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ASSESSMENT OF WIND REGIME AND WIND ENERGY POTENTIAL IN THE ABSHERON PENINSULA

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In the article, in order to assess the wind regime and the natural potential of wind energy in the coastal zone of the Absheron Peninsula, which is quite promising in terms of wind energy production, the wind speed-direction and wind power data were analyzed at 4 selected points in the study area. During the observation period covering 2001-2024, the average multi-year wind speed values and standard deviations were calculated for each point. The average annual and monthly indicators of wind speed and power, and the dynamics of their change over time were determined. At the same time, a map of the distribution of wind speed over the area and wind rose graphs for the selected points were compiled. The study showed that the wind regime is fairly well approximated by the Weibull distribution. Based on the parameters of this distribution, the capacity factor for two types of wind turbines was calculated and the achievable energy production was estimated.

Keywords: *Caspian Sea, wind speed, wind direction, wind energy, wind rose*

INTRODUCTION

The movement of air masses from an area of high pressure to an area of low pressure is called wind. In other words, wind is the horizontal movement of air depending on the distribution of atmospheric pressure [9]. At the same time, wind is a sustainable source of energy because it is renewable, widespread, and abundant. In addition, it contributes to the reduction of greenhouse gas emissions because it can be used as an alternative to fossil fuel-based electricity generation. Renewable sources such as wind energy play an important role in meeting the world's growing demand for electricity [7]. Human activities such as the burning of fossil fuels, are the most important factors causing climate change in the world which involve deforestation, agricultural other threats. These activities increase the amount of greenhouse gases such as carbon dioxide in the atmosphere. The increased greenhouse effect leads to global warming and an increase in average surface temperatures [8]. The goal of the 2015 Paris Agreement is to limit global warming to 1.5 degrees Celsius above pre-industrial levels and to prevent it from exceeding 2 degrees Celsius [2].

Renewable energy sources currently meet approximately 14% of global energy demand and will play an even greater role in future energy supply. In Germany, in 2024, the share of wind and solar energy was 58% in the production of electricity. Transition to renewable energy technologies provide a key component of efforts to mitigate climate change and can contribute to security of energy supply and environmental protection measures. Among these technologies used for electricity generation, wind power ranks second after hydroelectricity in terms of installed capacity and is developing rapidly [12]. In Azerbaijan, wind power has also seen a significant increase in recent years. The areas of Azerbaijan that are richest in wind energy are the Absheron Peninsula, the Absheron Sea and the Caspian Sea coast [7].

MATERIAL AND METHODS

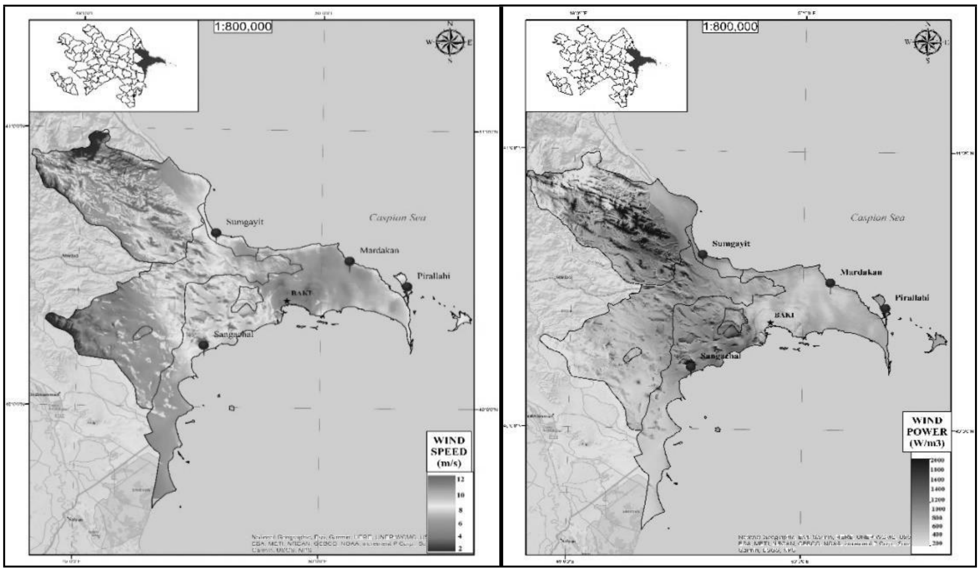
Satellite data were used to determine the wind regime and existing wind energy potential in the coastal zone of the Azerbaijani sector of the Caspian Sea. Thus, hourly data with a resolution of 0.5^{o} x 0.625^{o} at a height of 50 m were obtained from the NASA [11] space database. These data, collected and archived for 4 points included in the territory of the Absheron Peninsula located on the coast of the Caspian Sea, cover the years 2001-2024. Based on these data, average, maximum, minimum wind speed and power indicators were determined for different time periods in the area and appropriate graphs were drawn up. Also, using satellite data obtained from the Global Wind Atlas, a wind speed and power map was prepared in the area using ArcGIS software, and wind rose graphs were prepared for the observed points using Grapher software. The annual and intra-annual variability of the wind regime in the studied area was analyzed and the possible potential for electricity generation was assessed.

RESULTS AND DISCUSSION

Brief information about the climate and wind regime of the area. The Absheron Peninsula is the largest peninsula located on the western coast of the Caspian Sea. The peninsula is characterized by a semi-desert dry-steppe climate. The average wind speed on the Absheron Peninsula is 5.8-7 m/s. The number of days with strong winds (over 15 m/s) in different parts of the peninsula ranges from 64 to 145 days. Winds exceeding 30 m/s are often observed. North winds (strong winds), winds blowing from the northeast and south directions prevail.

In general, the influence of meridional atmospheric processes is characteristic of the Absheron-Gobustan region. This is explained by the influence of the Kara, Scandinavian, Azores maxima and high pressure areas formed in the south of the European part of Russia. As a result of the influence of these processes, the weather changes sharply, strong northerly winds blow, the air temperature drops, and precipitation is often observed. In the cold season of the year, the probability of the influence of Central Asian and subtropical anticyclones increases [1].

Figure 1 depicts the distribution of wind speed (a) and power (b) at a height of 50 meters in the coastal zone of the Absheron Peninsula. As can be seen, the highest speeds are observed in the coastal and northeastern areas, and in these areas the wind speed increases to 10–12 m/s. This distribution is similar to the wind power map.These data play an important role in selecting optimal sites for the placement of wind turbines in the region.



a) b)

Fig. 1. Distribution map of wind speed and force at a height of 50 m in the study area.

The map was prepared by the author using ArcGis software based on data obtained from the Global Wind Atlas [4].

Annual trend of wind speed and direction. The selected study points are located on the Absheron Peninsula, which is the richest zone in wind resources in Azerbaijan, especially close to the coast. Table 3 shows the exact coordinates of these points and the average multi-year statistical characteristics of the wind calculated for the years 2001-2024.

As can be seen from Figure 2, the average annual wind speed values in Pirallahi and Mardakan were higher than in other observation points. During the observation period, the average annual wind speed in Pirallahi was a maximum of 7.06 m/sec (2001) and a minimum of 6.18 m/sec (2012). In Mardakan, these indicators were 7.12 m/sec (2001) and 6.24 m/sec (2012), respectively. The negative direction of the trend line for Mardakan (-0.0064) indicates that the wind speed is in a decreasing trend over time. Although $R^2 = 0.0623$ is relatively weak, it gives reason to say that the decreasing trend is more pronounced than in other points. A weak decreasing trend (-0.0019) is observed in the average annual wind speed in Pirallahi. However, this change is characterized by a very weak statistical correlation ($R^2 = 0.0041$), and the overall trend is closer to stability.

In Sumgayit, located in the north of the peninsula, the maximum average annual speed was recorded as 6.34 m/sec (2001), and the minimum was 5.54 m/sec (2012). The presence of a negative coefficient (-0.0034) on the trend line indicates a very weak decreasing trend in wind speed. However, the statistical significance of this change is very weak ($R^2 = 0.0138$), that is, the change may be random.

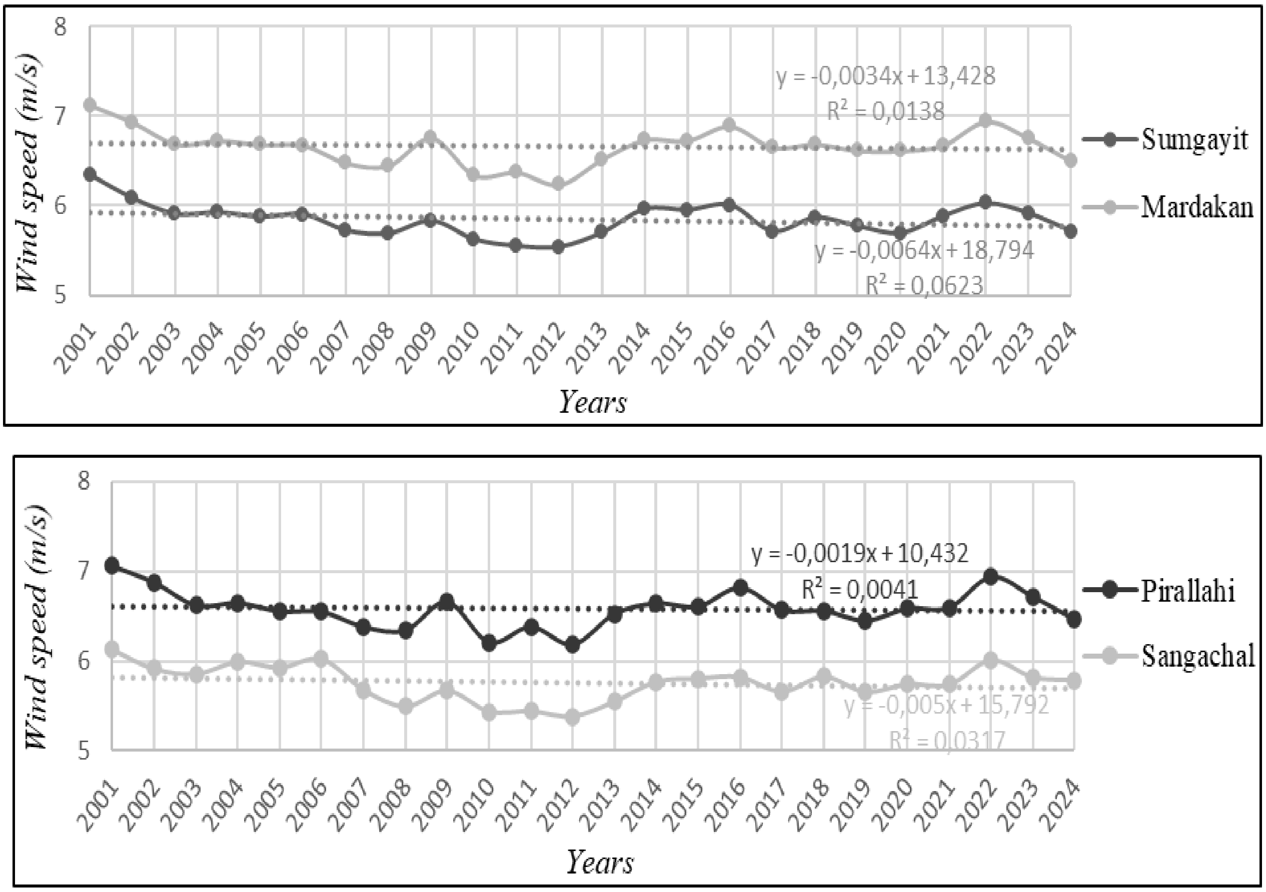


Fig. 2. Time-varying average annual wind speed at the study points during 2001-2024

In Sangachal, the average annual wind speed mainly varied in the range of 5-6 m/sec. Here, the minimum wind speed during the observation was recorded as 5.38 m/sec (2012), and the maximum was 6.13 m/sec (2001). In Sangachal, a weak decreasing trend is also observed over time (-0.0056). Since $R^2 = 0.0317$, this decrease is somewhat noticeable, but is still accompanied by a weak statistical explanation.

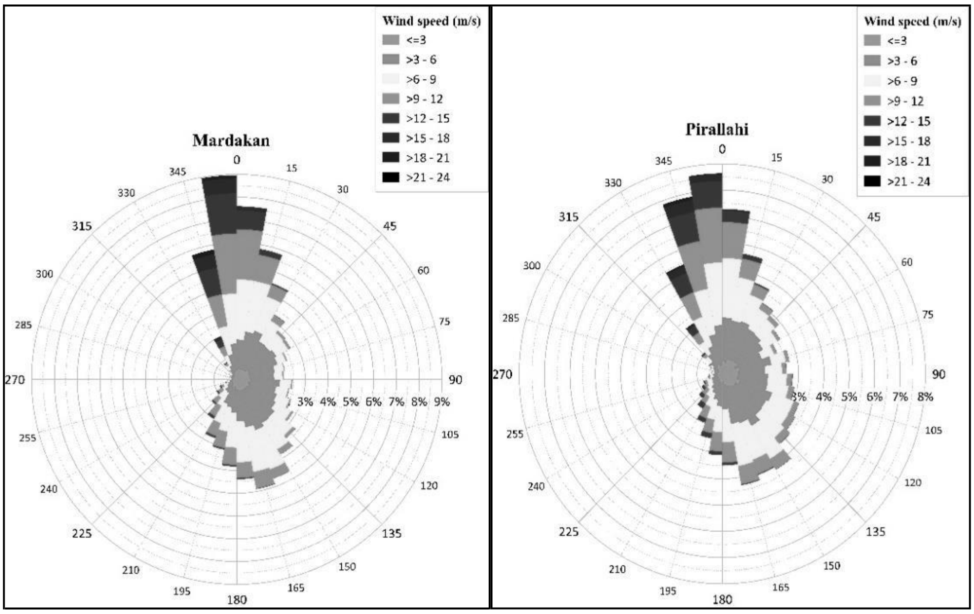


Fig. 3. Wind rose graphs at 50m altitude in Mardakan and Pirallahi (2001-2024)

Wind rose diagrams constructed at 50 m altitudes in the Mardakan and Pirallahi areas show that the main wind direction is predominantly from the north and north-west sectors. The most widely distributed speed intervals at both points are 3–6 m/s, 6–9 m/s and 9–12 m/s. The fact that speeds between 12–15 m/s are found in a wider area confirms the potential of this area in terms of energy production (Figure 3).

The prevailing wind direction in Sangachal is mainly north (0°) and northeast (45°–60°). The wind is mainly concentrated in the range of 3–9 m/s, which is considered an energy-efficient range. The graph also shows winds at speeds of 9–12 m/s and even above 12 m/s, which indicates the high wind energy potential of the area. The stability of wind directions and the concentrated distribution are positive indicators in terms of energy production (Figure 4). As can be seen from Figure 4, the main wind direction in Sumgayit is also north (0°) and northeast (30°–60°). Although the wind distribution is spread over a wider angular area than in Sangachal, the main concentration is still observed in the range of 3–9 m/s. In addition, the percentage of winds with a speed of 12 m/s and higher is relatively high, which creates more favorable conditions for wind energy production.

In general, the coastal region changes wind direction every day. This is because the sun heats the land faster than the water. Warm air over land rises, and cool air over water moves towards the land, creating a breeze. Therefore, the coastal zone is usually cooler than inland areas [6].

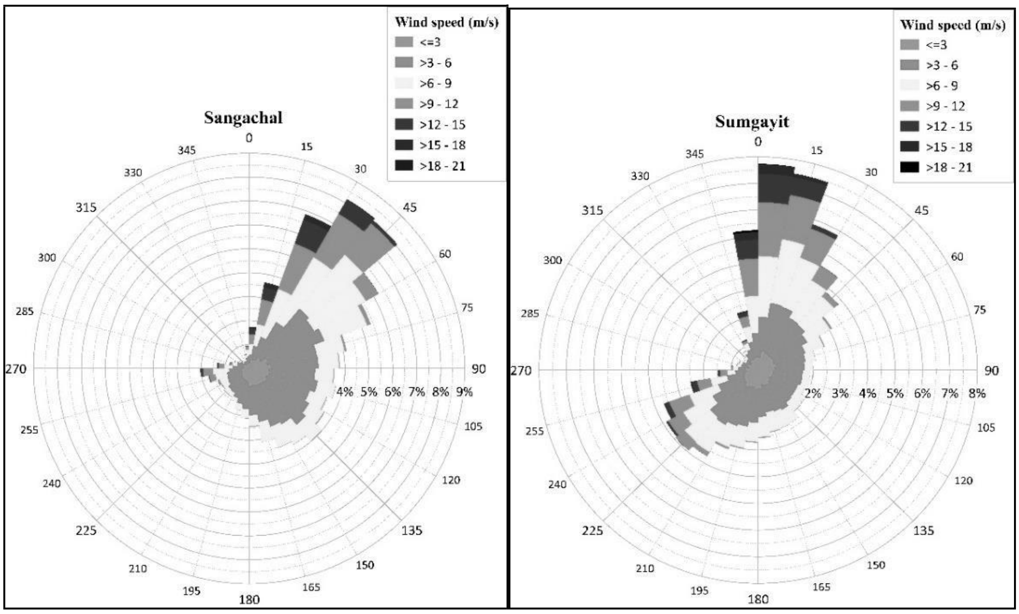


Fig. 4. Wind rose graphs at 50m height in Sangachal and Sumgayit (2001-2024)

Monthly wind speed trend. In order to better assess the existing wind potential in the study area, wind speed data were also analyzed by months for the period 2001-2024. As can be seen from Figure 5, the average wind speed by months at the 4 points considered varies in the range of 5-8.6 m/sec. In Mardakan, Pirallahi and Sumgayit, the wind speed is observed most often in the autumn and winter months. This advantage is also evident in March. Although the wind speed in Sangachal has similar values by month, higher wind speeds are observed in the warm period of the year.

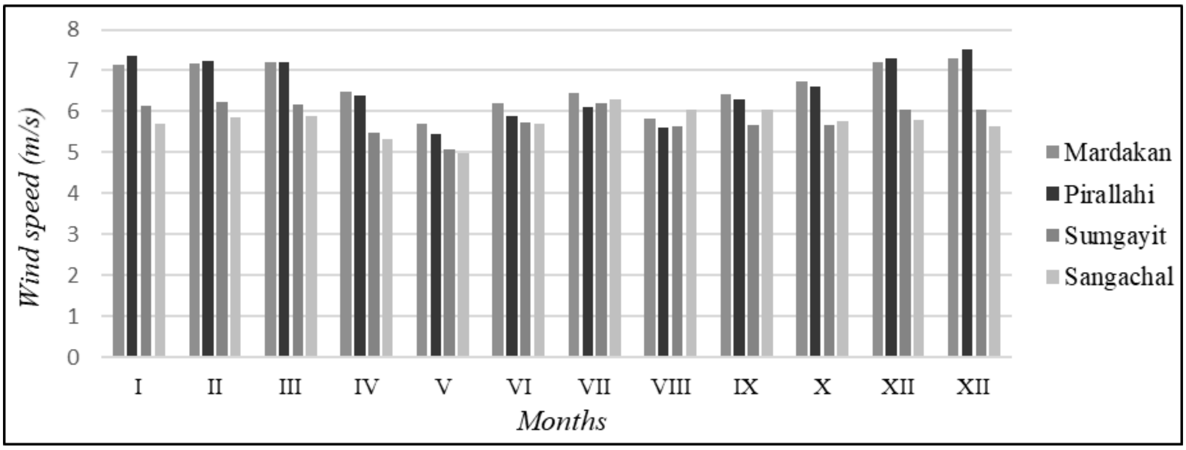


Fig. 5. Monthly trend of wind speed at the survey points

According to Figure 6, if we look at the seasonal changes in wind speed in the study areas, we can see that in general, wind speed is higher in all stations in the winter season, especially in Pirallahi, this indicator reaches the highest level (7.4 m/s). The lowest wind speeds are recorded in the spring and summer seasons. Mardakan and Pirallahi stations have more stable and higher wind speeds compared to other places, which makes the use of wind energy more favorable in these stations.

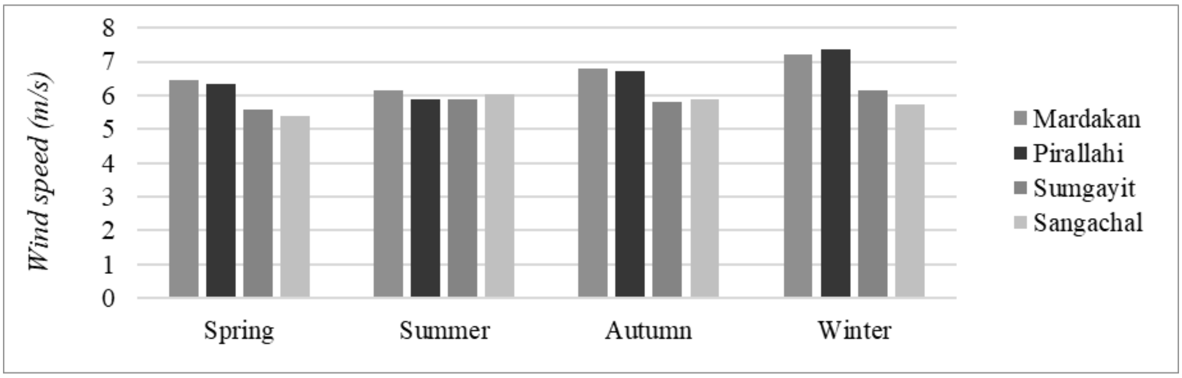


Fig. 6. Seasonal trend of wind speed at the study points

Table 1.

Distribution of windy days by speed intervals (%)

Wind speed gradations (m/s)	Percentage of windy days (%)			
	Mardakan	Pirallahi	Sumgayit	Sangachal
0-3	5	8	6	5
3-6	41	38	54	57
6-9	35	34	28	29
9-12	15	16	10	8
12-15	3	3	2	1
>15	0.7	0.38	0	0.1

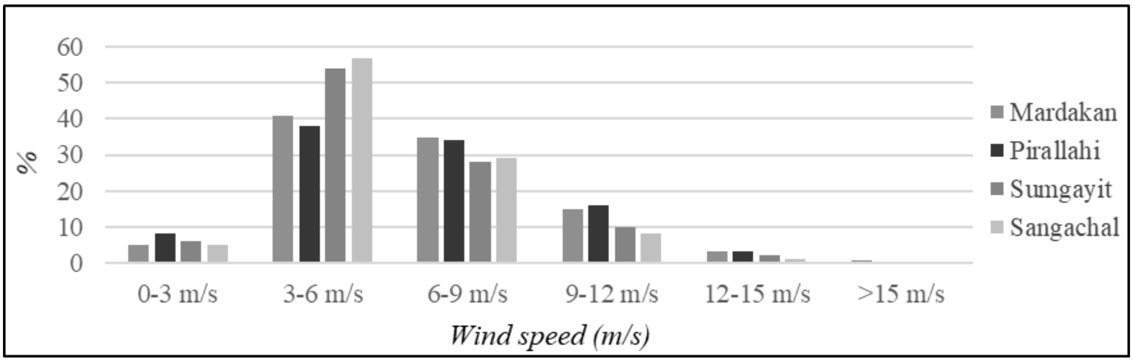


Fig. 7. Distribution of wind speed recurrence frequency at the survey points

Figure 7 shows the distribution of wind speed in different intervals at 4 stations, based on Table 1 and the table above.

- In Sangachal and Sumgayit stations, winds in the range of 3–6 m/s predominate (57% and 54%, respectively), which indicates that the main wind energy potential in these areas is based on medium-speed winds.
- In Mardakan and Pirallahi, winds in the range of 3–6 m/s as well as 6–9 m/s also have a significant share (35% and 34%), which indicates that the potential in these areas is relatively higher.
- High-speed winds (above 12 m/s) constitute a very small percentage in all stations (Mardakan: 3.7%, Pirallahi: 3.38%, and in others it is either absent or up to 0.1%), which indicates that extreme winds occur relatively rarely.

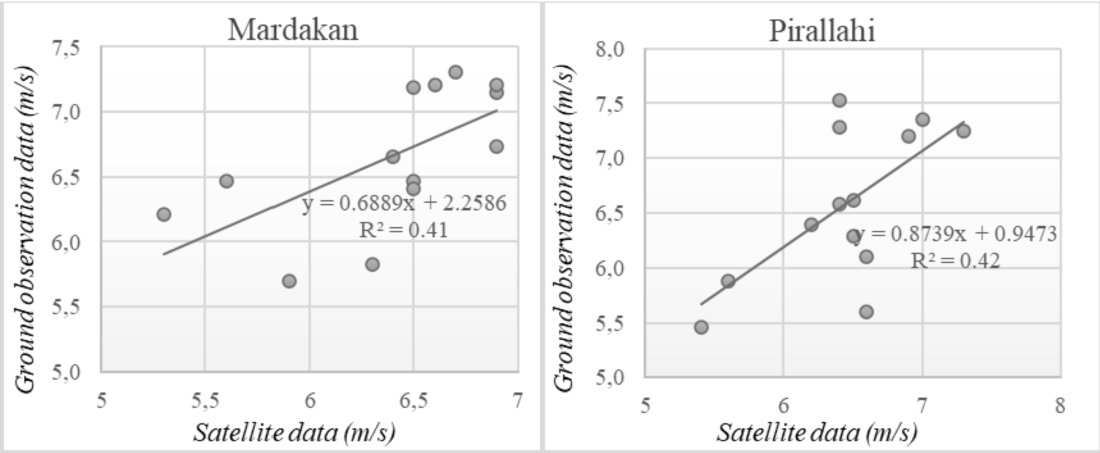


Fig. 8. Correlation between satellite and surface wind speed data

Figure 8 shows the correlation between satellite and ground data at Pirallahi and Mardakan. The ground data from the observation stations located in the coastal zone, presented in the "Hydrometeorological Atlas of the Caspian Sea" prepared by R.M. Mammadov [10], were compared with the satellite data obtained from [11]. According to the results, a moderate positive correlation is observed between the satellite and ground observation data at the Mardakan station. The R^2 indicator being slightly higher than 0.4 indicates that the satellite data are in some agreement with the ground data. Similarly, a positive and moderate correlation exists for Pirallahi. The higher coefficient in the equation (0.87) indicates that the satellite data are in closer agreement with the ground data. However, R^2 is still below 0.5, which indicates that there are some differences. The reason for this is that the satellite data covers 50m, while the ground-based data covers a lower height (mainly 10m), and the observation years do not overlap.

Wind power. Wind power P is proportional to the cube of the wind speed v and is calculated by the formula:

$$P = \frac{\rho}{2}\,\bar{v}^3 \qquad (1)$$

Here, $\rho = 1.225$ kg/m^3 is the air density [3].

As can be seen from Figure 9, Mardakan and Pirallahi stations have higher wind power than others. Mardakan in particular demonstrates more stable and higher energy potential year after year. Sumgayit and Sangachal are distinguished by lower and more stable wind power. In general, after 2017, an increasing trend is observed in Mardakan and Pirallahi (except for 2024), while stability is observed in the others.

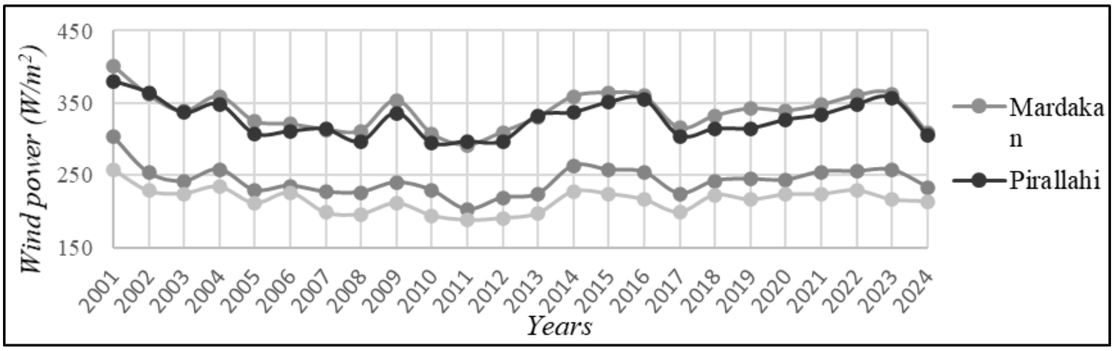


Fig. 9. Time-varying average annual wind speed at the study points during 2001-2024

If we look at the monthly changes in wind strength, we can see that Mardakan and Pirallahi are superior to the others in almost all months. Peak values are observed especially in the winter months. In the summer months (June-August), there is a relative decrease in wind strength at all stations. This can be explained by the weakening of the wind in the region in the summer. In the fall, the wind strength increases again (Figure 10).

If we look at the seasonal changes in wind power, we can see that its highest indicators are observed in the winter season (Figure 11). Especially in Mardakan and Pirallahi. The lowest values were recorded in the summer season. This may affect the year-round productivity of wind farms. Mardakan stands out as the most stable and high-potential region throughout the year. Sangachal has the lowest indicators.

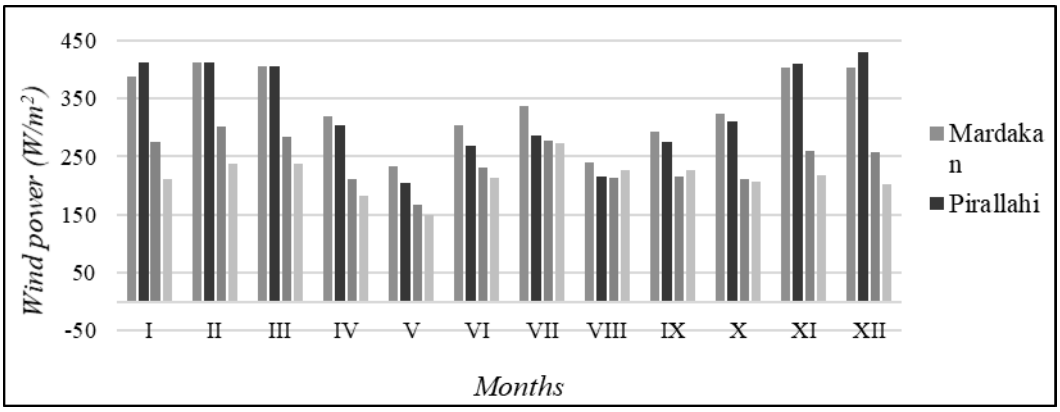


Fig. 10. Monthly trend of wind power at the research points

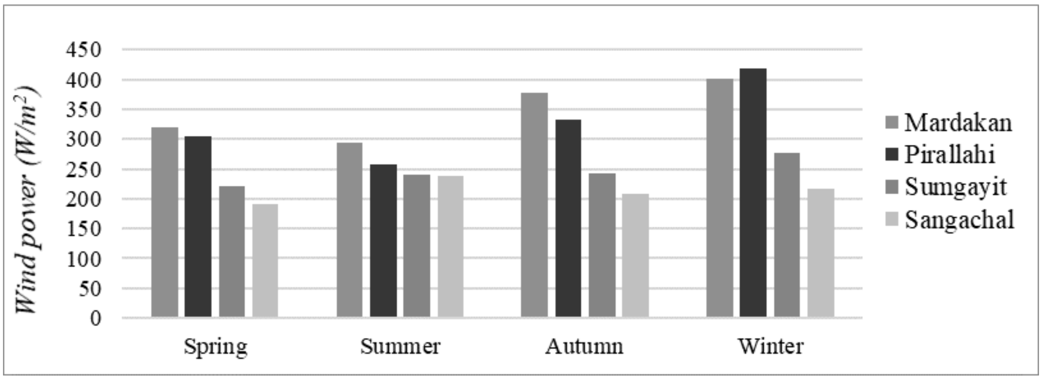


Fig. 11. Seasonal variation of wind speed at the study points

Table 2 shows the distribution of wind power density (W/m²) in four coastal locations (Mardakan, Pirallahi, Sangachal, Sumgayit) for the period 2001–2024. As can be seen from the table, the most frequent power range in all locations was 0–300 W/m², which was especially prevalent in Sangachal (79.2%) and Sumgayit (75.6%). The share of wind power above 600 W/m² was significant only in high-potential locations such as Mardakan and Pirallahi. These results indicate that the region's wind energy potential is mainly concentrated within medium and low power densities, and emphasize that Mardakan and Pirallahi are more favorable in terms of energy production.

Wind energy. The energy that a wind turbine can produce in a certain time interval [0,T] at selected locations, $E_{[0,T]}^{Tur}$ (kWh), is determined by the turbine's technical characteristic, "nominal power" $\mathbb{P}_r$ (kW), and its operational characteristic, capacity factor (CF) [3]:

$$E_{[0,T]}^{Tur} = CF \cdot \mathbb{P}_r \cdot T \qquad (2)$$

Table 2.

Distribution of wind power gradations in selected locations during 2001-2024

Wind power gradations (W/m^2)	**Mardakan**		**Pirallahi**		**Sangachal**		**Sumgayit**	
	Number of days	**%**	**Number of days**	**%**	**Number of days**	**%**	**Number of days**	**%**
0-300	5631	64.24	5590	63.77	6943	79.2	6628	75.6
300-600	1708	19.48	1747	19.93	1117	12.7	1268	14.5
600-900	720	8.21	739	8.43	420	4.8	494	5.6
900-1200	312	3.56	342	3.90	160	1.8	197	2.2
1200-1500	184	2.10	173	1.97	78	0.9	89	1.0
1500-1800	82	0.94	74	0.84	23	0.3	38	0.4
1800-2100	48	0.55	47	0.54	12	0.1	25	0.3
2100-2400	34	0.39	21	0.24	7	0.1	10	0.1
2400-2700	16	0.18	14	0.16	3	0	7	0.1
2700-3000	11	0.13	10	0.11	1	0	6	0.1
>3000	20	0.23	9	0.10	2	0	4	0

Note that the "capacity factor" CF of any turbine is an indicator of its performance at a selected location and is determined by both the wind power $\bar{P}$, which is an indicator of the wind energy potential of the location, and the "power curve", which is a technical indicator of the turbine.

Typical *CF* values for turbines operated in world practice are in the range of 20% – 40%. Using diagramms presented in [3] for two types of turbines (small and medium power) we estimate CF = 20 – 40 % at the studed locations. Thus, the energy that turbines with small ($\mathbb{P}_r$=100 kW) and medium ($\mathbb{P}_r$=1200 kW) power will produce in 1 year (T=365·24=8760 hours) is estimated as $E_{[1\ il]}^{Tur,small}$ 0.2·100·8760=175200 kW·h, $E_{[1\ il]}^{Tur,medium}$= 0.2·1200·8760=2102400 kW·h, respectively.

Four points with high wind speeds were selected in the Absheron coastal zone of the Caspian Sea (Table 3), and the statistical characteristics of the wind speed, Weibull distribution parameters and the energy that two types of turbines (small “Northwind 100C,95kW” and “FL 2500_90” could produce in an average year) were calculated (could be calculated in an average year). It should be noted that these types of turbines are designed for marine conditions and have been used previously.

The wind speed distribution at the locations we considered is fairly well approximated by the Rayleigh law and very well approximated by the Weibull law (Figure 12). In this case, the average wind power

$$\bar{P} = \frac{3\sqrt{2\pi}}{4}\rho s^3 = \frac{3}{\pi}\rho\bar{v}^3 \approx 1.18\ \bar{v}^3 \qquad (3)$$

is calculated by the formula (3) [13]. Here, $s = \sqrt{\frac{2}{\pi}}\,\bar{v}$ – Rayleigh parameter and $\rho = 1.225\ kg/m^3$ – is the density of air.

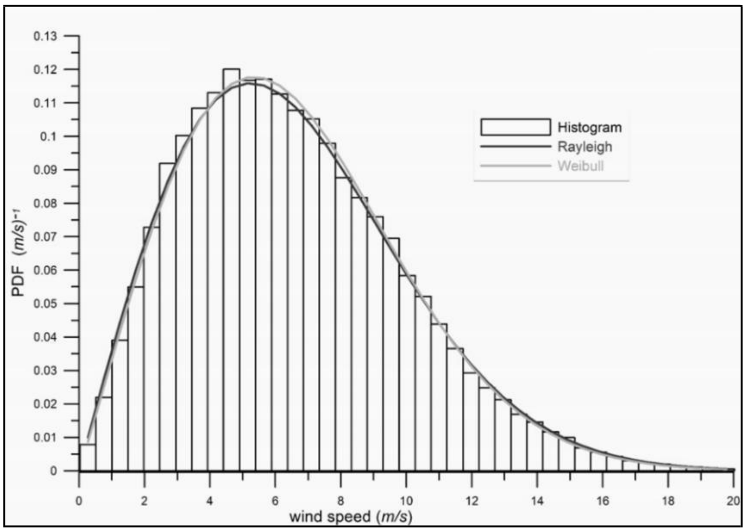


Fig. 12. Histogram of wind speed distribution in the Pirallahi (40.33°N/50.6°S) during 2001-2024; approximation with Rayleigh and Weibull distributions [3].

The data shown in Table 3 are derived from long-term satellite observations and the wind speed is extrapolated to the hub height of the selected turbine models. At the same time, the Wind Power Classification shown in Table 3 is based on accepted International Standards [5].

Table 3.

Statistical and energy potential indicators of wind at research stations

№	Points	Pirallahi	Mardakan	Sumgayit	Sangachal
1	Coordinate (°N/°E)	40.33/50.6	40.51/50.16	40.64/49.54	40.24/49.51
2	Average wind speed, $\bar{v}$ (m/s)	6.58	6.66	5.84	5.76
3	Standard devitation, σ_v (m/s)	3.36	3.38	3.13	2.88
4	Weibull parameter, a	7.44	7.50	6.69	6.66
5	Weibull parameter, b	2.05	2.03	1.31	2.23
6	Average wind power, $\bar{P}$ (W/m^2)	336	348	235	225
7	Wind Power Classifications	Moderate	Moderate	Marginal	Marginal
8	CF, % *“FL 2500_90”* Wind turbine	28.1	28.7	25.2	25.1
9	Energy, $E_{[0,1\ year]}$,(GW·hour) *“FL 2500_90”*	6.12	6.31	5.49	5.36
10	CF,%*“Northwind 100C,95kW”* Wind turbine	39.4	39.9	36.3	36.1
11	Energy, $E_{[0,1\ year]}$,(GW·hour) *“Northwind 100C,95kW”*	0.328	0.332	0.298	0.287

CONCLUSION

The analyses conducted for the years 2001–2024 showed that the wind regime in the Absheron coastal zone of the Caspian Sea is stable throughout the year and the energy potential is higher in some areas. In the Mardakan and Pirallahi areas, wind speed, power and frequency create more favorable conditions for wind energy production compared to other areas. A moderate positive correlation was observed between satellite and ground observation data, which confirmed the reliability of the data. In general, there are promising areas for wind energy use in the area and it is possible to effectively use this potential in the future.

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ABŞERON YARIMADASINDA ÇOXİLLİK KÜLƏK REJİMİ VƏ KÜLƏK ENERJİ POTENSİALININ QİYMƏTLƏNDİRİLMƏSİ

V.M. Rəsulzadə

Məqalədə külək enerjisi istehsalı baxımından kifayət qədər perspektivli olan Abşeron yarımadasının sahil zonasında külək rejimini və külək enerjisinin təbii potensialını qiymətləndirmək məqsədi ilə tədqiqat sahəsində seçilmiş 4 nöqtədə küləyin sürət-istiqamət və güc məlumatları təhlil edilmişdir. 2001-2024-cü illəri əhatə edən müşahidə dövründə hər bir nöqtə üçün orta çoxillik küləyin sürəti dəyərləri və standart kənarlaşmalar hesablanmışdır. Küləyin sürətinin və gücünün orta illik və aylıq göstəriciləri, onların zamanla dəyişmə dinamikası müəyyən edilmişdir. Eyni zamanda küləyin sürətinin ərazi üzrə paylanması xəritəsi və seçilmiş nöqtələr üçün külək gülünün qrafikləri tərtib edilmişdir. Tədqiqatda külək rejiminin Veybul paylanması ilə kifayət qədər yaxşı aproksimasiya olunduğu göstərilmiş, bu paylanmanın parametrlərinə əsaslanaraq iki tip külək turbinləri üçün tutum amili (capacity factor) hesablanmış və əldə edilə biləcək enerji istehsalı qiymətləndirilmişdir.

Açar sözlər: *Xəzər dənizi, küləyin sürəti, küləyin istiqaməti, külək enerjisi, külək gülü*

ОЦЕНКА МНОГОПЕРИОДИЧЕСКОГО ВЕТРОВОГО РЕЖИМА И ПОТЕНЦИАЛА ВЕТРОЭНЕРГЕТИКИ НА АБШЕРОНСКОМ ПОЛУОСТРОВЕ

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В статье для оценки ветрового режима и природного потенциала ветроэнергетики в прибрежной зоне Апшеронского полуострова, которая является весьма перспективной с точки зрения производства ветроэнергии, были проанализированы данные о скорости-направлении ветра и мощности ветра в 4 выбранных точках исследуемой территории. За период наблюдений, охватывающий 2001-2024 гг., для каждой точки были рассчитаны средние многолетние значения скорости ветра и среднеквадратические отклонения. Определены среднегодовые и месячные показатели скорости и мощности ветра, а также динамика их изменения во времени. Одновременно были составлены карта распределения скорости ветра по площади и графики розы ветров для выбранных точек. Исследование показало, что ветровой режим достаточно хорошо аппроксимируется распределением Вейбулла. На основе параметров этого распределения был рассчитан коэффициент использования установленной мощности для двух типов ветроэнергетических установок и оценена достижимая выработка электроэнергии.

Ключевые слова: *Каспийское море, скорость ветра, направление ветра, энергия ветра, роза ветров*