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Assessment of the wind and wave energy potential in the water area of the Caspian Sea

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ABSTRACT

Problem statement. In modern times, the rapid increase in energy demand in the world and the environmental consequences of traditional energy sources make it necessary to switch to alternative energy. The use of alternative energy is not only important for environmental protection, but also reduces the dependence of countries and economic systems on oil, gas and their prices. At the same time, global problems such as climate change and air pollution increase the importance of renewable energy sources.

Purpose. The main goal of the research is to scientifically assess the wind and wave energy potential in the Caspian Sea and to justify this energy production with calculations.

Research methods. In the article, the wind and wave field of the Caspian Sea was studied in order to exploit the potential of wind and wave energy, and the energy of the obtained energy was calculated. To develop the wind parameters, data from three databases were used, two of which were space data and one was long-term operations. To increase the power of the waves and the energy obtained from them with both northern and southern winds, terrestrial data were used. Based on the obtained data, plans for the payment of wind and wave energy in the Caspian Sea were drawn up.

Conclusion. Using the natural potential of the Caspian Sea, the involvement of alternative energy sources in the production of electricity and heat will allow for progressive changes in the future development directions of electricity. The affordable geographical location and climatic conditions of the Caspian Sea region allow for the widespread use of environmentally friendly alternative energy sources such as wind and wave energy. This will not only save a lot of fuel burned in thermal power plants, but will also significantly reduce the amount of hazardous waste discharged into the environment. As a result of the conducted research and calculations, it was determined that the amount of wind energy that can be obtained using the FL 2500_90 type wind turbine at selected points on the Absheron Peninsula and the coastal zone adjacent to it is approximately 5–7 GW/h, and from the Northwind 100C (95 kW) type wind turbine – 0.33 GW/h. At the same time, the capacity factor (CF) of wind turbines at these points varies in the range of 25–33% and 35–40% respectively. It was determined that in the region there is some difference in terms of wave annual average energy potential. Thus, for northern and northwestern winds, the wave energy density varies in the range of approximately 15,000–35,000 kW/m, and for southern and southeastern winds, it varies in the range of 20,000–35,000 kW/m.

Keywords*: Caspian Sea, wind speed, wind direction, wind energy, wave energy, wind rose, Rayleigh distribution, Weibull distribution.*

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Introduction. In recent years, the rising trend of electricity generation by renewable energy is taking a positive way all over the world. Owing to growth of renewable energy resource, the wind energy generation is ahead of all natural resources. There are some noteworthy reasons that played constructive role in development of wind energy generation including atmosphere, state-of-the-art design of wind turbines, and low cost [8].

In the modern era, when switching to alternative energy, one of the main issues is the assessment of the natural potential of alternative energy sources in the world, including in Azerbaijan, and the adoption of necessary measures for their optimal use. Favourable climatic conditions and the geographical location of our republic create the basis for the effective use of renewable energy sources, such as wind, solar, wave, geothermal, etc. The Absheron Peninsula and the surrounding areas are characterized by strong and stable winds throughout the year, especially the northerly winds blowing at a speed of 6-8 m/s and more, making this zone a favourable place for wind energy. At the same time, the permanent wave processes occurring on the coastline of the Caspian Sea indicate the presence of suitable climatic conditions for the use of wave energy. When studying the efficiency of using the renewable energy potential of any geographical region, the natural potential is assessed first, and at subsequent stages–technical, economic and market potential [18]. In the current work, the natural potential of wind and wave energies in the Caspian Sea region is studied, based on multi-year satellite and ground measurement data obtained from various bases. Additionally, it should be noted that the technical wind energy potential was also estimated by taking into account the characteristics of small and medium power wind turbines. The potential for wind energy in offshore areas is considered much higher than onshore areas due to the presence of more stable and intense winds. The integration of wind and wave energies is considered technically and economically viable due to their natural compatibility and the possibility of combining them within the same infrastructure.

Wind and wave regime of the Caspian Sea. The Caspian Sea, which is unique and rich in natural resources, also plays the role of a climatic and ecological indicator of our planet. Located between latitudes 47°07′N and 36°33′N and longitudes 45°43′E and 54°03′E, the sea is surrounded by 5 countries. The surface area of the Caspian Sea, which stretches for 1200 km along the meridian, is 392.600 km^2.

The Caspian Sea, which is considered one of the windiest seas in the world, experiences hurricane winds for 250 days a year. Wind is the horizontal movement of air from a high pressure area to a low pressure area. The speed and direction of the wind are determined by factors such as the nature of the general circulation of the atmosphere, the temperature field created by the wind itself, the relief of the coasts, etc. [20].

During the winter, the weather in the northern Caspian is dominated by the Asiatic anti-cyclone which creates easterly cold winds. During the summer, the weather is dominated by the Azores high-pressure that causes northerly winds. The region is also subjected to extra tropical cyclones at the rate of about 10 storms per year [14].

According to the general regularity of the wind regime, winds with a northern (north-western, north, north-eastern) and south-eastern direction prevail over the Caspian Sea. The probability of the formation of wind fields with a northern direction throughout the year is 41%, but in summer this probability increases slightly compared to other seasons and reaches 48.7%. Approximately half of them fall on the north-western direction. Northern direction winds are observed during the spread of the branches of the Azores anticyclone to the southern regions, the movement of the Barents and Kars, Scandinavian anticyclones, as well as during the activation of the southern Caspian anticyclone, which subsequently moves in a north-eastern direction and enters the western regions of Central Asia. Southeast winds make up an average of 35.9% of the annual wind speed. They are most often observed in winter, when an anticyclone is formed over Kazakhstan and the regions of Central Asia (41.3%). This anticyclone creates favorable conditions for the movement of air masses in a south-easterly direction. The most persistent of the wind types blowing over the Caspian Sea are south-easterly winds. The average annual wind speed within the sea area is in the range of 4-6 m/s [20]. When evaluating the performance of a selected turbine, the height of the turbine hub is approximated based on the logarithmic law of wind speed.

The wind regime of the Caspian Sea is defined by three principal factors: regional atmospheric activity, topography of the coasts (orography) and local circulation induced by the thermal increments between the land and sea [15].

The largest wave sizes in the North Caspian Sea are as follows: height -3 m, period-10 seconds, length - 85 m. The average wave values in this part of the sea are as follows: Average wave height − 0.5-0.7 meters, average wave period − 3-5 seconds (Kudryavtsev et al., 2019), average wave length −20-40 meters (Holthuijsen, 2017). In places of increasing depth, waves with a height of 2 m are observed, towards the south their height increases, and in some places they reach 4 m and more. In the western part of this region of the sea, southeast and east waves prevail, and in the northeastern part, west and east waves.

The waves in the Middle and South Caspian Seas have the following characteristic features: The most persistent storm winds and corresponding waves are observed in the Baku-Absheron Peninsula, Makhachkala-Derbend, and Fort-Shevchenko regions. The largest waves in the Caspian Sea are formed in the waters of the Absheron Peninsula. The center of storm waves has a wave height of 7.5-8 meters, and in extreme storms, the heights reach 9-10 meters [20].

Material and method. To comprehensively study the wind and wave power in the Caspian Sea, data from 3 separate databases were used. As the 1st database, the multi-year ground observations [19] was used. Those data covered a total of 60 points of Caspian Sea in which the wind speed and wave parameters (height, period, length, phase velocity) were measured. The 2nd database is NASA's [12] space database covering 2001-2022, with a resolution of 0.5x0.625. The 3rd database is the Global Wind Atlas [5], which includes wind speed and direction data. The multi-year ground-based observations are for a height range of 10 meters, and the space-based data are for a height range of 50 meters.

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

$$P = \frac{\rho}{2} v^3 \quad (1)$$

Here, ρ =1.225 kg/m^3 is the air density.

The energy that can be obtained from wind depends very strongly on the distribution of wind speed. Thus, the energy produced in two different geographical locations with the same average speeds but very different standard deviations may be more than twice as much in the location with the larger standard deviation [4].

In a series of studies, for example, [1,2,3,4,11], based on the analysis of measured wind speed data, it has been found that the probability distribution function (PDF), $w_0(v)$, of wind speed in many geographical locations can be well approximated by Rayleigh or Weibull distributions. In our study area, the probability of wind speed distribution is also well described by Rayleigh, and very well by Weibull distribution (Fig. 1).

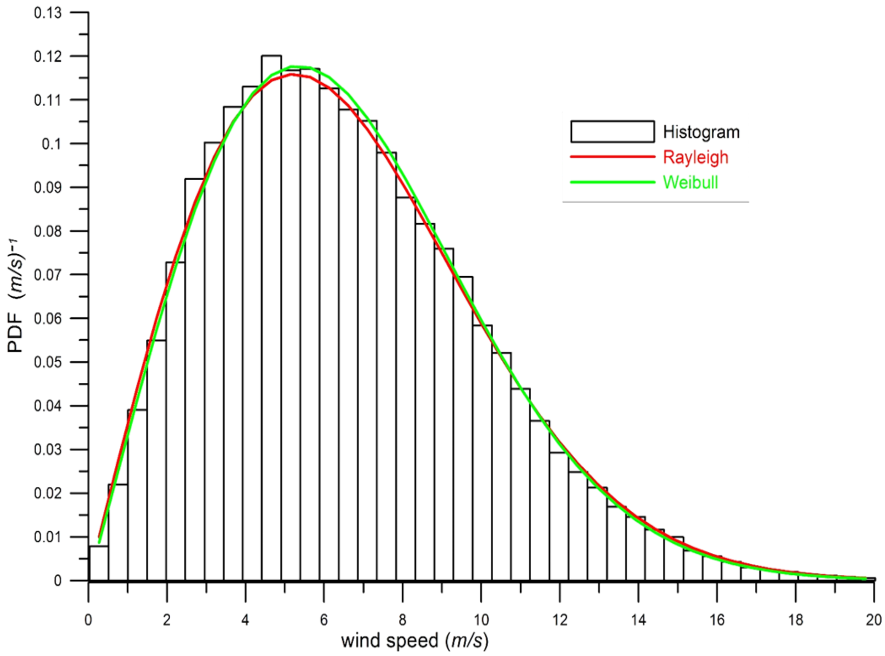


Fig. 1. Histogram of wind speed distribution in the Oil Rocks (40.33°N/50.6°S) during 2001-2022; approximation with Rayleigh and Weibull distributions

For average wind power from (1) is obtained:

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

If the wind speed distribution is the Weibull law, then (2) is transformed into the following formula:

$$\bar{P} = \frac{\rho}{2}\,a^3\Gamma\left(1+\frac{3}{b}\right) \quad (3)$$

Here $\Gamma(x)$ is the Gamma function; a, b are the parameters of the Weibull distribution, which are uniquely determined by the average wind speed $\bar{v}$ and the standard deviation σ_v [4].

Note that wind speed depends on altitude and varies with surface roughness; as altitude increases, wind speed increases [9]. The dependence of wind speed on altitude is theoretically expressed by a logarithmic law; however, an approximation of the measurement data by an exponent law is also used.

The efficiency of a wind turbine is characterized by its "power curve", which is a purely technical characteristic of the turbine and is determined by the manufacturer.

The capacity factor (CF) of a wind turbine for a selected geographical location is an indicator of the operational efficiency of the turbine to be installed there and is determined by the natural wind potential of the location (wind power distribution) and the turbine's "power curve". Thus, CF is the main criterion for selecting the type of turbine that will produce energy most efficiently at a given location [4]. The operating efficiency of a wind turbine at a selected site is characterized by the capacity factor (CF) of the turbine, which is determined as a ratio of mean turbine power $\overline{\mathbb{P}}_T = \int_0^\infty \overline{\mathbb{P}}_T(v)\, w_0(v)dv$ to turbine-rated power $\mathbb{P}_r$:

$$\mathrm{CF} = \frac{\overline{\mathbb{P}}_T}{\mathbb{P}_r} \quad (4)$$

Thus, the energy that the wind turbine will produce in the time intervals [0,T] is calculated by formula (5).

$$E_{[0,T]} = CF \cdot \mathbb{P}_r \cdot T \quad (5)$$

Here $\mathbb{P}_r$ – is the nominal power of the turbine and is indicated in the technical documentation of the turbine [4].

In general, the density of wind energy at sea is higher than on land [10].

Wave power calculation. Wave power P (W/m) is calculated based on the following formula [16,17]:

$$P = \frac{\rho g^2 T h^2}{32\pi} \quad (6)$$

Here, h (m) is the wave height, T (sec) is the period, g =9.81 m/sec^2 is the acceleration of free fall, $\pi = 3.14$, ρ is the density of seawater. Although this value is 1030 kg/m^3 for ocean water, it is taken as 1000-1025 kg/m^3 for seawater. Since the density of seawater varies depending on depth, salinity, etc., it is difficult to give an accurate estimate. During the calculations, the average water density for the Caspian Sea was taken as 1020 kg/m^3. Based on the wave height h (m) and period T (sec) given in the "Hydrometeorological Atlas of the Caspian Sea" [19], the wave power P (W/m) was calculated for each of the 60 points during both north, north-west and south-south-east winds. The amount of wave energy E (kWh) in existence during the year was calculated on the following formula:

$$E = P \cdot L \cdot T \,, T = 365 \cdot 24 \text{ (hour)} \qquad (7)$$

Here, L (m) is the length of the wavefront and this value was taken as 1 meter.

The wave power P, i.e. the energy flux, is usually defined as the average power per meter of wave front length and is expressed in W/m. This given value means the average energy passing from the surface to the seabed per second under one meter of wave front [10].

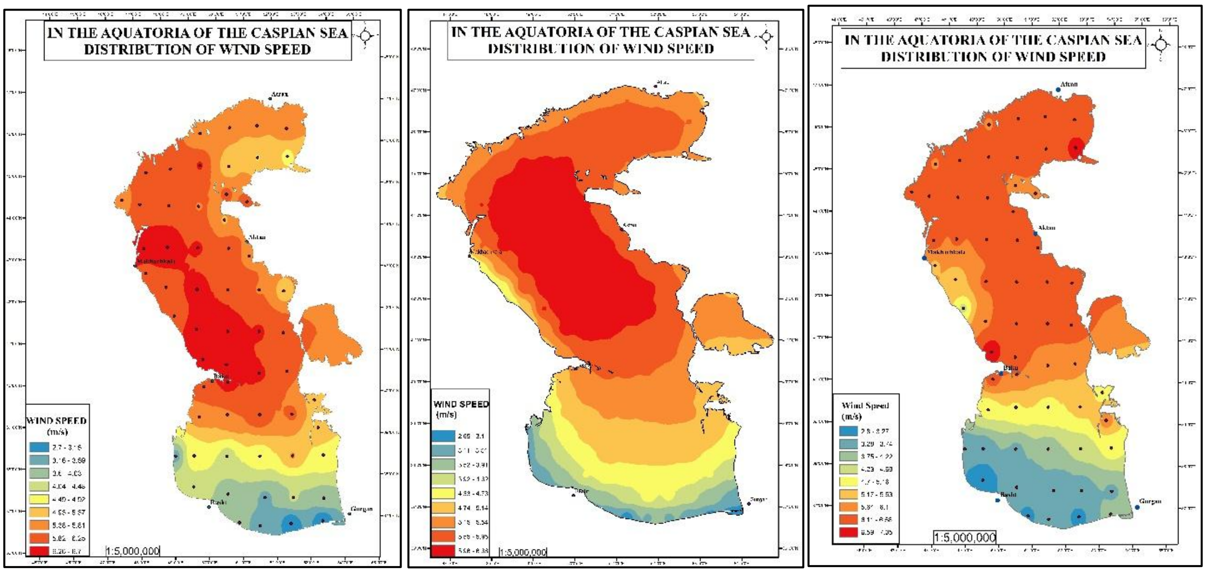
Analysis and Discussion. Wind power and energy were calculated using formulas (3) and (5), respectively, and wave energy was calculated using formula (7). Based on the calculated data, wind speed, wind energy, and wave power maps were drawn.

Wind speed, wind power. The map compiled on the 1st database, (Fig. 2a) shows that the wind speed varies between 2-6 m/sec. For considered turbines rotor hub height are 37, 120 meter are respectively and corresponding wind speed at those height we're determining according to the logarithmic law. The places where the wind speed is the highest are the Azerbaijani sector, especially the coasts of Baku and the Absheron Peninsula. The wind speed gradually decreases towards the north. But it takes its lowest value in the South Caspian.

In the wind map compiled based on NASA satellite data (Fig. 2b), the values of wind speed also vary in the range of 2-6 m/s. Here too, the lowest values are in the southern part of the sea. However, the places where the maximum values are observed are seen further north.

If we look at the map compiled on the basis of data taken from the "Global Wind Atlas" database (Fig. 2c), we will see that the change in the southern part of the sea is the same as in the other two regions. However, the difference is manifested in other parts of the sea. In almost all of the Northern Caspian and most of the Middle Caspian, the wind speed varies within the range of 5-6 m/s.

Figure 3 shows the distribution of wind power in



a) *b)* *c)*

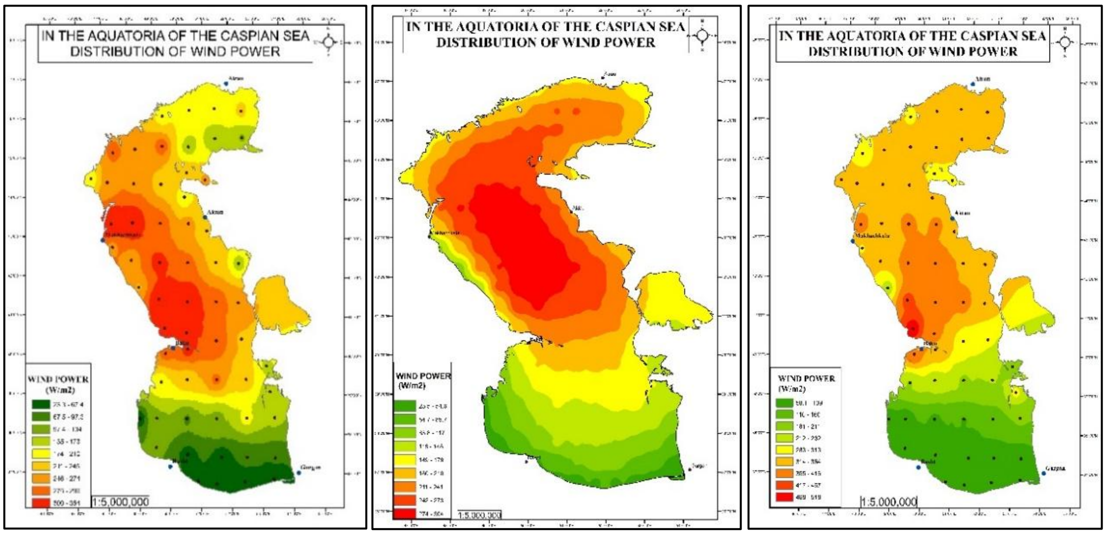
Fig. 2. Wind speed distribution map in the Caspian Sea area (a-Based on multi-year ground observation data; b-Based on NASA database; c-Based on Global Wind Atlas)

the Caspian Sea based on data obtained from various sources. Thus, in the map prepared based on data obtained from ground-based data, the wind power varies in the range of 23-354 W/m^2. The areas with the highest wind power are the coasts of Baku and the Absheron Peninsula (Fig. 3a).

In the map based on the NASA database [12], the wind power varies in the range of 23-304 W/m^2. The maximum value is observed more in the middle part of the sea, and the minimum value is observed in the southern part (Fig. 3b).

In the map based on the data taken from the Global Wind Atlas database [5], the wind power varies in the range of 58-518 W/m^2. The maximum value is higher than the value shown in the other two maps, but here it is also observed in the center of the sea (Fig. 3c).

An analysis of the trend of change in the annual average wind speed for the 10 sites considered for the period 2001-2022 shows a weak increasing trend in some sites (Figure 4), while the "wind rose" has noticeably shifted northward (Fig. 5).



a) b) c)

Fig. 3. Wind power distribution map in the Caspian Sea (a-Based on multi-year ground observation data; b-Based on NASA database; c-Based on Global Wind Atlas)

Thus, it is concluded that climate change has not reduced wind speed, but has even increased it slightly, which is a positive result in terms of using wind energy.

Wind rose diagrams are very helpful in defining the prevailing wind direction, the directional quantification of total energy and the direction of maximum wind speed intensity [13].

Five points with high wind speeds were selected in the Azerbaijani sector of the Caspian Sea (Figure 6), and the statistical characteristics of the wind speed at those points, the parameters of the Weibull distribution, and the energy that two types of turbines (small *"Northwind 100C,95kW"* and *"FL 2500_90"* medium-power) can produce in a year were calculated (Table 1). Notice that this types of turbines are intended for offshore conditions and previously were used.

The data shown in Table 1 were obtained from long-term satellite observations and the wind speed was extrapolated to the central height of the selected turbine models.

Wave power. There are a wide range of technological solutions proposed for wave energy harvesting. A one-size-fits-all technology that encompasses a few technologies has not yet emerged. Instead, using local parameters such as water depth and wave climate (i.e. wave height and period) will allow us to determine what the best technology is for a given area [7].

Based on the calculated data, a distribution map of the annual wave energy potential per 1 meter of the wave front in the Caspian Sea was compiled (Figure 7). As can be seen, high wave energy is observed in the Middle Caspian during both northern, north-western, and southern, southeaster winds. In general, although the two maps are similar at first glance, there are differences between the quantities. Thus, the lowest value of the wave energy potential per 1 meter

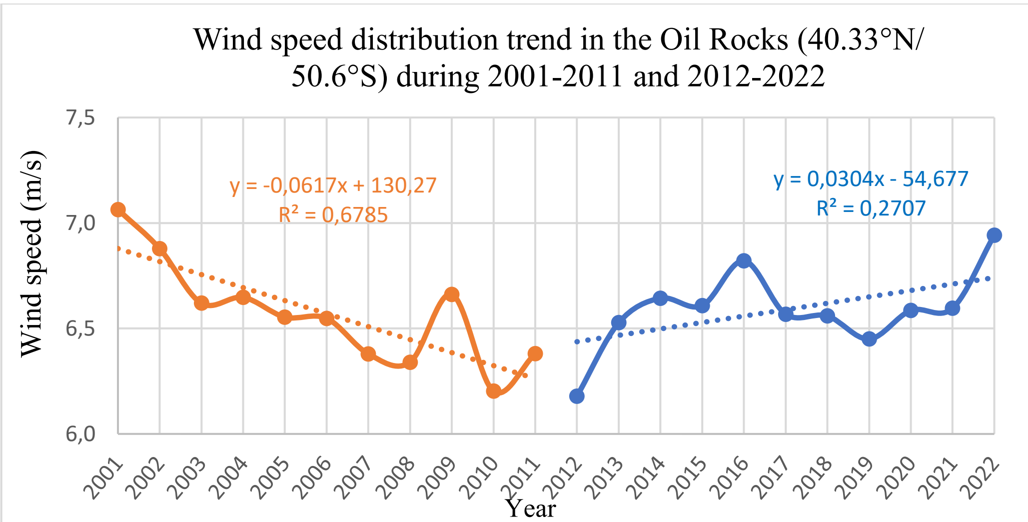


Fig. 4. Annual average wind speed change over the years in Oil Rocks (40.33°N/ 50.6°S)

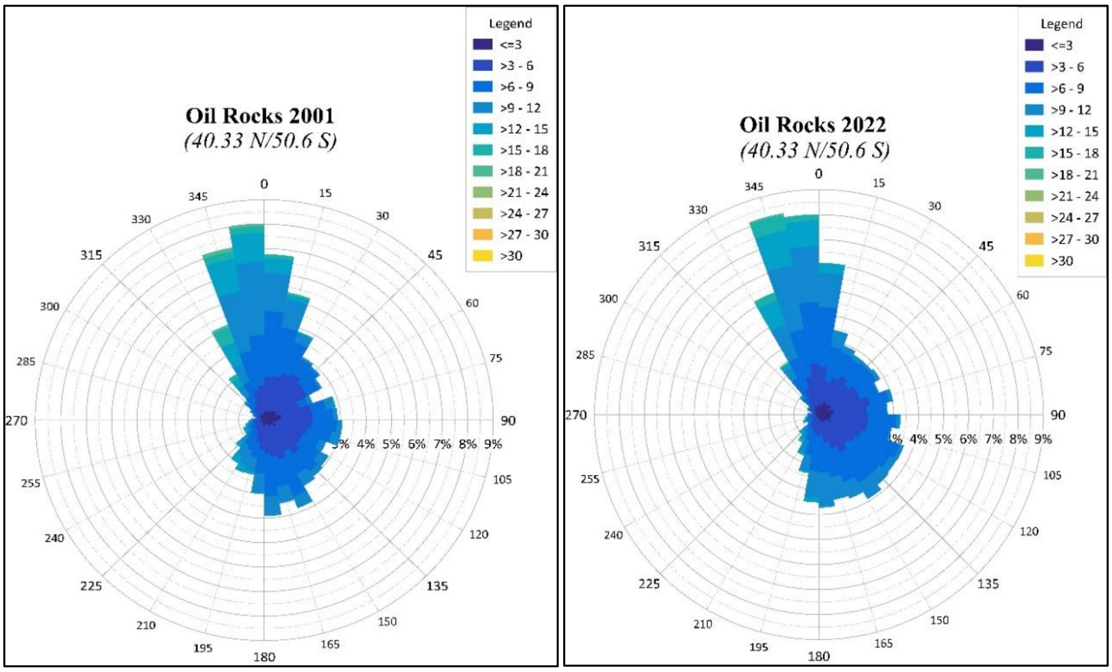


Fig. 5. Change in annual average wind direction over the years in Oil Rocks (40.33°N/ 50.6°S)

during northern and north-western winds is 145.4 kWh (Figure 7A), and during southern and south-eastern winds it is 128.5 kWh in the northern and southern parts of the Caspian Sea (Figure 7B). It is clear from the maps that the values of wave energy in the Caspian Sea are higher on the western coast than on the eastern coast. Especially high values are noticeable on the coast of Azerbaijan.

Wave power is often compared to wind power because the two energy sources have much in common physically, and wind has already proven itself as a viable energy source. A positive feature of wave power compared to wind power is that the average power delivered by waves varies more slowly than the sometimes very rapid changes in wind speed and direction [17].

It should be noted that S. Hadadpour et al. [6] studied the wave power assessment at Anzali station on the Iranian coast of the Caspian Sea, and they found the annual average value of the wave power P=0.66 (kW/m). This corresponds to the wave energy value E=5782 (kWh/m) shown in Figures 7A and 7B.

Conclusion. As a result of studies conducted on the basis of satellite and ground observation data, we can note that the wind speed in the Caspian Sea varies approximately in the range of 2.7-7 m/s. The minimum wind speed falls on the southern Caspian, and the maximum speed falls on the average partly on the northern Caspian (according to the NASA and Global Wind Atlas databases). The distribution of wind power in the Caspian Sea corresponds to the distribution of wind speed. Thus, the wind power mainly varies in the range of 23-350 W/m^2, and according to the Global Wind Atlas database, it varies in the range of

Table 1

Calculated parameters for the area under consideration

Point №	1	2	3	4	5
Coordinate (°N/°S)	40.76/49.50	40.33/50.6	40.51/50.16	41.02/50.07	40.22/50.19
Average wind speed, $\bar{v}$ (m/s)	6.77	6.58	6.66	7.13	6.25
Standard deviation, σ_v (m/s)	3.70	3.36	3.38	3.46	3.28
Weibull parameter, a	7.62	7.44	7.50	8.05	7.07
Weibull parameter, b	1.95	2.05	2.03	2.15	2.06
Average wind power, $\bar{P}$ (W/m^2)	365.8	335.9	348.3	427.3	287.8
CF, % *“FL 2500_90” Wind turbine*	29.9	28.1	28.7	33.0	25.2
Energy, $E_{[0,1\ year]}$, (GW·hour) *“FL 2500_90”*	6.54	6.12	6.31	7.26	5.54
CF, % *“Northwind 100C,95kW”* wind turbine	40.1	39.4	39.9	40.3	35.6
Energy, $E_{[0,1\ year]}$, (GW·hour) *“Northwind 100C,95kW”*	0.334	0.328	0.332	0.335	0.296

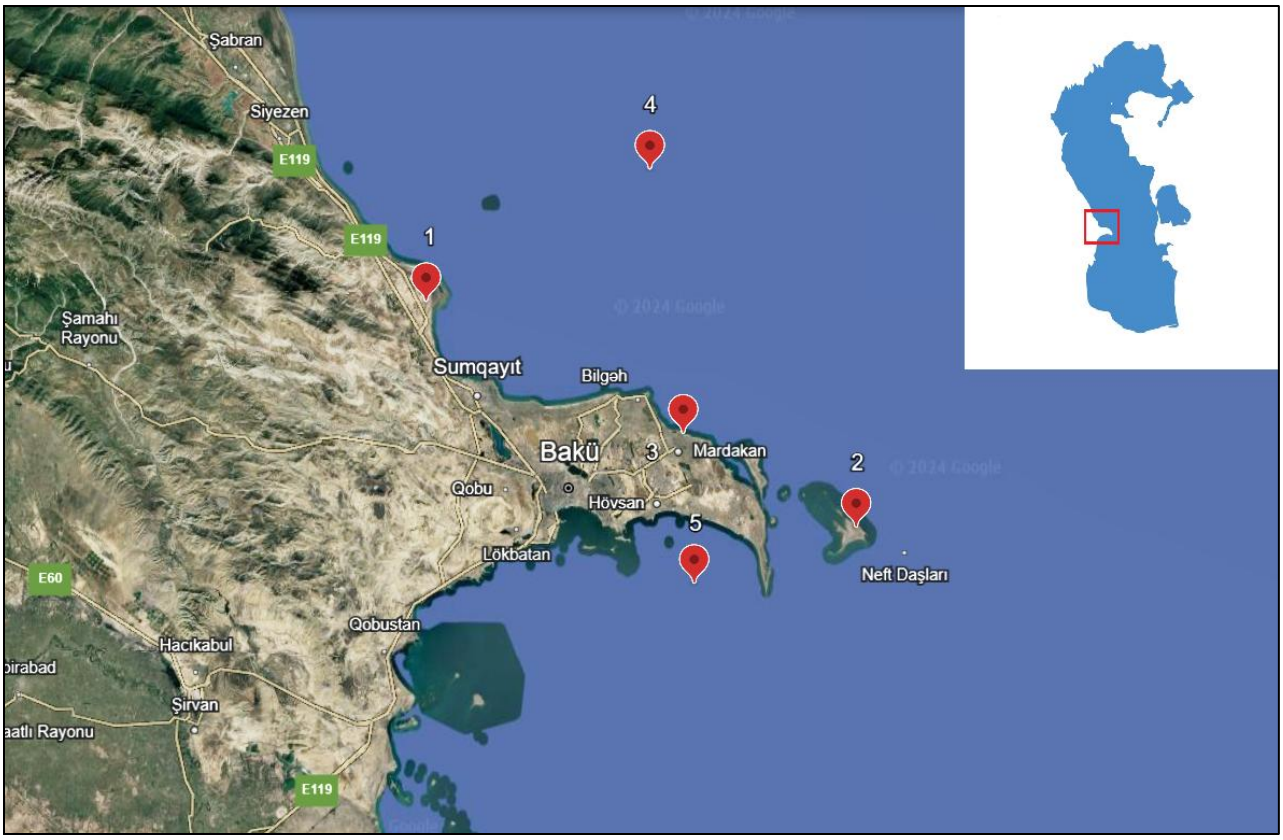
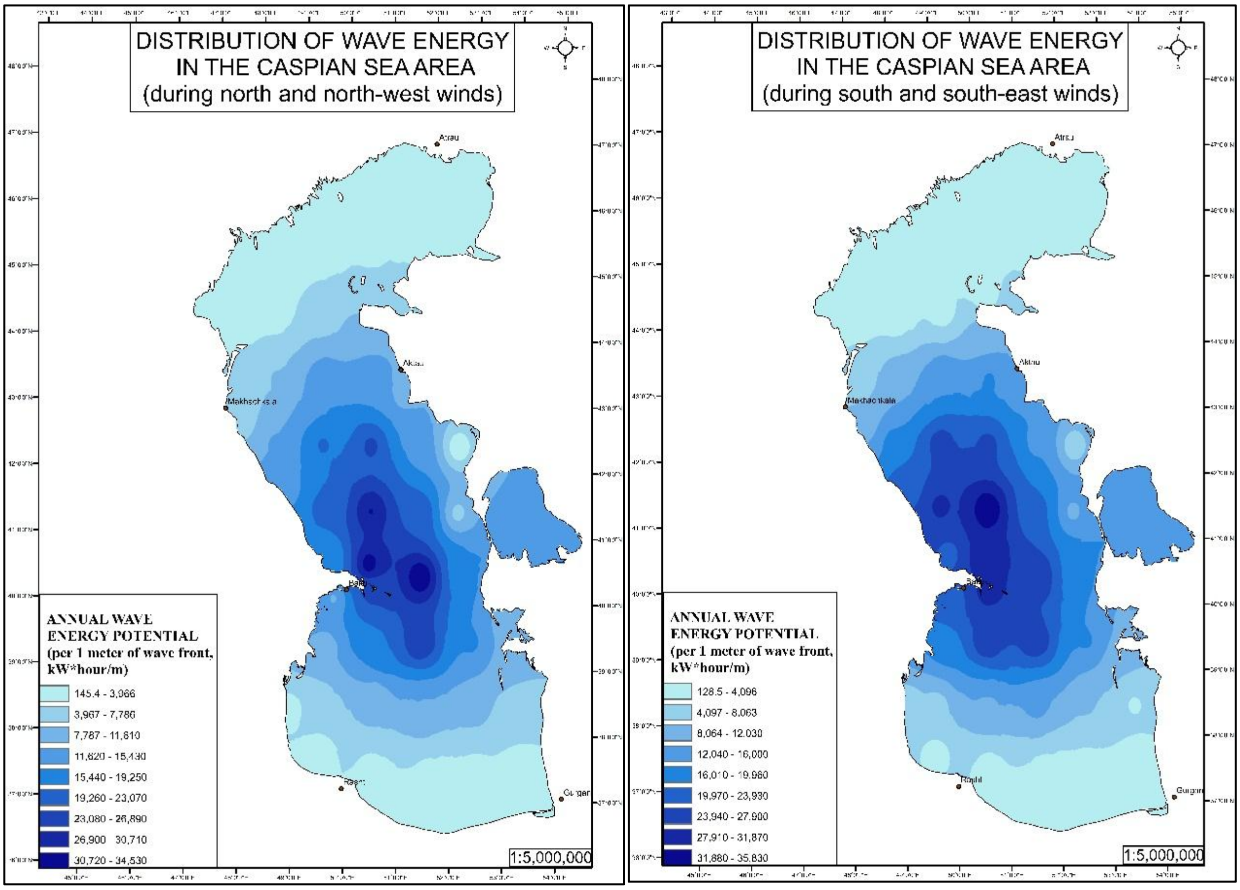


Fig. 6. Satellite image of survey points



A) B)

Fig. 7. Annual wave energy distribution map in the Caspian Sea
(Based on multi-year ground-based observation data)

58-518 W/m^2.

The potential of wave energy in the Azerbaijani sector of the Caspian Sea is high. In particular, this indicator takes the highest values off the coasts of Baku and the Absheron Peninsula. Here, the wave energy potential is 15000-35000 kWh/m during north and north-west winds, and 20000-35000 kWh/m during south and south-east winds. If we look at the Azerbaijani sector as a whole, it takes values between 3000-35000 kWh/m during north and north-west winds, and 8000-35000 kWh/m during south and south-east winds.

There is sufficient wave and wind energy in the Absheron Peninsula and nearby areas, especially in the oil-gas platforms. It is possible to make the electric energy usage in the platforms more efficient by replacing part of the energy used with these types of energy.

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Оцінка потенціалу вітрової та хвильової енергії в акваторії Каспійського моря

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У сучасний час швидке зростання попиту на енергію у світі та екологічні наслідки традиційних джерел енергії роблять необхідним перехід на альтернативну енергетику. Використання альтернативної енергії важливе не лише для захисту навколишнього середовища, але й зменшує залежність країн та економічних систем від нафти, газу та цін на них. Водночас глобальні проблеми, такі як зміна клімату та забруднення повітря, підвищують важливість відновлюваних джерел енергії. У статті досліджувалося поле вітру та хвиль Каспійського моря з метою використання потенціалу енергії вітру та хвиль, а також розраховувалася енергія отриманої енергії. Для розробки параметрів вітру використовувалися дані з трьох баз даних, дві з яких були космічними даними, а одна - довгостроковими операціями. Для збільшення потужності хвиль та енергії, що отримується від них як при північних, так і при південних вітрах, використовувалися наземні дані. На основі отриманих даних були складені плани оплати вітрової та хвильової енергії в Каспійському морі. Використання природного потенціалу Каспійського моря, залучення альтернативних джерел енергії у виробництво електроенергії та тепла дозволить здійснити прогресивні зміни в майбутніх напрямках розвитку електроенергетики. Доступне географічне розташування та кліматичні умови Каспійського регіону дозволяють широко використовувати екологічно чисті альтернативні джерела енергії, такі як енергія вітру та хвиль. Це не тільки дозволить значно заощадити паливо, що спалюється на теплових електростанціях, але й значно зменшить кількість небезпечних відходів, що викидаються в навколишнє середовище. В результаті проведених досліджень та розрахунків було визначено, що кількість вітрової енергії, яку можна отримати за допомогою вітрової турбіни типу FL 2500_90 у вибраних точках на Апшеронському півострові та прибережній зоні, що прилягає до неї, становить приблизно 5–7 ГВт/год, а від вітрової турбіни типу Northwind 100C (95 кВт) – 0,33 ГВт/год. Водночас, коефіцієнт використання потужності (КВ) вітрових турбін у цих точках коливається в діапазоні 25–33% та 35–40% відповідно. Було визначено, що в регіоні існує деяка різниця в середньорічному енергетичному потенціалі хвиль. Так, для північних та північно-західних вітрів щільність енергії хвиль коливається в діапазоні приблизно 15 000–35 000 кВт/м², а для південних та південно-східних вітрів – в діапазоні 20 000–35 000 кВт/м².

Ключові слова: *Каспійське море, швидкість вітру, напрямок вітру, енергія вітру, енергія хвиль, роза вітрів, розподіл Релея, розподіл Вейбулла.*

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