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An overview of the renewable energy potential in the coastal environment of the Black Sea

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Abstract. Nowadays the effects of the climate change on the environment and on the quality of our life become more and more obvious. Various studies pointed out the necessity to limit the global temperature increase below 1.5°C compared with pre-industrial levels. It is well known that a large part of greenhouse gas emissions is generated by the production of electricity and heat using fossil fuels. For this reason, an obvious measure to avoid the impacts of climate change is the utilisation of clean sources of energy to produce electricity. In the marine environment, there are various sources of renewable energy, and the exploitation of offshore wind energy is a successful example. The evaluations regarding the wind power potential in the Black Sea indicate that there are areas where the exploitation of wind energy would be effective, such as the Romanian nearshore. Also, the use of hybrid systems could make efficient also the exploitation of the wave energy if we take into account the high potential of certain seasons. Considering the above mentioned aspects, an analysis of the energy potential of the wind and waves in the Black Sea is made in this study based on some existing works, as well as on recent results. Aspects regarding the effect of the climate change on these resources in the future will also be discussed, under various scenarios, such as RCP4.5 or RCP8.5. These results are of interest to various stakeholders interested in investing in the exploitation of the renewable resources existing in the Black Sea and also for coastal protection.

Keywords: Black Sea, marine environment, renewable energy, climate change.

1. Introduction

The effects of climate change on the environment and weather conditions are currently more and more evident and have a great impact on the quality of our life. This indicates that the results of various studies pointing out the necessity to limit

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the global temperature increase below 1.5°C compared with pre-industrial levels must be taken into account. On the other hand, it is well known that a large part of greenhouse gas emissions is generated by the production of electricity and heat using fossil fuels. For this reason, an obvious measure to avoid the impacts of climate change is the utilisation of clean sources of energy to produce electricity. The recent global energy crisis has shown us the urgency of accelerating the transition to clean energy [1]. Of course, renewable energy has an essential role in this way, and the measures established by the European Green Deal will help the European Union countries to reduce greenhouse gas emissions [2].

In the marine environment, there are various sources of renewable energy and the exploitation of offshore wind energy is a successful example. For this reason, their potential has been intensively evaluated, from global [3, 4] to regional [5,6] and local scales [7], in order to find the most promising areas for wind energy exploitation. Sustained efforts are also made to improve the existing technologies or to find new ones, to increase the efficiency of the devices [8].

Another source of renewable energy found in the marine environment is wave energy, but its exploitation is not as advanced as in the case of offshore wind exploitation. However, in recent years, considering the high potential of this renewable energy source [9], considerable efforts are being made to improve the efficiency of wave energy converters (WECs), [10,11]. The implementation of some new wave farms near the wind farms already deployed is a viable option from several points of view, such as reducing the variability of renewable energy and the costs of implementing the energy transport network, as well as increasing the energy production in a certain area [12].

For the countries bordering the Black Sea, the proximity of this marine environment can bring an important advantage regarding accessibility to renewable energy. The assessments of the offshore wind power potential in the Black Sea indicate that there are areas where the exploitation of wind energy would be effective, such as the Romanian nearshore [13,14]. Regarding the potential of wave power in the Black Sea, various studies have also been carried out [15,16]. The use of hybrid systems could also make the exploitation of wave energy efficient if we take into account the high potential of certain seasons [17,18].

Taking into consideration the above mentioned aspects, an analysis of the energy potential of the wind and waves in the Black Sea is presented in this study based on some existing works, as well as on recent results. Aspects regarding the effect of climate change on the wind and wave power in the future are also discussed, under various Representative Concentration Pathways (RCPs) scenarios, such as RCP4.5 or RCP8.5.

The idea of developing this study appeared due to the increased interest in implementing some renewable energy exploitation projects in the Black Sea, especially for wind farms. The first step is made by the BLOW project [19], with support from the European Commission’s Horizon Europe research, which aims to harness the offshore wind energy potential in the western Black Sea, more precisely in the Bulgarian offshore area. The objective of this project is to demonstrate the competitiveness of floating offshore wind installed in this region.

The results included in this study represent an overview of the renewable energy potential in the coastal environment of the Black Sea, that could be of interest to various stakeholders interested in investing in the exploitation of these resources. Implementing such wind or/and wave farms represents also a solution for coastal protection [20,21].

2. Methods and materials

As previously mentioned, investments in renewable energy (wind and/or wave farms) require a previous evaluation of the resources in the target area to estimate the efficiency of the system. The target area of this study is the Black Sea basin characterized by a medium to high potential in certain areas regarding wind power, while the wave power presents a lower potential that is in general affected by the seasonal aspect. However, using appropriate devices, the Black Sea environment can be a source of efficient energy.

The wind power in a location can be evaluated based on the wind speed simulated by numerical models and provided by various databases, or using measurements. The most well-known and used databases, which provide information on global wind speed, are ERA5 (the abbreviation of European Center for Medium-RangeWeather Forecasts - ECMWF RE-analysis fifth generation, [22]) and NCEP-CFSR (U.S. National Centers for Environmental Prediction, Climate Forecast System Reanalysis, [23]).

The advantage in the case of numerical simulations is that the available information covers extended areas. Usually, the values of the wind speed components (u and v) are provided by the numerical models at the reference height of 10 m above sea level, but the wind turbines are operating at higher heights. For this reason, methods to extrapolate the wind speed from a known height to the wind turbine hub height are often used in offshore wind farm designs. Considering that the wind speed increases roughly logarithmical with the height in the statically-neutral surface layer, the following relationship can be applied [24]:

$$U_z = U_{z\,ref}\,\frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_{ref}}{z_0}\right)}, \tag{1}$$

where U_z represents the wind speed value at the operational hub height z, U_{zref} is the wind speed corresponding to the reference height z_{ref} above sea level and z_0 represents the surface roughness length (usually the value considered for offshore wind is 0.0002 m).

The energetic capacity of the wind is provided by the wind power density (P_w in W/m^2), calculated with the following equation:

$$P_w = \frac{1}{2}\rho_{air}(U_z)^3. \tag{2}$$

where ρ_{air} is the air density (an average value of 1.225 kg·m^{-3} is considered).

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Under a World Bank Group (WBG) initiative on offshore wind, funded and led by the Energy Sector Management Assistance Program (ESMAP, https://www.esmap.org/esmap_offshore-wind), a global map of offshore wind technical potential was provided, including the Black Sea area. Offshore wind technical potential was estimated for the Black Sea area within 200km of the shoreline using the amount of generation capacity that could be technically feasible, considering only wind speed and water depth (without other technical, environmental, social, or economic constraints). The wind speeds with a 250m spatial resolution were provided by Global Wind Atlas, a free database of the latest input datasets and modelling methodologies. A very important aspect in choosing the type of turbine that can be installed in a location is the water depth, and this information is indicated in Figure 1. For the Black Sea area, the mean wind speed is illustrated in Figure 1. The offshore wind technical potential in the Black Sea was evaluated to be around 269 GW for fixed turbines and around 166 GW for floating turbines.

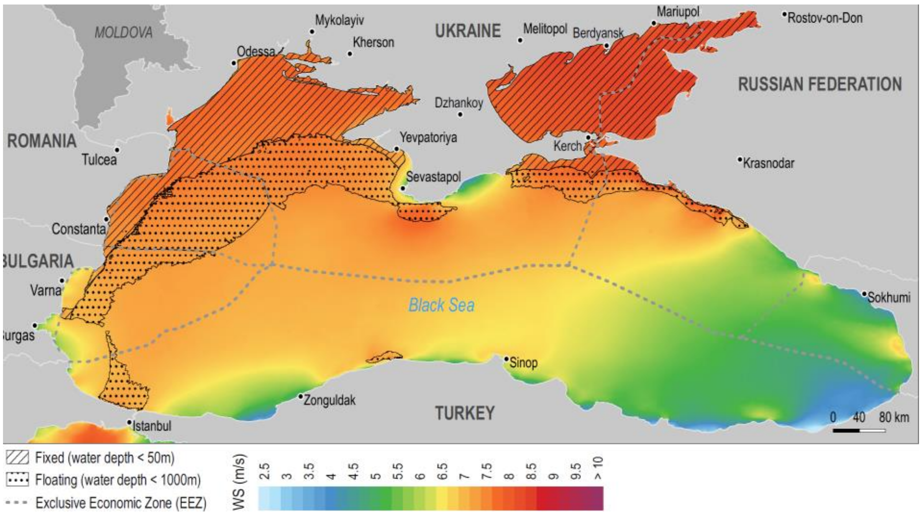

Fig. 1. Map of the mean wind speed in the Black Sea, [25].

As in the case of wind power, the evaluation of the wave power resource (WP) in deep water, defined as the amount of wave energy flux per unit length of the wave front (expressed in kW/m), can be made based on the main wave parameters provided by measurements or simulation, and using the following relationship, [26]:

$$WP = \frac{\rho g^2}{64\pi} H_s^2 \, T_e \qquad (3)$$

where H_s (m) is the significant wave height, T_e (s) is the wave energy period, ρ = 1025 kg/m3 is the density of the seawater, and g (m/s) is the gravitational acceleration.

Various databases, of which ERA5 is the most widely used, provide reliable information on wave parameters at a global scale. Based on them, evaluations of wave power can be made all over the world, as presented in Figure 2. However, these simulations being carried out with a rather low resolution, they cannot accurately indicate all the changes induced by the local bathymetry on the wave conditions. For this reason, in order to have a more accurate evaluation of the wave conditions in a target area, simulations using high-resolution bathymetry are necessary. Such simulations are performed with wave models such as the SWAN (Simulating WAves Nearshore, [28]) model.

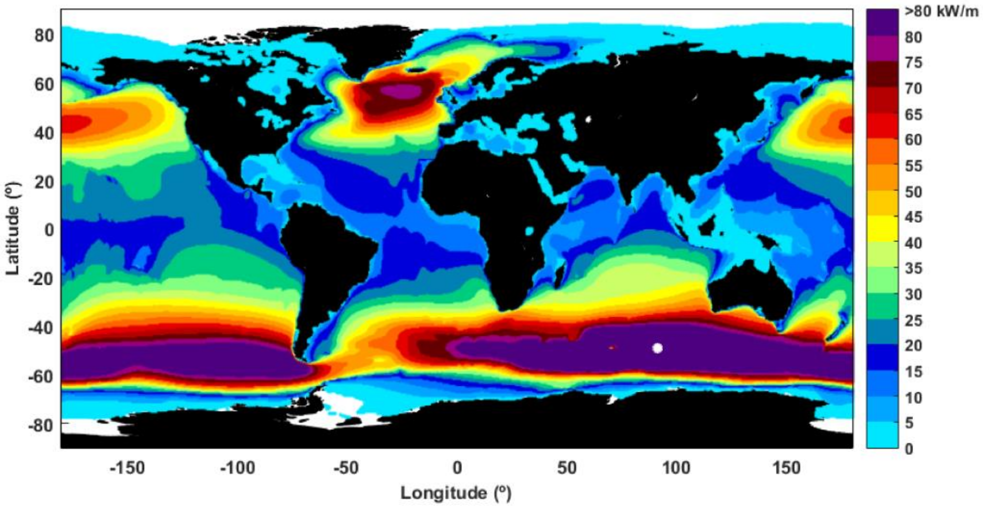

Fig. 2. Mean wave power over the 30-year time interval considered (1989–2018 based on data from ERA5, [27].

Wave models like SWAN provide various wave parameters in each grid node of the computational domain, and some of them are the transport components, denoted also as wave power. The energy transport components are computed based on the next relationships:

$$\begin{aligned} Etr_x &= \rho g \iint c_x E(\sigma,\theta) d\sigma d\theta \\ Etr_y &= \rho g \iint c_y E(\sigma,\theta) d\sigma d\theta \end{aligned} \tag{4}$$

where $E(\sigma,\theta)$ is the directional wave energy density spectrum, x and y are the grid coordinate system (for the spherical coordinates x-axis corresponds to longitude and y-axis to latitude), and c_x, c_y are the propagation velocities of wave energy in the geographical space (absolute group velocity components).

The absolute value of the wave power is computed as:

$$Etr = \sqrt{Etr_x^2 + Etr_y^2}. \tag{5}$$

To have a perspective of how the renewable resources available in the Black Sea, namely wind and wave power, will evolve under the action of climate change, studies at the regional level were carried out. Aspects regarding the effect of climate change on future wind power were analysed in various studies, using in general the wind fields provided by Regional Climate Models (RCMs) under various scenarios, such

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as RCP4.5 or RCP8.5. These high-resolution wind fields (EUR-11, ~12.5km) at 10 m above the sea level are freely distributed through EURO-CORDEX database and cover the entire Europe and also the Black Sea basin [29].

3. Results

In recent years, various studies have been carried out and their results were published in prestigious journals in the field. In this section, a review of the most important results is made and based on them, an analysis of the wind and wave power potential of the Black Sea is carried out.

3.1 Wind energy resource characterization

Although the potential of wind power in the Black Sea is lower than that found for example in the North Sea, it still has characteristics that can make it efficient in exploitation. These aspects were analysed in various studies included in Table 1. Some indications regarding the period covered by the data as well as the origin of the data used in the analysis are also included in Table 1.

As mentioned before, NCEP-CFSR provides wind speeds at 10 m above sea level, and due to the quality of these data, they are widely used to assess wind power over extended periods. Such a study was carried out for the Black Sea basin [15], using data for a period of 20 years (1997–2016). The mean wind power density at a height of 80 m was evaluated and its spatial distribution is presented in Figure 3.

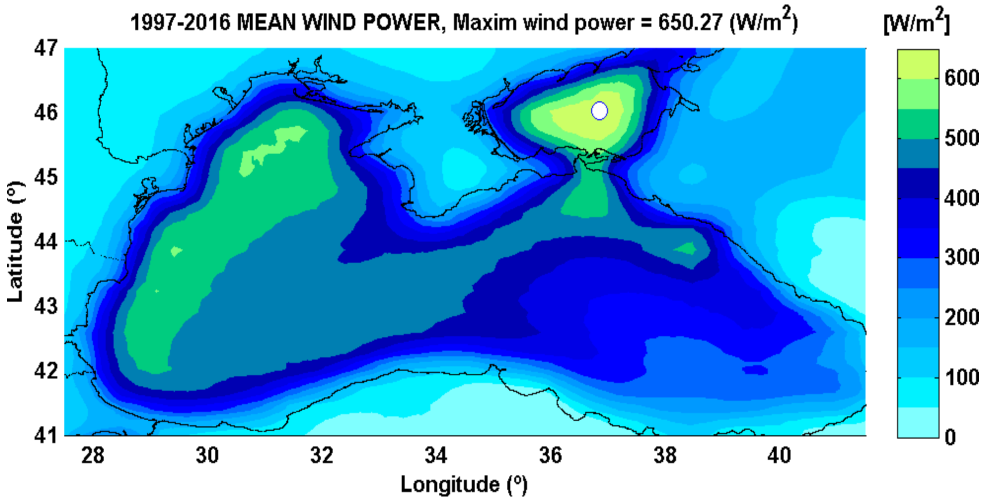

Fig. 3. The spatial distribution of the mean wind power density for the period 1997-2016, [15].

Table 1. Studies regarding the evaluation of the wind power potential in the Black Sea, specifying the periods and characteristics of the data used in the analysis.

Authors	**Period**	**Wind field**	**Analysis**
Rusu, et al., 2018, [15].	1997–2016	NCEP-CFSR	Wind power at 80m
Rusu, 2019, [30].	1987–2016	NCEP-CFSR	Wind power at 80m on the western side of the Black Sea
Onea and Rusu, 2019, [13].	1998-2017.	ERA-Interim	Wind power at 80m
Davy, et al., 2018, [31].	1979–2004 2021-2050 2060-2090	Historical period: ERA-Interim and RCA4. Future period: RCA4 under RCP4.5 and RCP8.5 scenarios.	Wind power at 120m
Rusu, 2019, [32].	1976–2005 2021-2050	Historical period: RCA4 Future period: RCA4, under RCP4.5, RCP8.5 scenarios	Wind power at 80m
Islek and Yuksel, 2022, [33].	1970-2005 2021-2100	Historical period: RCA4, ERA5, NCEP-CFSR for historical period Future period: RCA4 under RCP4.5 and RCP8.5 scenarios	Wind power at 100m
Diaconita, et al., 2021, [14].	2021-2050 2071-2100.	RCA4 under RCP4.5 scenario	Wind power at 90m in six locations on the western side of the Black Sea

From Figure 3 it can be noticed that the highest values of the mean wind power are over the Azov Sea (with a maximum value of around 650 W/m^2) and on the western side of the Black Sea (extended zone with values of around 550 W/m^2). It is well known that the weather in this region presents seasonal variability and, as expected, this is present also in the wind power potential (see Figure 4). For seasonal analysis, the following partitions were considered: winter - DJF (December-January-February), spring - MAM (March-April-May), summer - JJA (June-July-August) and autumn - SON (September-October-November).

From Figure 1 it can be seen that these areas with high energy potential are suitable for the deployment of the wind farms because they are also characterised by water depths suitable for such activities. Even in the summer season, characterized by the lowest mean values of the wind power density, in the above-mentioned areas mean values of about 300 W/m^2 can be found.

The previous study was extended to a period of 30 years (1987-2016), with a focus on the western area of the Black Sea basin and along the Romanian coast, [30]. In Figure 5 the mean wind power density fields at 80 m for the western side of the Black Sea and along the Romanian coastal environment are presented. The wind power distribution illustrated in the maps from Figure 5, indicates quite high mean values (over 400 W/m^2) near the coast, and for this reason, these target areas (namely the western side of the basin and Romanian nearshore) can be suitable for efficient exploitation of the wind resources.

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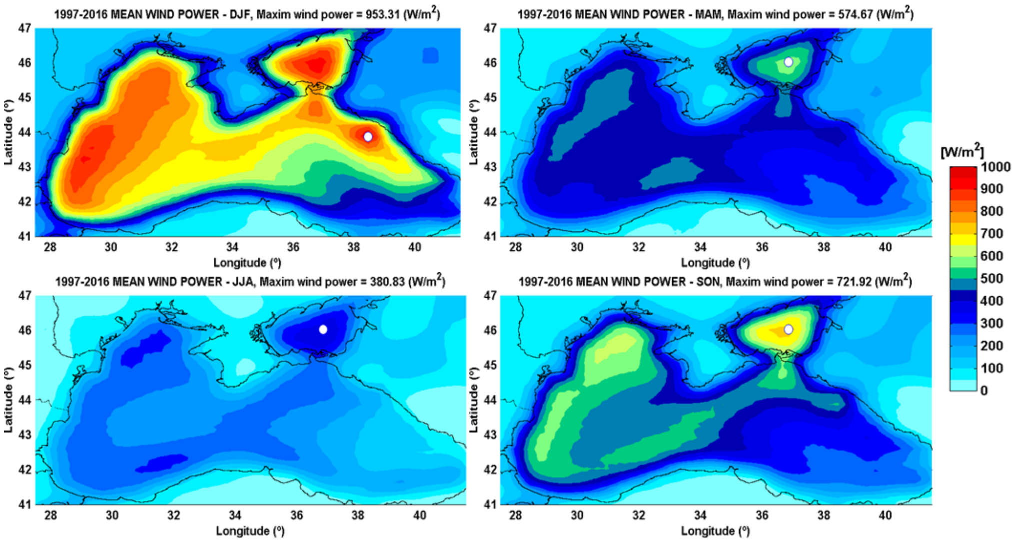

Fig. 4. The spatial distribution of the mean wind power density at 80 m for the period 1997-2016 for each season: winter (DJF), spring (MAM), summer (JJA), autumn (SON), [15].

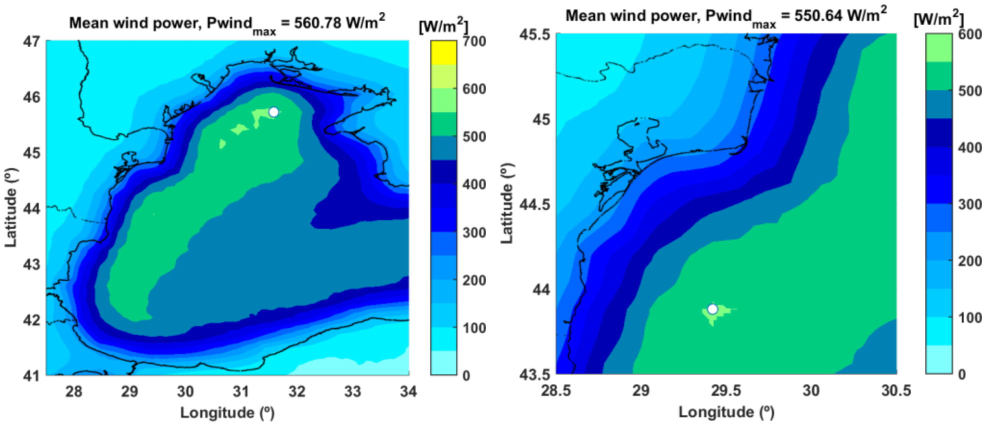

Fig. 5. The spatial distributions of the mean wind power density fields at 80 m corresponding to the 30-year period 1987–2016 for: the western side of the Black Sea (left panel) and the Romanian coastal environment (right panel), [30].

A more in-depth study of the wind energy potential in the Romanian coastal environment was carried out taking into account the wind speeds provided by ERA-Interim [13]. In that study, in addition to the depth of the water, the distance from the shore was also taken into account. They clearly showed that the potential of the wind resources increases from the coast to the offshore zone (until 20 km) by about 55.85%.

In recent years, taking into account the obvious climate changes of the weather, increased attention has been directed to the evaluation of the impact of these changes on renewable resources. These types of evaluations are important to highlight whether the investment in a certain area is sustainable in the future. The conclusions of the study developed by Davy et al. [31], where an ensemble of RCA4 products was used, indicate no negative influence of climate change on wind resources in the Black Sea region under either the RCP4.5 or RCP8.5 scenarios.

For the near future, another study indicates moderate enhancements in the average wind power under RCP4.5 and RCP8.5 scenarios, [32]. The study pointed out that more worrying is the increase in the maximum values of wind speed, and in some cases, this does not necessarily indicate that the turbines will produce more energy considering their cut-out limit (in general about 25 m/s). The results obtained for both scenarios indicate a movement of the location of the maximum values to the western side of the Black Sea, although the enhancement in terms of the average values is not very high (see Figure 6).

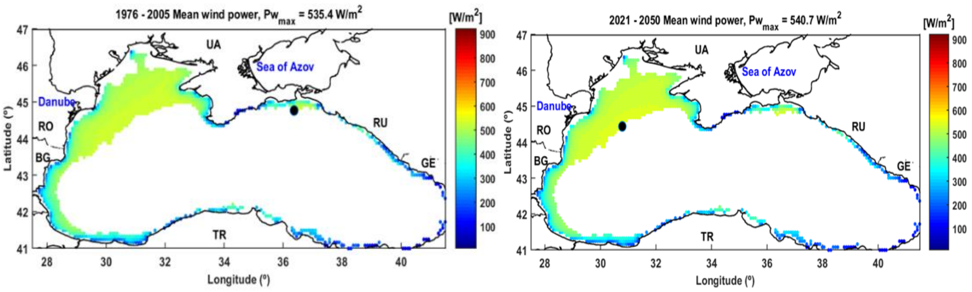

Fig. 6. Average values of the wind power at 80m height (P_w) corresponding to the historical period 1976-2005 (left side) and for the near future period 2021-2050, under RCP4.5 scenario, [32].

Another recent study was focused on evaluating the projected changes in the future wind power potential in the Black Sea, [33]. To find possible stable locations for wind farms was one of the objectives, and their results show that until the end of this century the western Black Sea, and especially the southwestern basin, will continue to be characterized by great wind power potential and with lower variability than other parts of the sea. Having an approach focused on the local impact of climate change under the RCP4.5 scenario, Diaconita et al. [14] consider in their analysis two periods of 30 years each from the future (2021-2050 and 2071-2100) and six reference locations from the western part of the Black Sea basin. The results indicate the same trend observed in previous studies regarding wind energy in the future. The study also analysed the efficiency of five types of turbines, resulting in only four of them being efficient in the conditions of the target locations.

3.2 Wave energy resource characterization

In the marine environment, another source of renewable energy is represented by wave energy that can be captured using specific devices, namely wave energy converters (WECs). Compared to the coastal areas of the oceans where the swell is present, the sea state conditions in the Black Sea do not present characteristics that could be considered as having high wave energy resources. However, by using specific devices for seas with milder conditions or hybrid devices, the exploitation of wave energy could be profitable. An important aspect, as in the case of wind energy, it is necessary to identify the so-called hot-spot areas.

In Table 2, a summary of the studies carried out regarding the wave power potential in the Black Sea basin, both in the recent past (hindcast simulations) and in the future (projections under various scenarios), has been made. In addition to the information specifying the period of the study, information about the model used in the simulations, the spatial resolution of the wave data and the wind fields used to force the wave model are included. Some results regarding the spatial distribution of the mean wave power in the Black Sea are presented in Figures 7 and 8.

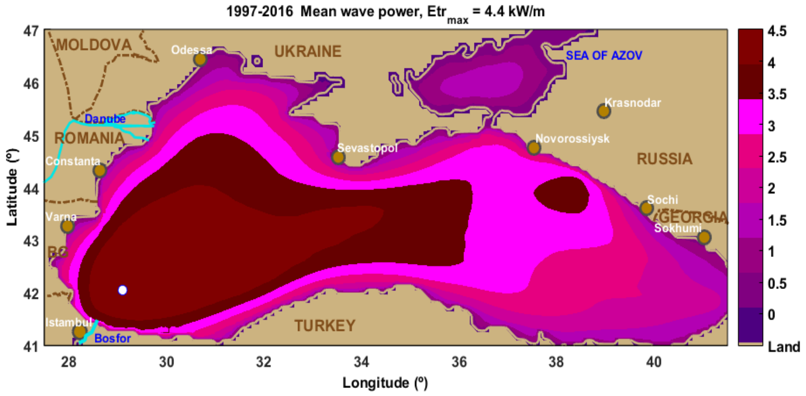

Fig. 7. The spatial distribution of the mean wave power for the period 1997-2016, [15].

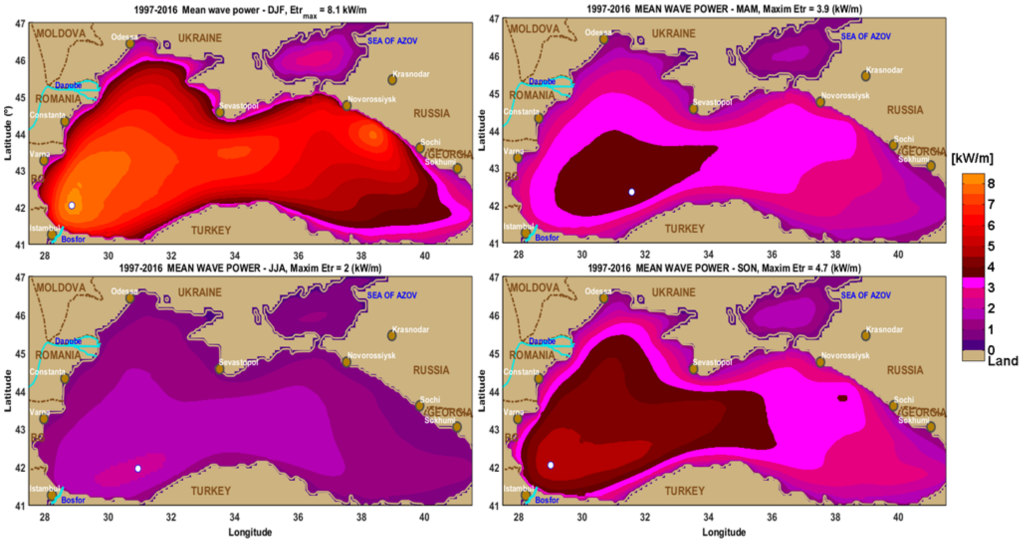

Fig. 8. The spatial distribution of the mean wave power for the period 1997-2016 for each season: winter (DJF), spring (MAM), summer (JJA), autumn (SON), [15].

Table 2. Studies regarding the evaluation of the wave power potential in the Black Sea, specifying the periods and characteristics of the data used in the analysis.

Authors	**Period**	**Wind**	**Wave**	**Analysis**
Akpınar and Kömürcü, 2012, [34].	1995–2009	ERA-Interim	SWAN hindcast – regular grid, resolution of 0.0167°	Wave power
Rusu, 2015, [35].	1999-2013	NCEP-CFSR	SWAN hindcast with data assimilation - regular grid resolution of 0.08°	Wave power
Akpınar, et al., 2017, [16].	1979–2009	NCEP-CFSR	SWAN hindcast – regular grid resolution of 0.067°	Wave power
Rusu, 2018, [36].	1999-2013	NCEP-CFSR	SWAN hindcast - high-resolution areas on the Romanian coast	Wave power
Saprykina and Kuznetsov, 2018, [37].	1960–2011	-	Voluntary Observing Ship Program measurements	Wave power
Rusu, et al., 2018, [15].	1997–2016	NCEP-CFSR	SWAN hindcast with data assimilation - regular grid resolution of 0.08°	Wave power
Bingölbali, et al., 2020, [38].	1979–2009	NCEP-CFSR	SWAN hindcast, high resolution areas in the south west coasts of the Black Sea	Wave power
Islek and Yuksel, 2021, [39].	1979-2018	NCEP, Era-interim	SWAN hindcast - regular grid resolution of 0.05°	Wave power
Rusu, 2019, [30].	1987–2016	NCEP-CFSR	SWAN hindcast with data assimilation - regular grid resolution of 0.08°	Wave power on western side of the Black Sea
Rusu, 2019, [40].	2021-2050	RCA4 under RCP4.5, RCP8.5	SWAN hindcast - regular grid resolution of 0.08°	Wave power
Rusu, 2020, [41].	2021-2050, 2071-2100	RCA4 under RCP4.5, RCP8.5 scenarios	SWAN - regular grid resolution of 0.08°	Wave power
Aydoğan, et al., 2021, [42].	1979-2005 2040-2100.	Downscaled wind fields for RCP 4.5 and RCP 8.5 scenarios.	SWAN - regular grid resolution of 0.125°	Wave power

In some of the studies like [34,38,39,42], the spatial distribution of the wave power is analysed, but for its computation, the same equation valid for deep water is applied, although WECs are generally installed in shallow water. However, the wave power can be calculated considering the capabilities of the SWAN model to compute the wave energy transport components (see equations 4 and 5), [15,30,35,36,40,41]. The long-term measurements of the wave parameters can also be used for wave power assessment, [37].

As expected, the highest values of the mean wave power are found in wintertime (about of 8 kW/m). Sometimes, over extended areas, the wave power in wintertime is about twice that of those computed for the entire period (see Figures 7 and 8). In general, like in the case of wind power, the western side of the basin presents a more significant wave power potential. The greatest mean wave power fields are found in the southwestern basin, and the mean wave power potential in this area and also in the Romanian coast are presented in Figure 9.

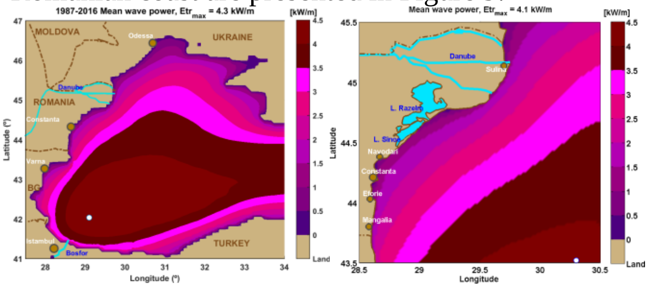

Fig. 9. The spatial distributions of the mean wave power corresponding to the 30-year period 1987–2016 for: the western side of the Black Sea (left panel) and the Romanian nearshore (right panel), [30].

4. Conclusions

In this study, an overview of the wind and wave power potential in the coastal environment of the Black Sea was made, in order to provide a perspective on the possibilities of extracting efficient the energy from these renewable resources. Through several results presented here and additional information included, the objective was accomplished, and the potential investors interested in developing projects to extract wind and wave energy from the Black Sea can find useful information.

The spatial distribution maps of the mean wind and wave power indicate the western side of the Black Sea basin as being characterized by higher wind and wave power potential. On the other hand, the Azov Sea has a high potential for efficient wind power extraction.

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