# STUDY ON THE WIND ENERGY POTENTIAL OF THE BLACK SEA CONTINENTAL SHELF IN THE COASTAL AREA OF ROMANIA

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**Abstract.** The main objective of this paper is to analyse wind data from the western shore of the continental shelf of the Black Sea. For this study, wind data spanning a 10-year period (2014-2023) was collected and used from the ERA5 database. The analysis determined the seasonal nature of wind speed, with maximum values in winter and minimum values in summer. Using the Weibull distribution, the wind energy potential in the area was calculated, with values ranging between 528.9 – 757.7 W/m$^2$.

**Key words:** wind energy, offshore, Black Sea, ERA5

## 1. INTRODUCTION

Climate change represents an urgent challenge that requires immediate action. At the same time, the continuous growth of the global population leads to increased energy demand, which amplifies greenhouse gas emissions, a problem largely attributed to the energy sector based on fossil fuels. Renewable energy sources, derived from virtually inexhaustible natural resources, offer a sustainable alternative because they do not emit pollutants such as $CO_2$ into the atmosphere. From this perspective, progress in combating climate change inherently stimulates the expansion of the renewable energy sector (Diaconita *et al.*, 2021; ECMWF, n.d.).

Moreover, promoting renewable energy generates benefits that go beyond ecological considerations, such as reducing national energy dependency and positively correlating with a country's gross domestic product (GDP) growth. Therefore, it is not surprising that the European Union and many governments worldwide are increasingly supporting the renewable energy industry. At the same time, individuals and communities are increasingly embracing sustainable production methods while striving to reduce waste and lower gas emissions on a personal level. This growing social support for renewable energy represents another catalyst for this transition (Diaconita *et al.*, 2021).

Wind energy stands out as a proven and viable renewable resource. As one of the most cost-effective options for renewable energy, it has become a well-established industry that has steadily expanded over the years. Historically, wind farms were predominantly developed onshore, where notable technological advancements have occurred. The current trend focuses on scaling up turbine size to enhance energy production (ECMWF, n.d.).

In recent years, offshore wind farm projects have grown significantly in importance. The remarkable energy characteristics of coastal winds, where irregularities are fewer and wind speed is typically higher than onshore, have sparked widespread interest in offshore wind energy. Fixed offshore turbines can operate at depths of up to approximately 60 meters and rely on onshore turbine technology, with the main difference being the type of foundation used. On the other hand, floating turbines allow these wind farms to be installed in areas further from the shore, where the sea floor depth is greater (MathWorks, n.d.; Constantin *et al.*, 2024).

The present study investigates the Romanian sector of the Black Sea, particularly the region extending from the shoreline to the shelf break. Romania is a country that increasingly uses renewable energy, both wind and solar. However, at present, there is no project for the installation of wind turbines in the coastal area of the Black Sea (Constantin *et al.*, 2024).

## 2. MATERIALS AND METHODS

### 2.1. Study Area

The continental shelf extends from the coastline to the shelf break and its width varies significantly along different coastal regions of the Black Sea. The Romanian continental shelf extends along the coast for 245 kilometres and reaches depths of up to 130 meters (Nedelcu and Toma, 2023). To determine the wind potential, 6 study points were chosen, located at different distances from the shore to create a comprehensive understanding of the wind potential in the area. The offshore study points represented in figure 1, were denominated to A1-A3 for the closest to the shore and B1-B3 for those farthest in the sea. Table 1 provides an overview of the primary characteristics of the six offshore locations analysed in this study.

**Table 1.** Key characteristics of the offshore locations analysed

| Point | Latitude | Longitude | Distance from Shore (km) |
|---|---|---|---|
| A1 | 44° 47′ 39″ | 29° 49′ 31″ | 18 |
| A2 | 44° 25′ 41″ | 29° 14′ 46″ | 37 |
| A3 | 43° 51′ 13″ | 29° 06′ 47″ | 38 |
| B1 | 44° 57′ 34″ | 30° 35′ 22″ | 75 |
| B2 | 44° 28′ 45″ | 30° 09′ 44″ | 60 |
| B3 | 43° 49′ 10″ | 29° 54′ 38″ | 101 |

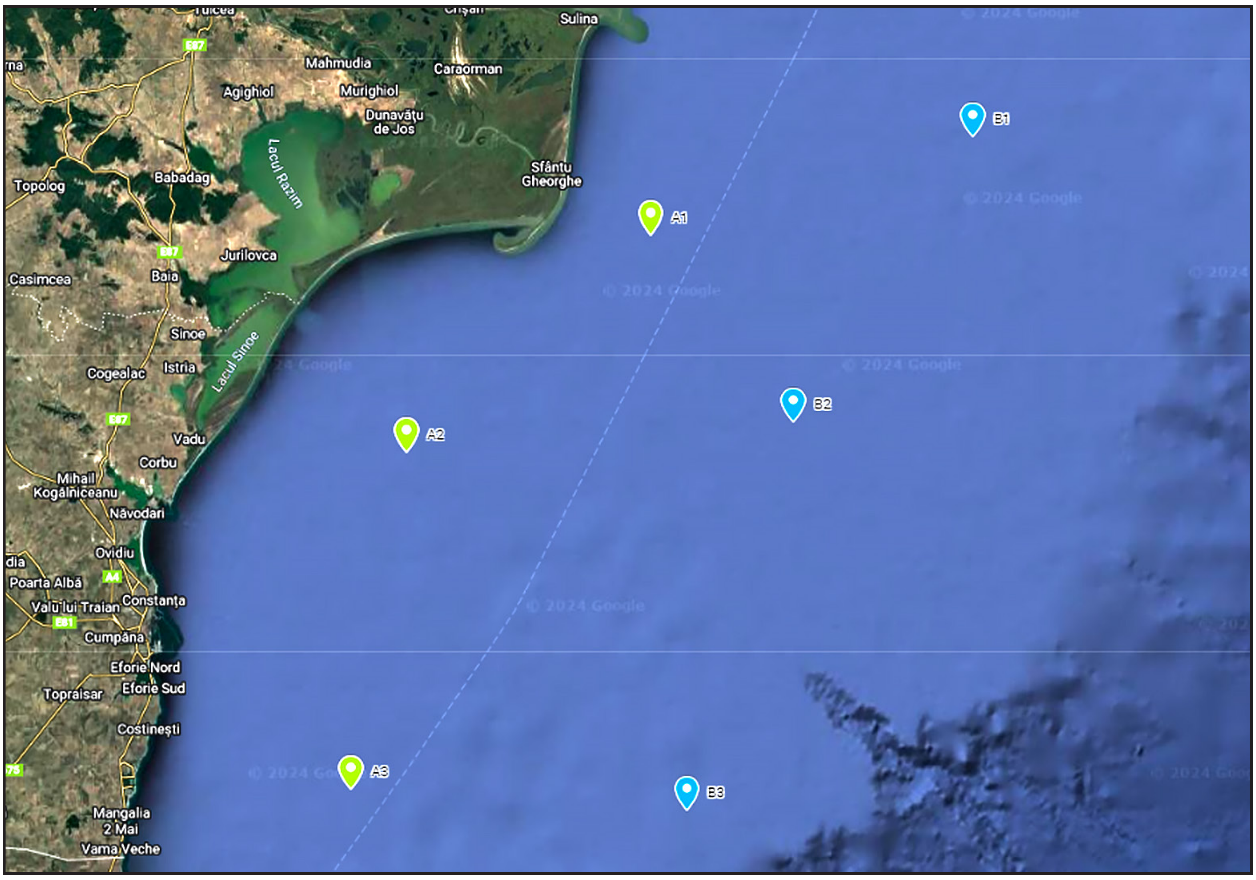


**Fig. 1.** The Romanian Black Sea Coast and the locations considered (map processed from Google Earth, 2025).

### 2.2. Wind dataset

For the reanalysis conducted in this study, the historical ERA5 database, the successor to the well-known ERA-Interim, was utilized. This database represents the most recent global atmospheric reanalysis created by "ECMWF", the European Centre for Medium-Range Weather Forecasts, covering the period from 1950 up to five days behind real-time. The historical time series includes information on atmospheric parameters at the surface and sea levels, with a temporal resolution of 1 hour and a high spatial resolution of 0.25° × 0.25° (approximately 31 km²) (Onea and Rusu, 2018).

The model provides hourly fields for wind speed and atmospheric pressure, consistent with the historical evolution of modelled parameters. This study uses the time series of historical wind speed values at a height of 10 meters over a 10-year period, from 2014 to 2023, for the selected offshore points, with a temporal resolution of 6 hours (corresponding to 00:00, 06:00, 12:00, and 18:00 UTC). Based on these data, statistical analysis was performed using the MATLAB computational tool to identify relevant wind parameters at the studied locations (Onea and Rusu, 2021; Răileanu and Onea, 2016).

### 2.3. Methods

To analyse the dataset mentioned earlier, several characteristic wind parameters and operational parameters deemed important for wind turbines were obtained. The wind speed values provided by the ERA5 dataset are reported at a height of 10 meters above sea level. However, to study this parameter at a height of 100 meters – the operational height considered for the turbines analysed in this study – it is necessary to determine the wind speed relative to the surface roughness of the terrain:

$$vm(z) = cr(z) \times vb \quad \text{(CR 1-1-4/2012)} \tag{1}$$

where:
*vm*(*z*) – average wind speed at height z;
*cr*(*z*) – roughness factor for wind speed, depending on surface characteristics;
*vb* – reference wind speed at a specific reference height.

These parameters are essential for accurately modelling and analysing wind behaviour at various heights, particularly for assessing wind energy potential at turbine operational heights.

The roughness factor for wind speed, *cr*(*z*), models the variation of the average wind speed with height *z* above the terrain. This variation depends on different terrain categories, which are characterized by the surface roughness length $z_0$, and is calculated based on the reference wind speed:

$$c_r(z) = \begin{cases} k_r(z_o) \times ln\left(\dfrac{z}{z_0}\right) & for \quad z_{min} < z \le z_{max} = 200m \\ c_r(z) = z_{min} & for \quad z \le z_{min} \end{cases} \tag{2}$$

(CR 1-1-4/2012)

The wind speed values at the operational height of wind turbines allow for the study of relevant wind characteristics. Once these parameters are determined, wind energy capacity for each location can be classified. For this purpose, wind capacities are typically categorized into classes, ranging from C1 to C7, based on wind speed magnitude. Higher classes indicate locations that are more attractive for offshore wind farm development, as they offer higher wind speeds and, consequently, superior energy potential (IEC 61400.).

Similar to how wind capacity is categorized by wind speed magnitude, turbine technologies are classified according to their operational wind speed characteristics. Given the substantial economic investment required for each turbine, it is crucial to ensure that the selected technologies perform efficiently and reliably throughout their operational lifespan. This requires careful consideration of the specific wind conditions at the proposed offshore wind farm site to avoid catastrophic failures and maximize project viability.

In this regard, the International Electrotechnical Commission (IEC) has developed a safety standard, adopted by the European Union, which classifies turbines based on the wind speed for which they were designed to operate (Spinato *et al.*, 2009; Weisser, 2003).

The technical specifications of a turbine define its IEC wind class, indicating the turbine's efficient performance under specific wind conditions. A turbine class is characterized by several key parameters, such as the average wind speed, the intensity of turbulence, and extreme wind gusts measured over a 50-year period. This study considers only the average wind speed, covering the following four wind classes: C1 – 10 m/s, C2 – 8.5 m/s, C3 – 7.5 m/s, C4 – 6 m/s.

Given that irregularity is a fundamental characteristic of wind, it is important to assess how wind speed magnitude varies across different time periods. Such fluctuations can result in locations where wind energy potential is exceptional during specific months or seasons, yet the annual average wind speed is lower compared to other sites with more stable but consistently moderate wind speeds throughout the year (Wikipedia, n.d.).

To analyse this aspect, monthly averages of wind speeds at the operational height were studied, as well as the seasonal variability at each of the analysed locations.

Once the wind speed at a specific height has been determined, energy parameters can be calculated. Power density is typically quantified in watts per square meter (W/m²) or kilowatts per square meter (kW/m²), denoted as *Pw*. Power density can be calculated using the simplified formula:

$$P_w = \frac{1}{2} \rho_{air} \times v^3 \times A \quad \text{(Burton \textit{et al.}, 2021)} \tag{3}$$

where $\rho_{air}$ the air density, is typically valued at 1.225 kg/m³, representing standard conditions at sea level. The wind speed, *v*, is the interpolated wind speed at the desired height, expressed in m/s.

If the probability density for the average wind speed is also considered, the formula for power density becomes:

$$P_w = \int_0^\infty \frac{1}{2} A \times \rho_{air} \times v^3 pd(v)\,dv \quad \text{(Manwell } et\ al. \text{ 2010)} \quad (4)$$

In this case, the power density is determined by integrating the cube of wind speed weighted by its probability distribution, $pd(v)$. This approach is particularly useful in wind energy studies, as it captures the variability of wind speeds over time and their impact on energy generation. The $pd(v)$ is often modelled using a Weibull distribution in wind energy assessments, given its suitability for representing wind speed distributions.

To apply statistical methods to the wind speed parameter, a suitable probability distribution is required for its description. The two-parameter Weibull distribution is widely regarded as the most commonly used in offshore wind farm studies. This is due to its proven ability to accurately model wind speed, making it a reliable choice for precisely defining this parameter.

The probability associated with the wind speed within the Weibull distribution is given by the formula:

$$pd(v) = \left(\frac{k}{A}\right) \times \left(\frac{v}{A}\right)^{k-1} \times e^{\left(-\frac{v}{A}\right)^k} \quad \text{(Aziz and Tsuanyo, 2023)} \ (5)$$

The parameters $k$ and $A$ are characteristics of the Weibull distribution used for modelling wind speed in each of the analysed locations. The parameter $A$ (also known as the scale parameter) is expressed in m/s and always has a value equal to or greater than zero (Wikipedia, n.d.).

The parameter $k$, referred to as the shape parameter, indicates the variability in wind speed values, reflecting the width or narrowness of the distribution curve. Conversely, the parameter $A$, known as the scale parameter, defines the magnitude of the wind speed values. The Weibull distribution enables the adjustment of these dimensionless parameters, allowing the distribution to align accurately with different time periods. As a result, monthly or seasonal Weibull distributions can be derived, offering a precise representation of wind speed behaviour over varying temporal scales (Wikipedia, n.d.; Ziegler *et al.*, 2018).

After defining the Weibull probability distributions for each considered location and for a specific time period, statistical methods can be applied to the wind speed parameter. This process facilitates a detailed and adapted evaluation of the wind characteristics to support decisions related to the design and viability of offshore wind farms.

## 3. Results

This section presents the results obtained from studying the parameters for each analysed location. Figure 2 illustrates the seasonal wind values, with maximum values observed during the December-February period, ranging from 6.3 to 7.5 m/s, and minimum values during the summer months (June-August), ranging from 4.5 to 5.1 m/s.

After calculating the average wind speed at a height of 100 m, Table 2 highlights the annual mean values across the six studied locations for the period 2014-2023. The B2 zone stands out with the highest average wind speeds compared to all other locations analysed. Situated 56 km offshore, the B2 zone consistently outperforms the closer A zones (located 18-40 km from the shore) as well as the more distant B1 and B3 zones, positioned 75 km and 104 km from the coast, respectively. The average wind speed for the B2 zone reaches an impressive 15.4 m/s, making it the most promising location in terms of wind energy potential. Figure 3 illustrates the 10-year trend of wind speed variations across all studied locations, showcasing seasonal and long-term dynamics.

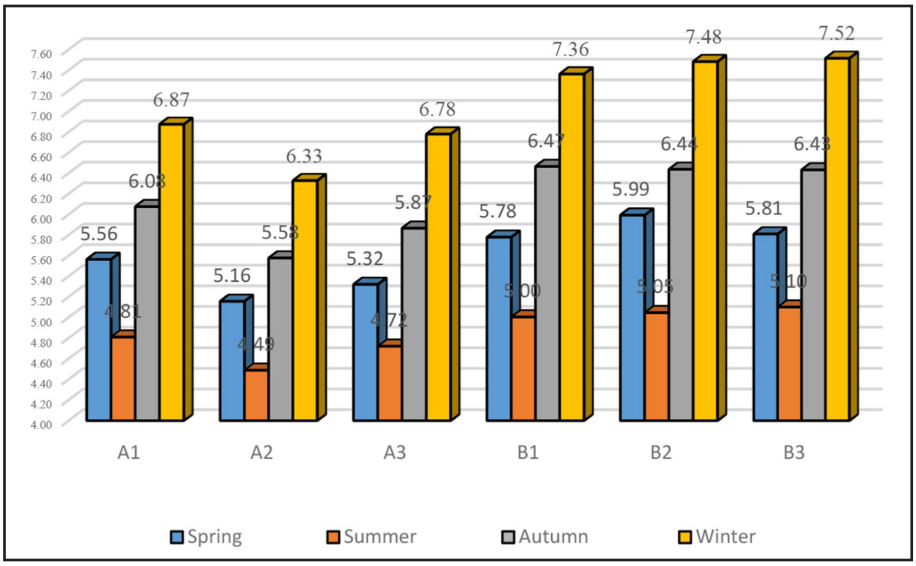


**Fig. 2.** Average wind speed values by season for the period 2014-2023.

**Table 2.** Annual average values at the reference height of 100 m for the period 2014-2023

| | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A1 | 14.09 | 14.40 | 14.25 | 14.61 | 14.23 | 13.66 | 13.88 | 14.61 | 15.21 | 15.67 | **14.46** |
| A2 | 12.52 | 12.78 | 12.69 | 13.09 | 12.78 | 12.28 | 12.49 | 12.97 | 15.69 | 16.31 | **13.36** |
| A3 | 13.34 | 13.66 | 13.73 | 14.04 | 13.92 | 13.26 | 13.49 | 13.95 | 15.37 | 15.92 | **14.07** |
| B1 | 14.90 | 15.25 | 15.09 | 15.40 | 15.00 | 14.36 | 14.52 | 15.45 | 16.18 | 16.44 | **15.26** |
| B2 | 15.02 | 15.46 | 15.43 | 15.74 | 15.44 | 14.76 | 14.94 | 15.87 | 16.05 | 16.05 | **15.48** |
| B3 | 14.78 | 15.24 | 15.44 | 15.58 | 15.53 | 14.81 | 14.90 | 15.69 | 15.91 | 16.24 | **15.41** |

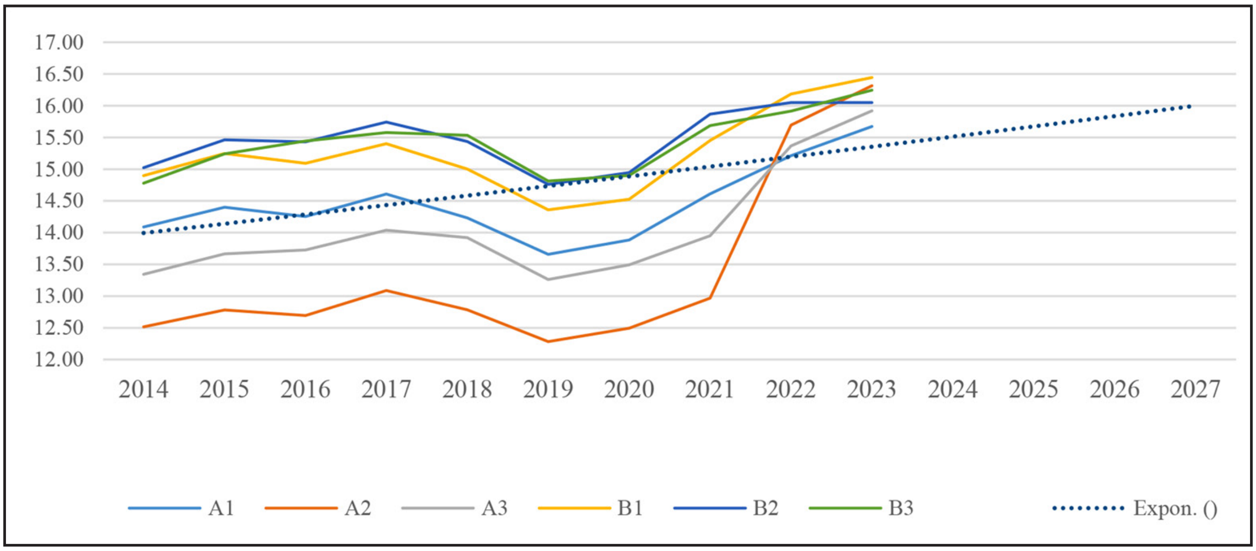


**Fig. 3.** Average wind speed values at a height of 100 m for the period 2014-2023.

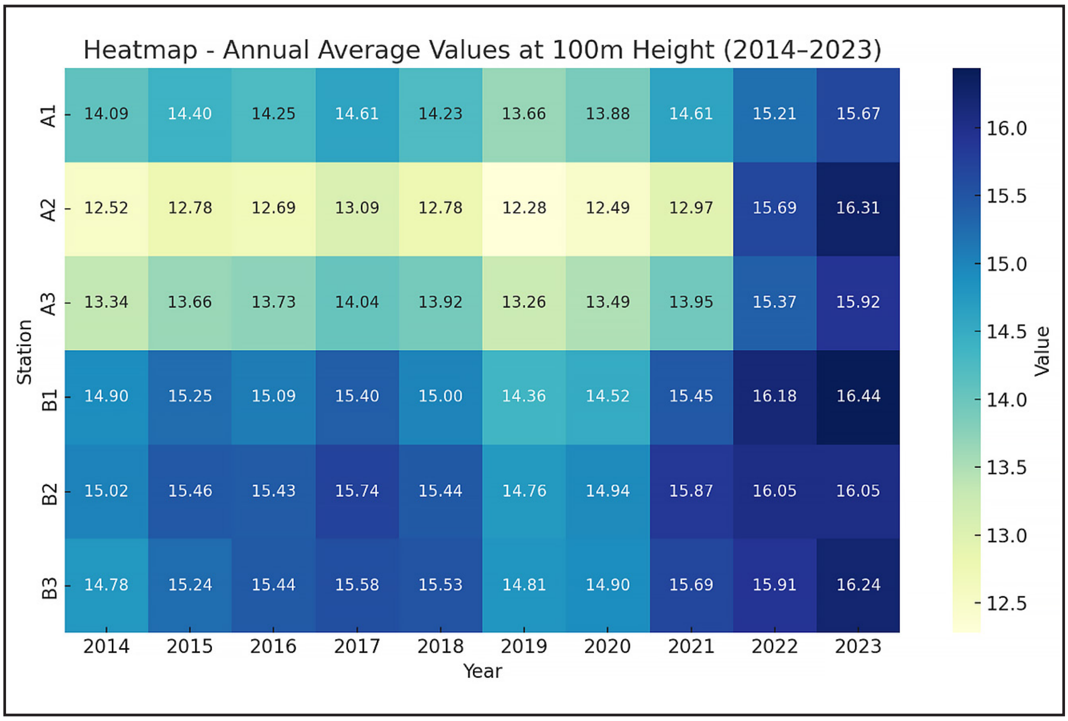


**Fig. 4.** Heat map for Average wind speed values at a height of 100 m for the period 2014-2023.

As previously mentioned, this study analyses wind speed at a height of 100 m based on the Weibull distribution, which accounts for two key parameters. Table 3 presents the shape parameter k and the scale parameter A for the analysed locations. The maximum scale parameter A is 10.78, observed at location B2.

**Table 3.** Weibull distribution parameters for wind speed at 100 m for each location.

| | A1 | A2 | A3 | B1 | B2 | B3 |
|---|---|---|---|---|---|---|
| k | 3.05 | 2.70 | 2.88 | 3.17 | 3.10 | 3.17 |
| A | 10.25 | 9.36 | 9.83 | 10.70 | 10.78 | 10.63 |

Through the Weibull analysis, the hourly frequency of wind speed occurrences was thoroughly examined for the six selected locations. Figure 5 provides a detailed representation of the hourly distribution of wind speeds for each specific location, offering a clear visualization of wind behaviour over time. In addition, figure 6 summarizes the wind speed ranges with the highest frequency of occurrence. From the data, it is evident that the predominant wind speed regime across all six locations is concentrated within the range of 7.8 m/s to 9.51 m/s, underscoring the consistency of favourable wind conditions in these areas.

This analysis not only identifies the most common wind speed intervals but also highlights their potential impact on energy production, offering valuable insights for optimizing the design and placement of offshore wind turbines.

Table 4 provides a detailed comparison of key wind parameters across the six zones, highlighting B2 as the location with the highest power density and most favourable wind conditions for offshore wind energy development. The wind energy potential was assessed by calculating the power density for the studied locations. Figure 7 depicts the distribution of wind speeds and the corresponding power densities across the analysed areas. The instantaneous power output ranges from 86 to 96.65 W/m$^2$, while the power density spans between 528.9 and 757.7 W/m$^2$.

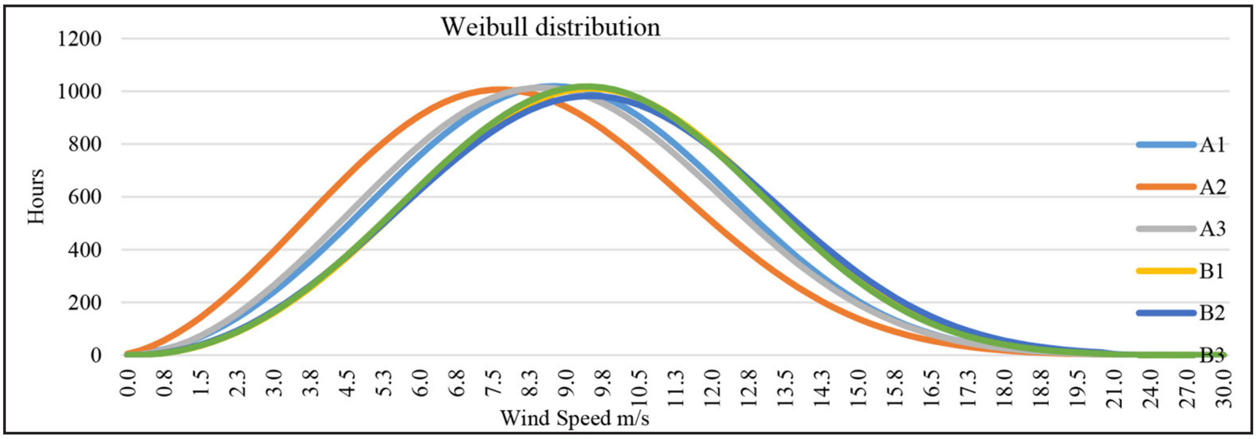


**Fig. 5.** Weibull diagram for the six analysed points, showing the annual distribution of wind speed in hours.

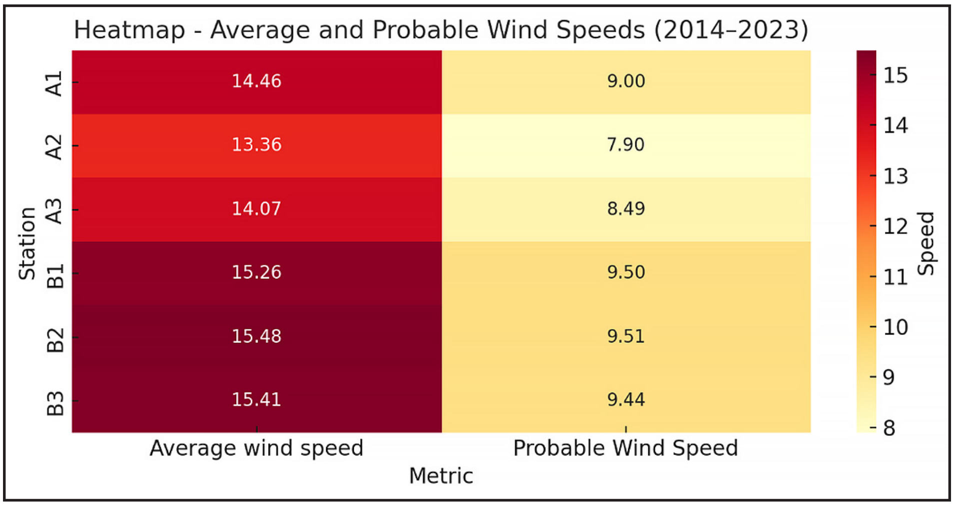


**Fig. 6.** Annual average values at the reference height of 100 m and the wind speed with the highest probability rate for the period 2014-2023 as heat map.

**Table 4.** Wind potential analysis for the six analysed zones

| Zone | Average wind speed (m/s) | Most frequent wind speed (m/s) | Maxim power W/m² | Wind speed at maximum power m/s | Power density W/m² |
|---|---|---|---|---|---|
| A1 | 14.46 | 9.002507 | 86.46 | 12.09 | 655.4127 |
| A2 | 13.36 | 7.895296 | 66.83 | 11.49 | 528.9684 |
| A3 | 14.07 | 8.490110 | 76.75 | 11.79 | 592.3807 |
| B1 | 15.26 | 9.501455 | 96.80 | 12.48 | 734.1212 |
| B2 | 15.48 | 9.510659 | 96.65 | 12.66 | 757.7997 |
| B3 | 15.41 | 9.437704 | 95.51 | 12.39 | 719.3868 |

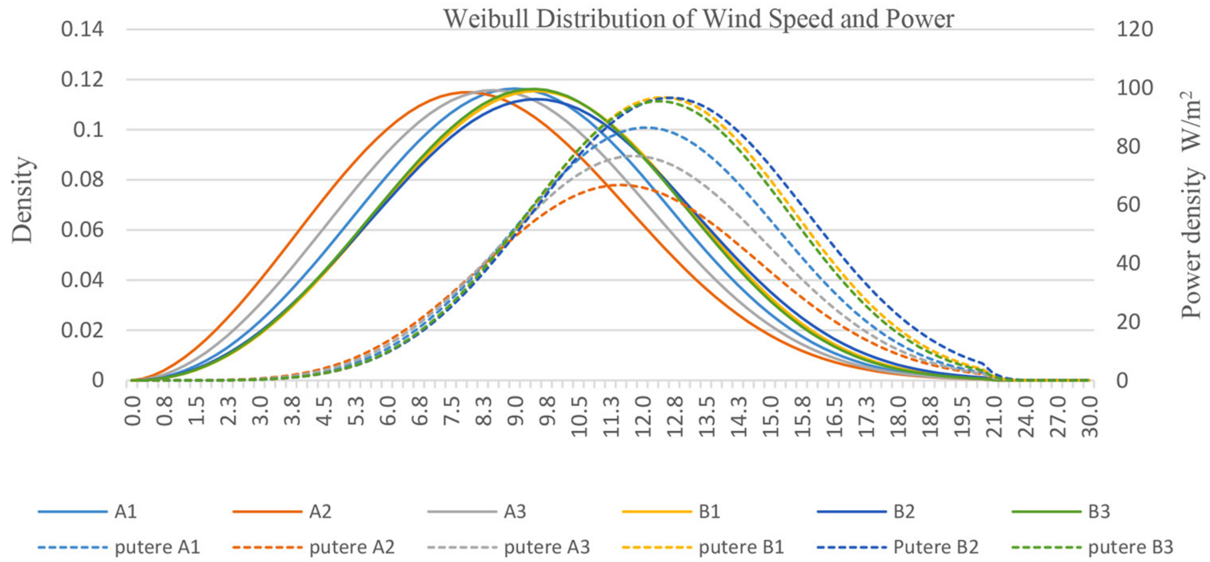


**Fig. 7.** The Weibull function of power density for wind speed in zones A1–B3.

## 4. CONCLUSIONS

This study conducted a comprehensive evaluation of wind energy resources on the Romanian continental shelf of the Black Sea, focusing on wind characteristics at six strategically selected locations.

Through an in-depth analysis of the collected data, the monthly, annual, and seasonal average wind speeds for the six sites were determined. The findings indicate that the December-February period consistently exhibits the highest average wind speeds, regardless of the year under consideration. This pattern underscores the seasonal variability of wind energy potential in the region. Among the analysed sites, B2 emerges as a standout location, demonstrating the highest average wind speed during the winter months, making it a particularly promising site for wind energy development.

Wind conditions over marine and coastal areas are generally characterized by reduced surface roughness and lower mechanical friction, contributing to more stable and favourable wind profiles compared to inland regions. In the context of the present study, which focuses on the Romanian sector of the Black Sea, wind characteristics observed near the shoreline provide relevant insights into the local wind energy potential. While broader offshore assessments may reveal additional advantages related to wind stability and intensity, such aspects fall outside the scope of the current analysis. Therefore, the findings presented here pertain strictly to the nearshore coastal zone and highlight the importance of localized measurements in evaluating wind energy resources.

For optimal energy production, the selection of sites at higher elevations, particularly offshore, is clearly advantageous. Elevated offshore sites not only provide stronger and more consistent winds but also align more effectively with the operational needs of modern wind turbine technologies. These findings emphasize the necessity of thoroughly understanding the wind energy profile across different environmental conditions and at various heights. Such insights are vital for optimizing turbine placement, ensuring operational efficiency, and achieving the highest possible energy output. By carefully selecting locations with optimal wind conditions and aligning turbine technologies to these environments, the potential for renewable energy production can be significantly enhanced.

Moreover, the assessment of wind energy potential in the coastal and offshore areas of the Black Sea contributes meaningfully to global efforts to combat climate change. By maximizing the use of clean, renewable energy sources like wind, such studies support both the reduction of fossil fuel dependence and the transition toward a more sustainable and environmentally friendly energy landscape. This research represents a foundational step in identifying and harnessing the offshore wind energy potential of the Black Sea region, paving the way for impactful and long-term sustainable energy solutions.

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