in the cold months of the year is a suitable feature for the construction of wind turbines at the above-mentioned stations. Moreover, the lowest winds with speeds of more than 3 m/s indicate the lack of suitable wind conditions and exploitation of wind power potential at Sari, Alasht, Ramsar, Galoogah, Gharakhil, Babolsar, and Amol stations (Figure 7).

Wind power density

Wind power density (WPD) is the quantitative amount of wind energy available at a given location. In addition to wind speed, WPD also depends on the air density at the desired height relative to sea level, which is a function of atmospheric pressure and temperature. WPD relative to wind is an important feature in the introduction and comparison of power plants because air density decreases with increasing altitude and air molecules collide less. The wind density values of the stations calculated by equation 12 and presented in Table 5 are considered as one of the parameters defining the degree of proportionality in the utilization of wind power potential. According to the data in the table also Figure 8, Baladeh station has the highest wind energy density among the studied stations. This station has a wind energy density of 51 W/m2 at a height of 10 m above the ground, 142 W/m2 at a height of 30 m above the ground and 228 W/m2 at a height of 50 m above the ground during a statistical period. After the Baladeh station, Kojoor station has better conditions in terms of wind power density, with densities of 28, 79 and 103 W/m2 at heights of 10, 30 and 50 m above the ground, respectively. Amirabad, Siahbisheh and Pol-e Sefid stations follow in Mazandaran Province in terms of wind power density. Sari station has the lowest wind power density calculated at 10, 30 and 50 m height with 4, 8 and 12 W/m2 respectively. Moreover, the WPD values at Alasht, Gharakhil, Ramsar and Amol stations are also low (Bairamvand et al, 2022a, b).

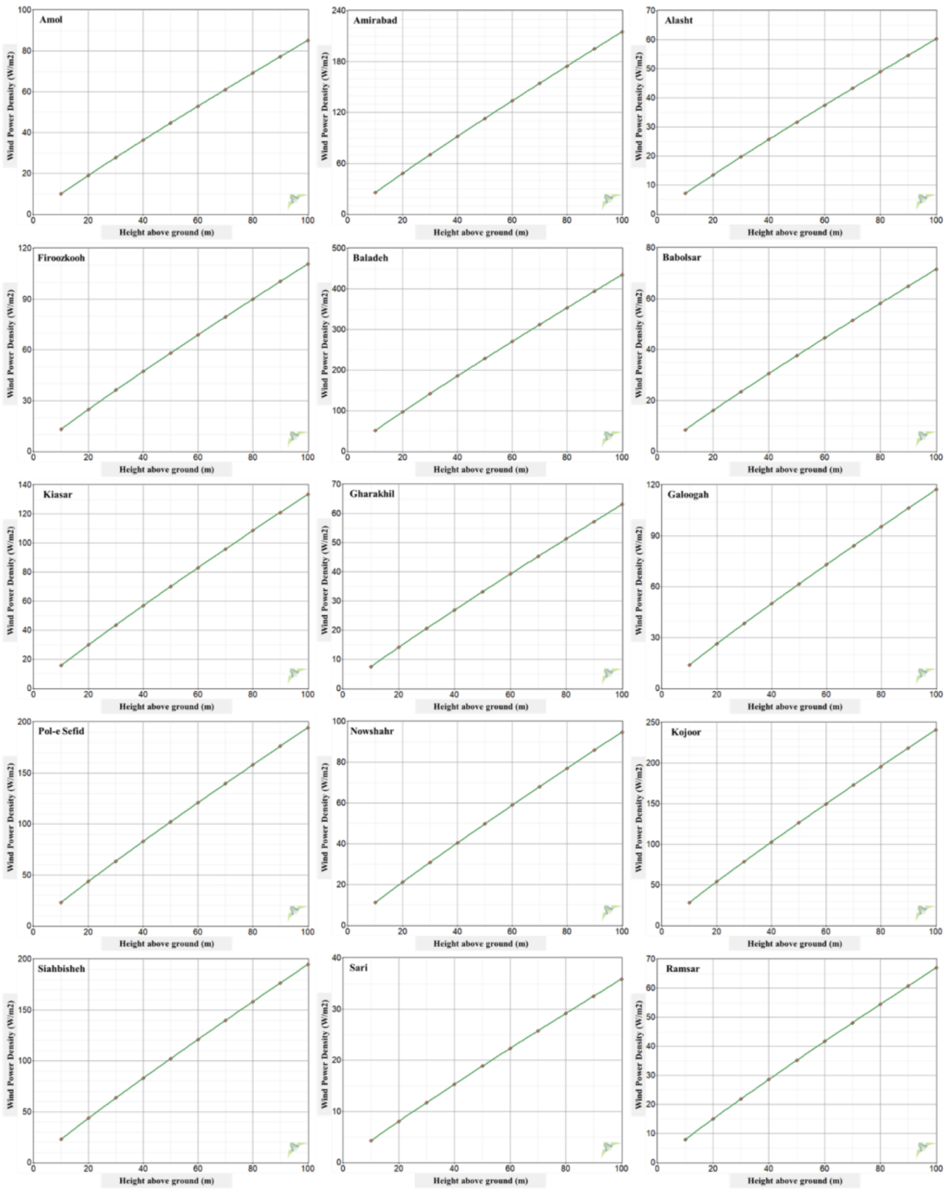

Fig. 8: Plot of wind power density and its obtained energy based on the ground height in Mazandaran Province meteorological synoptic stations

Table 5: The values of wind power density (W/m2) in Mazandaran Province meteorological synoptic stations at a height above the ground up to 100 m

Height/ Station	10	20	30	40	50	60	70	80	90	100
Alasht	7	13	20	26	32	37	43	49	55	60
Amirabad	25	48	70	92	113	134	154	175	195	215
Amol	10	19	28	36	45	53	61	69	77	85
Babolsar	8	16	23	31	38	44	51	58	65	72
Baladeh	51	97	142	185	228	270	312	353	394	435
Firoozkooh	13	25	36	47	58	69	79	90	100	111
Gagloogah	14	26	38	50	62	73	84	95	106	117
Gharaakhil	7	14	21	27	33	39	45	51	57	63
Kiasar	16	30	44	57	70	83	96	108	121	133
Kojoor	28	54	79	103	126	150	173	196	218	241
Nowshahr	11	21	31	40	50	59	68	77	86	95
Pol-e Sefied	23	43	63	83	102	121	139	158	176	194
Ramsar	8	15	22	29	35	42	48	54	61	67
Sari	4	8	12	15	19	22	26	29	33	36
Siahbisheh	23	44	63	83	102	121	140	158	176	195

The study area is located in the lowest category in terms of wind power, namely category 1, according to the wind power classification and 7-category classification of the National Renewable Energy Laboratory of the USA (NREL). In the first category, the average annual wind speed is less than 4.4 m/s2 and the wind power density is less than 100 W/m2 at a height of 10 m. At a height of 50 m, the average annual wind speed is less than 5.6 m/s2 and the wind power density is less than 200 W/m2. Except Baladeh station, all stations in the study area belong to the first category (tables 5 and 6). Regarding Baladeh station, it is worth mentioning that the average wind speed at a height of 50 m above the ground is more than 5.6 m/s2 and the wind power density is more than 200 W/m2, which places it in the second category. However, with a height of 10 m above the ground, Baladeh station, like other stations in Mazandaran Province, belongs to the lowest category in terms of wind power (Table 6).

Table 6: Classification of Mazandaran Province meteorological synoptic stations based on wind power density 7-category classification of the National Renewable Energy Laboratory of the USA (NREL)

	Height 10 m			Height 50 m		
Station	**Average wind speed (m/s)**	**Wind power density (W/m2)**	**Wind power category**	**Average wind speed (m/s)**	**Wind power density (W/m2)**	**Wind power category**
Alasht	1.57	7		2.58	32	
Amirabad	2.81	25		4.64	113	first
Amol	1.87	10		3.08	45	
Babolsar	1.84	8		3.04	38	
Baladeh	3.65	51		6.01	228	second
Firoozkooh	2.47	13		4.07	58	
Galoogah	1.81	14		2.98	62	
Gharakhil	1.82	7	first	3	33	
Kiasar	2.29	16		3.78	70	
Kojoor	2.86	28		4.71	126	
Nowshahr	2.18	11		3.59	50	first
Pol-e Sefid	2.84	23		4.67	102	
Ramsar	1.81	8		2.97	35	
Sari	1.48	4		2.44	19	
Siahbisheh	2.48	23		4.08	102	

Based on the calculations of wind power density and comparison of annual isodensity maps of wind power at 10, 30 and 50 m above ground with the zones of wind speed maps, wind power density is directly dependent on wind speed. Moreover, the highest values of wind density are recorded at Baladeh, Kojoor, Amirabad, Pol-e Sefid, Siahbeisheh and Firoozkooh stations while the lowest values are found at Sari, Alasht, Gharakhil, Ramsar, Babolsar, Amol and Nowshahr stations. Figure 9 shows the zonal map of wind power density of meteorological stations in Mazandaran Province. Baladeh station has a maximum wind power density of about 51 W/m2 and wind speed of more than 4 m/s during 6 months of the year (especially in the warm months of June and July). Kojoor, Amirabad, Siahbisheh and

Pol-e Sefid stations are in the next categories of wind power density in the province with 28, 25, 23 and 23 W/m2 respectively. Sari, Alasht, Gharakhil, Ramsar and Babolsar stations have the lowest wind power density at 10 m height with 4, 7, 7, 8 and 8 W/m2 respectively in the studied statistical period (2006-2017).

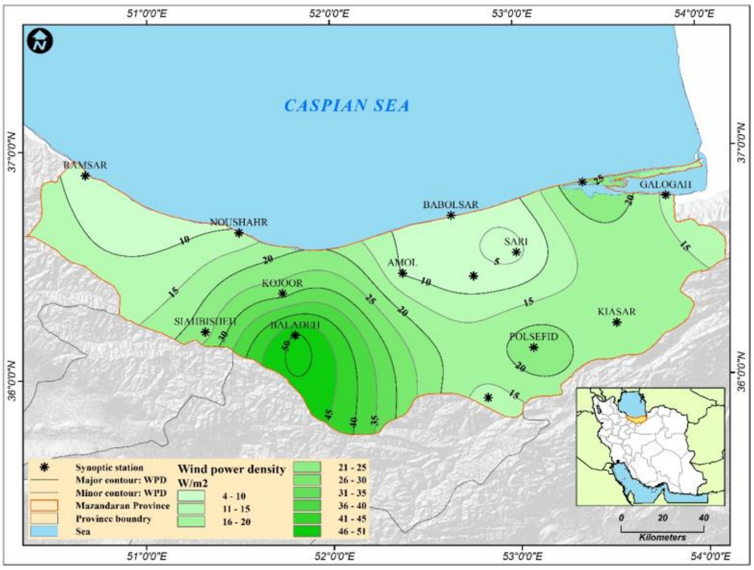

Fig. 9: Annual wind power density (WPD) of Mazandaran Province at a height of 10 meters above the ground (Bairamvand et al, 2022a).

Zonation of wind power density of stations in Mazandaran Province at a height of 30 m above the ground (Figure 10) shows that Baladeh station has the highest value of wind power density (~140 W/m2) compared to the other stations in the province with wind speed more than 6 m/s in 7 months of the year. In addition, Kojoor, Pol-e Sefid, Amirabad and Siahbisheh stations have wind power density of 79, 70, 63 and 63 W/m2 respectively with more than 5 months of wind and speed more than 4 m/s in a year. On the other hand, Sari, Alasht, Gharakhil, Ramsar and Babolsar stations have wind power densities of 12, 20, 21, 22 and 23 W/m2 with wind speeds less than 3 m/s during most months of the year. From this point of view, they account for a relatively modest share of wind power generation from turbines in the province.

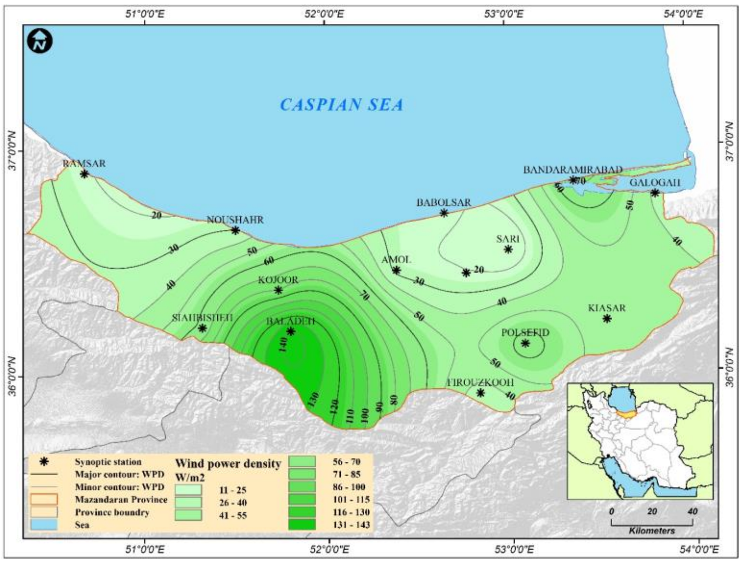

Fig. 10: Annual wind power density (WPD) of Mazandaran Province at a height of 30 meters above the ground

According to the map of wind power density at 50 m above the ground (Figure 11), Baladeh station has a wind power density of about 228 W/m2 with a wind speed of more than 5 m/s and the highest frequency of wind speed values in the range of 3 to 5 m/s. Baladeh station is in the second category (average) in terms of classification by turbine height and using the American Energy Union Wind Atlas. Moreover, the highest wind power density of up to 200 W/m2 is associated with the warm months of the year, which provide favorable conditions for turbine installation and power generation. Kojoor, Amirabad, Siahbisheh and Pol-e Sefid stations have wind power densities of 126, 113, 102 and 102 W/m2, respectively with wind speeds of about 2 to 5 m/s. The lowest wind power densities are assigned to Sari, Alasht, Gharakhil, Ramsar and Babolsar stations with values of 19, 32, 33, 35 and 38 W/m2, respectively.

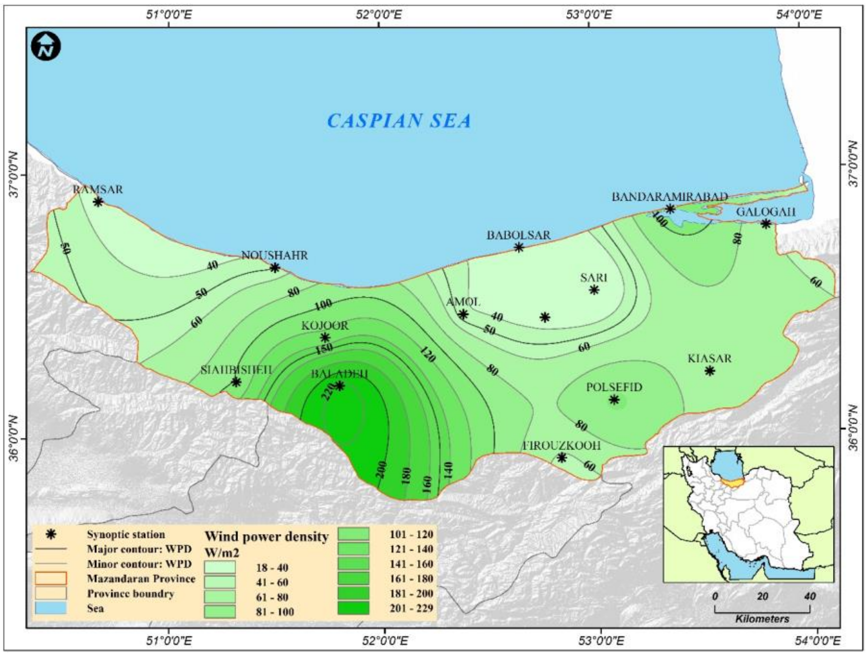

Fig. 11: Annual wind power density (WPD) of Mazandaran Province at a height of 50 meters above the ground

Wind power extraction

The amount of wind power that can be extracted by wind turbines depends not only on the speed and continuity of the wind but also on factors such as the efficiency of the turbine, the hub height, the rotor sweep height and blade radius. Currently, turbines with a capacity of 3 to 5 MW are available in the world market. However, transportation and installation of these turbines require the use of special equipment and infrastructure. The turbines installed in Iran with Vestas technology from Denmark have a height of 40 m and a speed range of 4 to 25 m/s. Table 6 shows the results of the calculations of extractable wind power at a height of 40 m at each of the synoptic meteorological stations in Mazandaran Province. Baladeh station has the highest percentage of electrical energy in the province with an average annual wind power of 58.4 kW, an annual produced electricity of about 511452 kWh/year and a network capacity of 17.7% (Table 7). Therefore, this area is a suitable place for the installation and construction of wind turbines in Mazandaran Province. Kojoor, Amirabad, Pol-e Sefid and Siahbisheh stations belong to the next categories of wind power potential. Due to lower wind speeds, Sari, Alasht, Gharakhil, Ramsar and Babolsar stations are not considered as suitable places for wind power extraction. Figure 12 shows the map of annual produced electrical energy of the stations in Mazandaran Province at a height of 40 m above the ground (Bairamvand et al, 2022a, b).

Table 7: Estimation of wind power and output energy production at a height of 40 meters in synoptic meteorological stations of Mazandaran Province by Enercon E33 / 330kW turbine

Station	Wind speed (m/s)	Wind power (kW)	Average of produced energy (kWh/yr)	Network capacity (%)
Alasht	2.41	7.1	62073	2.15
Amirabad	4.33	30.8	269427	9.32
Amol	2.87	11.1	97658	3.38

Babolsar	2.83	9.4	82236	2.84
Baladeh	5.6	58.4	511452	17.69
Firoozkooh	3.8	15.5	136039	4.71
Galoogah	2.78	14.3	125435	4.34
Gharakhil	2.8	8.4	73549	2.54
Kiasar	3.52	17	149047	5.16
Kojoor	4.39	33.8	295763	10.23
Nowshahr	3.35	12.9	112842	3.9
Pol-e Sefid	4.36	27.3	239183	8.27
Ramsar	2.77	8.8	77235	2.67
Sari	2.28	4.4	38410	1.33
Siahbisheh	3.8	25.2	220690	7.63

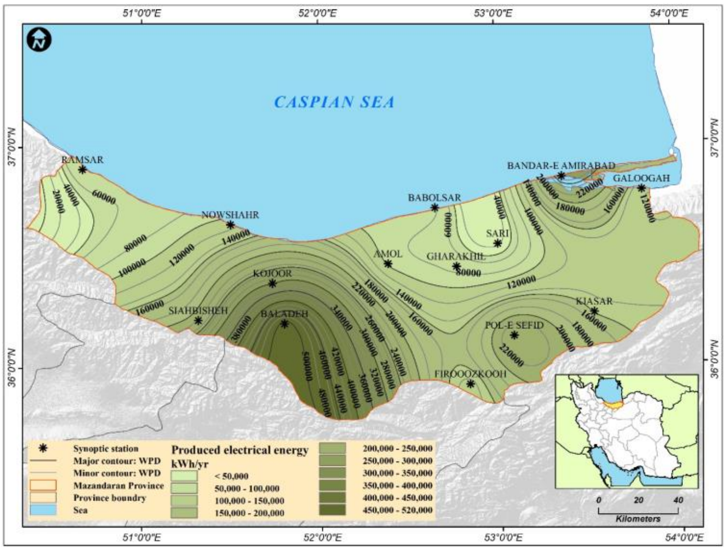

Fig. 12: Zoning map of annual produced electrical energy in Mazandaran Province at a height of 40 meters above the ground (Bairamvand et al, 2022a)

Topography effect on wind variables

To investigate the influence of topography on wind variables such as wind speed, continuity, and wind power density, the relationship between height and slope indicators was evaluated with each of the aforementioned factors. One of the fundamental assumptions for employing Pearson's statistical test is the normal distribution of data. In this study, the Kolmogorov–Smirnov (K–S) statistic was used to assess data normality. The K–S test is a non-parametric method for evaluating the distribution of observations. The approximate significance level (p-value) appears at the end of the K–S output, and by comparing it with the significance threshold α, a decision can be made regarding normality at that significance level. If α is set to 0.05 and the p-value exceeds 0.05, the data may be assumed to follow a normal distribution. According to the results of the K–S test, all datasets used in this study follow a normal distribution at a confidence level exceeding 95% across all ten categories. Table 8 shows the Pearson correlation coefficient between wind variables and topographic indicators. The correlation coefficient between wind speed and altitude above sea level was 0.677, indicating a 95 percent positive correlation (P-value 0.05). Accordingly, as the altitude of the meteorological stations in the province above sea level increases, the wind speed increases at a height of 10 meters above the ground. Considering this correlation coefficient, the effect of altitude on the change of wind speed is shown in equation 17 and Figure 13.

Eq. 17)

$$wind\ speed\ (m/s) = 0.0004 \times altitude\ (m) + 1.9985$$

Table 8: Findings of Pearson correlation test of wind variables in synoptic meteorological stations of Mazandaran Province with altitude index

Variable	**Correlation coefficient**	**P-value**
Wind speed at a height of 10 meters	0.677	0.001
Wind power density at a height of 10 meters	0.647	0.012
Number of wind speed hours equal to or more than 3 m/s	0.392	0.165

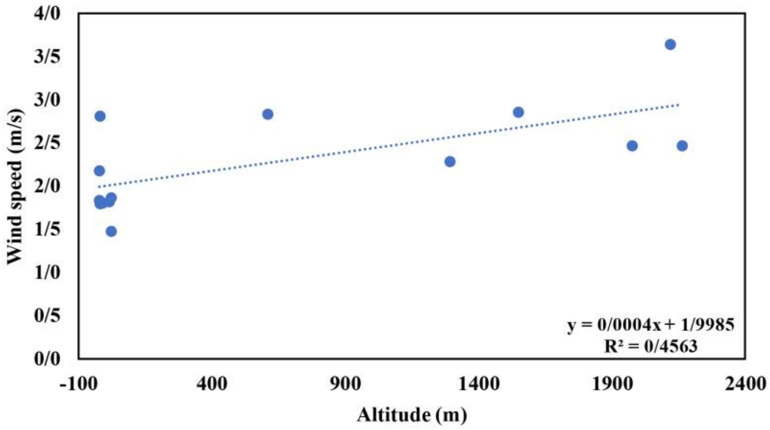

Fig. 13: Regression plot of the wind speed at a height of 10 meters above ground with the synoptic meteorological station's altitude

Examination of the spatial distribution of wind speed at different altitudes shows that as the altitude increases, the average wind speed also increases. This increase results in the average wind speed increasing from 2.05 m/s at altitudes less than 200 m to 2.52 m/s at altitude 2500 m. The general trend of increase in wind speed with increasing altitude in Mazandaran Province is shown in Table 9.

Table 9: Average wind speed at different altitudes of Mazandaran Province

Altitude category (m)	Average wind speed (m/s)
< 200	2.05
200 - 500	2.19
500 - 1000	2.3
1000 - 1500	2.35
1500 - 2000	2.41
2000 - 2500	2.52

The correlation coefficient between wind power density and altitude is 0.647, indicating 95% positive correlation (P-value 0.05). Thus, like wind speed, wind power density also increases with by increasing the altitude. Considering this correlation coefficient, equation 18 and Figure 14 show the influence of altitude variations on wind power density at the stations in Mazandaran Province. However, due to a P-value greater than 0.05, the correlation between wind hour continuity with a speed 3 m/s and more was not significant at 95% level. Therefore, changes in altitude have no significance effect on the continuity of wind hours.

Eq. 18)

$$\textit{wind power density}\ (W/m^2) = 0.0087 \times \textit{altitude}\ (m) + 0.4195$$

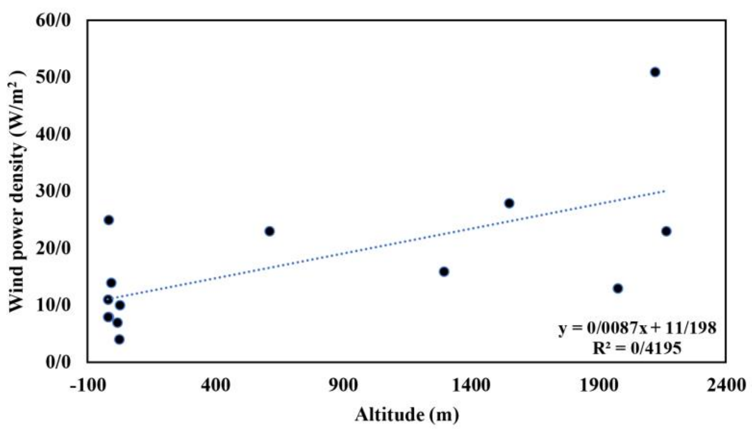

Fig. 14: Regression plot of the wind power density at a height of 10 meters above ground with the synoptic meteorological station's altitude

Table 10 shows the correlation coefficients of the wind speed variable, continuity of wind hours with speeds greater than 3 m/s, and wind power density with the slope index. According to P-values greater than 0.05, none of the wind variables is correlated with the slope index. Therefore, changes in the slope values have no noticeable effect on the wind variables and the correlation between them cannot be investigated.

Table 10: Findings of Pearson correlation test of wind variables in synoptic meteorological stations of Mazandaran Province with slope index

Variable	Correlation coefficient	P-value
Wind speed at a height of 10 meters	0.374	0.188
Wind power density at a height of 10 meters	0.326	0.255
Number of wind speed hours equal to or more than 3 m/s	0.124	0.674

Table 11 shows the correlation coefficients of the wind speed variables, the continuity of wind hours with speeds greater than 3 m/s and the wind power density with the hillslope aspect index. After P-values greater than 0.05, among the wind variables, only the number of hours of wind with speeds greater than 3 m/s shows a strong positive correlation with the hillslope aspect. Thus, changes in the aspect of hillslopes have a discernible effect on the continuity of wind hours with speeds greater than 3 m/s at the 95% confidence level (P-value = 0.039), indicating that the hillslope aspect variable affects the number of wind hours with high-speeds in the region.

Table 11: Findings of Pearson correlation test of wind variables in synoptic meteorological stations of Mazandaran Province with hillslope aspect index

Variable	Correlation coefficient	P-value
Wind speed at a height of 10 meters	0.38	0.18
Wind power density at a height of 10 meters	0.278	0.335
Number of wind speed hours equal to or more than 3 m/s	0.499	0.039

Considering this correlation coefficient, the effect of the hillslope aspect on the continuity variations of the number of wind hours with speeds greater than 3 m/s at the stations of Mazandaran Province is shown in equation 19 and Figure 15. This effect results in the maximum number of wind hours with speeds greater than 3 m/s occurring in the southwestern hillslopes with 2950 hours. The southern and southeastern hillslopes, with 2897 and 2740 hours, respectively, are in the next categories with the highest number of wind hours with the minimum suitable speed threshold for wind turbine operation and installation. Hillslopes with no direction (flat) and those with northwestern direction, with 2336 and 2628 hours, respectively, have the least wind speeds greater than 3 m/s, (Table 12). The correlation between the wind speed and density variables with the hillslope aspect index cannot be investigated because there is no meaningful correlation between them.

Eq. 19)

$$wind\ speed\ hours = 6.7293 \times hillslope\ aspect + 2039.1$$

This study focuses on the spatial distribution of wind energy in Mazandaran Province and, for the first time, presents elevation-based maps at 10, 30, and 50 meters. In contrast, previous research, such as the studies by Bairamvand et al, (2022), only included 10-meter and occasionally 50-meter wind maps. Earlier studies frequently employed multi-criteria decision-making models such as AHP and ANP to identify suitable sites for wind turbine installation, incorporating environmental, topographic, economic, and social variables.

Table 12: The number of wind hours with speeds greater than 3 m/s at the stations of Mazandaran Province at different hillslope aspect

Hillslope aspect	Number of wind speed hours equal to or more than 3 m/s
Flat	2336
North	2690
Northeast	2718
East	2656
Southeast	2740
South	2897
Southwest	2950
West	2732
Northwest	2629

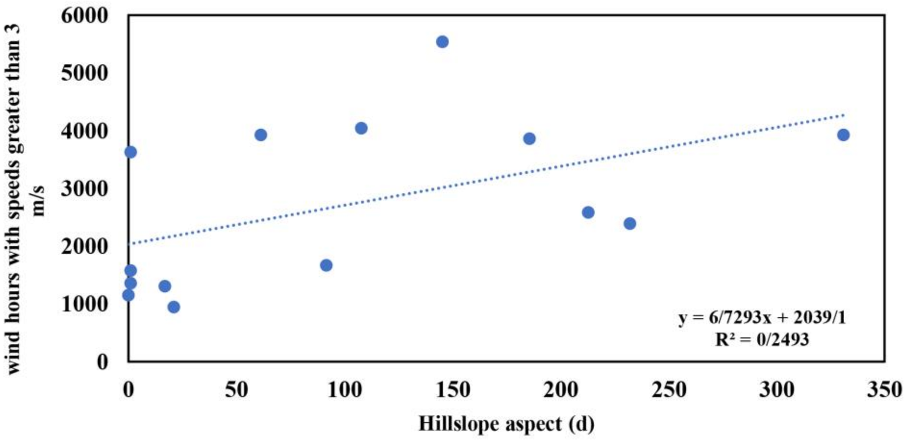

Fig. 15: Regression plot of the number of wind hours with speeds greater than 3 m/s at the stations of Mazandaran Province with hillslope aspect index

These studies ranked climatic factors with the highest relative weight (approximately 0.543) in location prioritization. Likewise, the present research places strong emphasis on topographical influences, such as elevation, slope, and hillslope aspect, which notably affect wind behavior and the duration of wind speeds exceeding 3 m/s. Additionally, this study offers a more nuanced analysis of wind behavior in mountainous regions, highlighting the role of slope orientation. Southwest-facing slopes were observed to have the highest continuity of favorable wind hours, reaching up to 2950 hours. This finding corresponds with the dominant wind regime in the area, characterized by prevailing west and southwest winds throughout most months of the year, a level of atmospheric interpretation that has been less explored in previous research. While studies such as Analysis of Wind Power and Topography Influence have identified stations like Baladeh as having peak wind speeds at 50 meters, the present study advances this knowledge by evaluating multiple stations simultaneously and integrating elevation-based assessment. This approach has enabled a more precise identification of high-potential zones, including Noor, Amol, Nowshahr, Savadkooh, and parts of Chaloos. Allouhi et al, (2017) in Morocco and Ilkilic and Aydin (2015) in Turkey have emphasized the role of climatic and topographic variables in wind site selection, often using AHP and ANP models. The current study aligns with these methodologies but extends them by incorporating detailed slope orientation analysis, revealing that southwest-facing slopes in Mazandaran exhibit the highest continuity of favorable wind hours, up to 2950 hours annually. This finding corresponds with the dominant west-southwest wind regime observed in the region, a level of atmospheric interpretation that remains underexplored in global literature (cf. Yamaguchi et al, 2024; Archer and Jacobson, 2013). Moreover, while previous research identified Baladeh station as a high-potential site (Bairamvand et al, 2022a), this study expands the scope by evaluating multiple stations and identifying additional high-potential zones such as Noor, Amol, Nowshahr, Savadkooh, and Chaloos. This broader spatial assessment contributes to more informed regional planning and supports the development of topography-informed wind energy strategies, in line with global efforts to optimize renewable energy deployment (Marvel et al, 2012; Rehman et al, 2020).

Conclusion

Among renewable energy sources, the use of solar and wind energy seems to be more economical and cost-benefit in Iran. Due to the high cost of converting solar rays into electrical energy, several countries around the world, including Iran, have turned their attention to wind energy. Given the enormous resources needed to generate one kilowatt of electricity, the question is what should be done to reduce consumption and provide cheaper energy. Wind energy is one of the most cost-benefit renewable energy sources for power generation, which is not only polluting the environment and being abundant and permanent, but also has the lowest price fluctuations. The objective of the study was to determine the spatial capability of wind power in Mazandaran Province, with emphasis on topography. With the increase of altitude of meteorological stations of the province, the wind speed and power density of the station increases at a height of 10 meters above the ground. Although there is no significant correlation between the number of wind speed hours equal to or more than 3 m/s and it cannot be assumed that variations in altitude affect wind hour continuity values. Examination of the spatial distribution of wind speed with increasing the altitude showed that the average wind speed increases from 2.05 m/s in the altitude less than 200 m to 2.52 m/s in the altitude 2500 m. The effect of the hillslope aspect on the changes in the number of the continuity wind hours with a speed greater than 3 m/s in Mazandaran Province, is such that its maximum value occurs in southwestern hillslope with 2950 hours. This may be influenced by the general pattern of air current in the region, where west and southwest winds are considered to be the prevailing winds at all seasons of the year and during most months of the year. The western, coastal strip, as well as the plain areas of Mazandaran Province have poor wind continuity conditions, which are a minimum threshold for wind turbine installation. The foothills and highlands, on the other hand, are in a relatively favorable position in terms of the persistence of winds with speeds of 3 m/s or more. The mountainous and highland areas in Noor Township are generally considered the best locations for wind turbine installation. The maximum wind speed occurs at different heights above the ground, in the southern and high parts of Noor, Amol, Nowshahr, Savadkooh and to some extent in Chaloos, with the highest wind speed in the southern parts of Noor. The plains and coastal areas of Mazandaran Province, particularly the townships of Jooybar, Babolsar, Mahmoudabad, Sari, Ghaemshahr, the north of Savadkooh, Babol, Amol and the western parts of Ramsar and Tonekabon, and the eastern parts of Behshahr and Neka, have the lowest average annual wind speed.

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