Evaluation of the Wind Energy Resources in the Black Sea Area

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Abstract: - The objective of the present work is to give a general overview of the spatial and seasonal wind conditions in the Black Sea. Compared to onshore areas, the offshore wind patterns are difficult to be evaluated because of the limited in-situ measurements. This is because alternative sources of data need to be considered in such case. In the current analysis, a complete assessment of the Black Sea wind climate is made by considering 13 years (1999-2011) of data coming from various weather stations, Topex/Poseidon altimeter missions and two reanalysis wind models. The results indicate that the measurements and data from numerical models indicate in general similar spatial and seasonal evolutions of the wind conditions, with higher energetic characteristics during the winter time, especially in the western area of the basin. Moreover, from the analysis of the satellite data resulted that in wintertime the annual energy production of the western part of the sea is similar to those from several offshore locations where wind farms are known to operate.

Key-Words: - wind resolution, satellite data, statistical parameters, Black Sea, wind turbine

1 Introduction

As far as the non-conventional energy sources developed globally are concerned, wind energy clearly stands out with a high competitive industry and a significant technological growth, which, during the last years (1995-2011), has registered a 15.6% increase on a European scale. At the end of 2011, the total installed wind capacity in Europe was estimated to be around 96000 MW, with Germany sharing almost 30% of this capacity followed by Spain with 22% [1].

A mention should be made in relationship with the fact that the idea of using wind energy is not new, but it is only during the last years that this conversion was made on an industrial scale by using wind turbines to extract energy from the air flow. A major contribution to the current expansion of this industry consists in efficiently harnessing the wind power by using multiple wind turbines, which are designed to work in wind farms [2].

These days, onshore wind energy is widely developed in Europe especially in rural and industrial regions where large areas are available. From a prospective view of this industry, the offshore locations will turn out to play an important role due both to the limited areas of land available and to the constant increase in wind turbine capacity. It is an established fact that offshore wind farms successfully operate now in the North Sea (Horns Rev project) and in the Baltic Sea (Rødsand I project). In addition, similar projects are likely to be developed in the Mediterranean and the Black Sea [3].

As compared to the onshore area, the offshore locations are considered to have a higher wind climate, around 6-8 m/s (especially in winter), with a constant evolution due to the smooth sea surface. Other advantages are represented by large marine areas, suitable for wind farm development, an increase in wind speed depending on the distance from the coastline, and less turbulence which allow the turbine to extract more energy than a similar one in an onshore area [4].

As regards the marine areas, another aspect is that they are suitable to develop hybrid energy farms by using both wind and wave resources. This may be a solution to increase the energy output by reducing the variability of the natural resources and at the same time by reducing the investments needed to develop a single wind or wave farm. Combined use of wind and wave energy resources has the potential to reduce the power output variability that may occur due to intermittent nature of the resources and also to increase the energy output by using the same location [5, 6].

The Black Sea is an enclosed basin, with an elliptical shape, demarcated by the latitude 40º-46ºN and the longitude 27º-41ºE. As compared to other European seas, it is on the third place, after the Mediterranean and the North Sea, with an area of 411540 km^2, 555000 km^3 for its volume, 1315 and 2258m for the mean and maximum depths, respectively. The Black Sea coastlines are about as long as 3400 km, being divided between: Bulgaria and Romania to the west; Georgia, Russia and Ukraine to the north and east; and Turkey to the south. The Black Sea bathymetry is characterised by a narrow shelf except for the north-west area, and seems to be surrounded by mountains, like the Caucasus Mountains to the east and Pontic Mountains to the south.

Short-term climatic pattern in the Black Sea region is influenced by the North Atlantic Oscillation (NAO) and El Nino-Southern Oscillation (ENSO) which create conditions for cyclone formation and cold air-mass transport over the warm sea [7, 8]. These two atmospheric systems also reduce the strength of polar air masses coming from the northern areas in winter. The joint evolutions of NAO and ENSO systems influence the storm occurrence over the Mediterranean region being directly involved in the cyclone variability over the Black Sea basin, which is much higher in winter [9].

Previous studies of the wind conditions indicate the western part of the sea to be more energetic with an average wind speed of 5 m/s for the summer time and 8 m/s recorded during the winter season [10]. It is considered that the wind conditions in the western area of the sea register high seasonal variations while the eastern side is characterized by much stable conditions [11]. In the winter time, severe storm conditions occur mostly in the western area under the influence of the east and northeast winds. During a storm event, wind speed can easily exceed 40 m/s in open sea and can reach 25 m/s over the nearshore areas.

Regarding the wave resources, the region has a higher energy potential especially in the western sector [12-16]. Besides, in the countries located around the basin there is an increasing interest in the development of various wave energy systems [17].

2 Analysis of wind measurements over the Black Sea basin

2.1 In situ measurements

The meteorological stations considered for in situ measurements are presented in Figure 1 (denoted from A1 to A11) with the corresponding data sets divided in two parts. The first set contains representative wind measurements for the Romanian area and were recorded at: Mangalia station (point A1) and Gloria drilling platform (point A2). The A1 weather station is located nearby Mangalia dam (at 8m water depth) with data available for a seven-year period (January 2003 - December 2009) while the second station is located in an offshore area (30km eastward from Portita Inlet) with data available for the same time period.

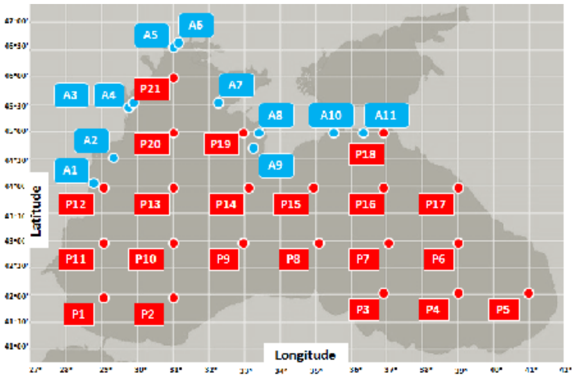

Fig. 1. Map of the Black Sea illustrating the locations of the study sites

For the A1 location the wind measurements are available at a 10m height above the mean sea level while for the A2 location they are recorded at a 36m height. To evaluate the wind speed (*V*) at a 10m, the measurements from the location A2, were recompiled by using the logarithmic law [18]:

$$V = V_{ref}\frac{\ln(z/z_0)}{\ln(z_{ref}/z_0)} \qquad (1)$$

where: z_0 = 0.2 mm, is the roughness factor of a calm sea surface [19] while, z_{ref} and V_{ref} are the initial height and the measured wind speed, respectively.

The second data set is provided by 9 weather stations (denoted from A3 to A11) which are representative for the Ukrainian coastal areas. These wind measurements cover a ten-year period (January 1999 - December 2009) and were recorded at 10m height above the mean sea level.

For this study, the analysis is mainly focused on total and winter time (October-March) which is considered to be more energetic.

In Figure 2 is presented the monthly evolution of the averaged wind speed during January 1999 – December 2009 illustrated by the meteorological data. The presence of the winter season is more clearly highlighted in the location A2 with a maximum wind speed of 8.5m/s registered in

December, while during the summer time a maximum value of 5.8 m/s was recorded in July.

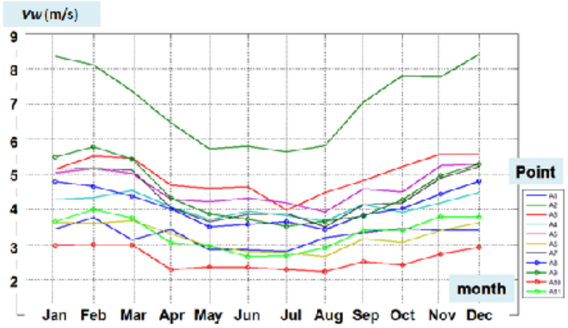

Fig. 2. Monthly averaged values of the wind speed (m/s) for the North –West sector of the Black Sea based on meteorological data.

Also, the locations A3 and A5 indicate wind conditions with a minimum value of 4m/s encountered during the summer season while during the winter time the wind conditions higher than 5m/s are more frequent. During the winter time the location A9 indicates the occurence of wind speed higher than 5m/s (especially during January, February and March).

The locations A1, A6, A10 and A11 do not register wind conditions over 4m/s (not even during the winter season). The point A10 can be considered to be the less energetic with a maximum wind speed of 3m/s recorded during the winter season.

One of the reasons for what the location A2 register much higher wind conditions comes from the fact that this point is located in an offshore area where wind is more powerful while for the rest of the points (located in shallow water areas), the general air circulation is influenced by the interaction with the land.

To give a practical overview of how the local wind conditions can contribute to the power production, the Vestas V90-3.0 MW [20] wind turbine was considered as a reference. Since this turbine is rated to work at 80m height over the sea, the wind measurements where adjusted to this level by using the logarithmic law (presented in Equation 1). The theoretical extractable power from the air flow is obtained by using the following relationship:

$$P_{avail} = \frac{1}{2} \rho A V^3 C_p \qquad (2)$$

where ρ = 1.225kg/m^3 is the standard air density, A represents the swept area computed from the length of the turbine blades, V is the wind speed (at 80m height) and Cp is a power coefficient based on the Betz law [21].

In the analysis of the offshore wind turbine Vestas V90-3.0 MW (Vestas 3.0) the following assumptions are made:

a) The power output of the wind turbines was computed based on the power curve, where the wind data under/over the cut-in (3.5m/s) and cut-out (25m/s) speed were not taken into account. The wind data higher than the rated turbine speed are considered to be equal with this value, because over this level there will be no increase in the power output.

b) A power coefficient (Cp) of 45% is used to assess the performances of the wind turbine.

c) Following the work of Pimenta [18] the power output of the turbines was indicated in terms of *kW* and not *kWh* because this represents a more consistent way to identify the relations between wind speed and the performance of a selected wind turbine.

Figure 3 presents the mean power output of the Vestas 3.0 wind turbines based on meteorological observations for the time interval: January 1999 – December 2009. The location A2 appears to be the most energetic one with almost 2380kW, followed by the location A3 with 1520kW. The large difference between these two locations is mainly given by the fact that the power content in the air flow varies with the cube of the wind speed and for example by doubling the wind speed, an increase by a factor of eight will result for the turbine power output. The remaining locations, do not register power output higher than 1100kW, with the lowest value being reported in the location A10 (495kW).

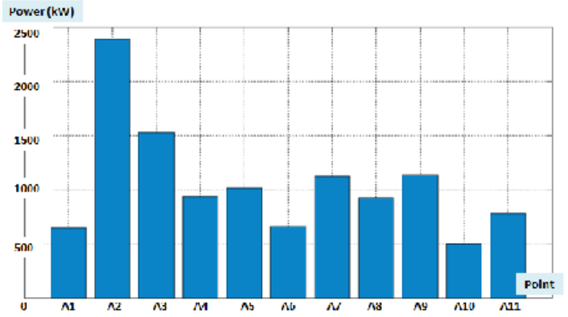

Fig. 3. Mean power output (kW) of the Vestas 3.0 wind turbine based on meteorological observations (interval January 1999-December 2009)

2.2 Remotely sensed data

The lack of an extended network for meteorological observations in the Black Sea can be compensated by considering satellite data which provide wind observations over the entire basin with a good spatial resolution. In 2001, AVISO started a multi-mission project which involved combining data from several inter-calibrated satellites (with the Topex/Poseidon altimeter mission as reference). For each of the satellite missions, the average over each cycle are processes and adjusted by a new parametric fit, developed in [22], to obtain consistent and homogeneous wind measurements at 10m height above the mean sea level with an accuracy of 2m/s. The main source of satellite data considered for the present work comes from AVISO web site (www.aviso.oceanobs.com) and is focused on the time interval December 2006 – March 2011. This data correspond to daily wind measurements averaged for square sectors with a length of 1°.

The locations considered for the satellite measurements consist of 21 reference points covering the entire basin of the sea with their position being also illustrated in Figure 1. They were denoted from P1 to P21 and are counted from West to East.

In Figure 4 is illustrated the monthly evolution of the mean wind speed by considering the satellite data for the time period: December 2006-March 2011. All the reference points indicate a similar seasonal evolution of the wind conditions with the months January and December being more energetic, while during the months May and June a much lower wind speed (*Vw* < 3.5 m/s) is encountered.

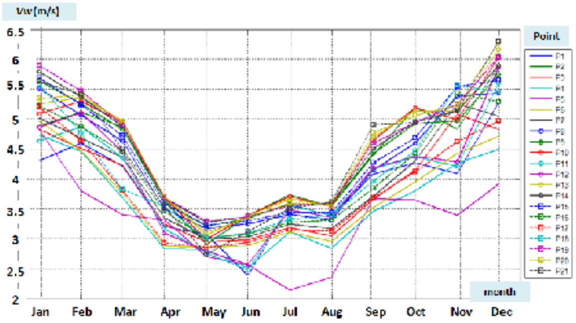

Fig. 4. Monthly averaged values of the wind speed (m/s) based on the satellite data (time interval: December 2006 – March 2011).

By considering the annual mean wind speed value, it can be noticed that the western part of the sea is more energetic, with the following locations being representatives: P19 (4.55m/s), P20 (4.53m/s), P13 and P14 (4.5m/s). For the eastern part of the sea, most of the locations register wind conditions under 4.2m/s with the lowest mean wind speed values reported at the locations P5 with 3.31m/s and P4 with 3.58m/s.

In Figure 5 is presented the spatial distribution of the power output based on the Vestas 3.0 characteristic and satellite data. For the western side of the sea, it is expected that a power output between 900-1000kW to be extracted from the offshore area.

For this region, the shalow water area indicates a much higher power output (with almost 50kW) but this increases in the power output is not due the fact that the local orography influences the air circulation, being associated more with the possibility that the satellite data could sometimes suffer from low accuracy due to interference effects when the track comes close to the shore.

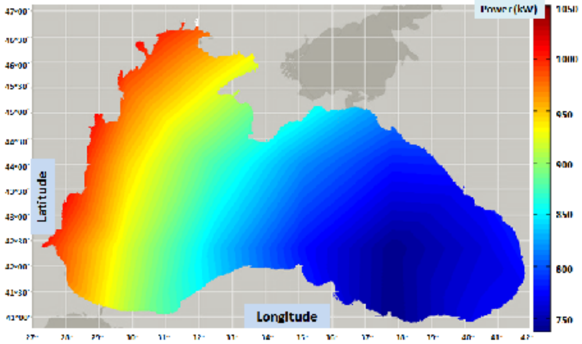

Fig. 5. Mean power output (kW) of the Vestas 3.0 wind turbine based on satellite data (time interval December 2006-March 2011)

For the central part of the basin, a power output of 850kW is probably to be obtained while for the eastern side of the sea an output of 750kW can be expected.

2.3 Reanalysis wind data provided by numerical models

To obtain a complete picture of the wind climate in the Black Sea basin two reanalysis data sets have been considered. The first one is ERA-40 from the European Centre for Medium-range Weather Forecasts (ECMWF) while the second one is provided by the National Centre for Environmental Prediction NCEP, [23]. Both models provide daily wind data at 10m height, reported to every 6 hours (00-06-12-18 UTC) that cover the time period: January 1999 - December 2007. The main difference between these two data sets is that ECMWF wind data are given with a spatial resolution of 1.875° while NCEP model data are available for a resolution of 1.5°. Both wind datasets provided by the models have been recompiled through a spatial interpolation onto a grid with the resolution 1°x1° to obtain identical grid points with that considered in the previous analysis with the satellite data. The reference points for the reanalysis data are denoted from P1 to P21.

In Figure 6, the monthly evolution of the mean wind speed conditions based on the ECMWF data is presented. As in the case of the satellite data, can be notice large variations between winter and summer season and also between the western and the eastern part of the sea.

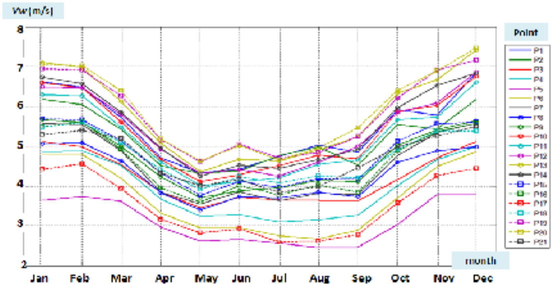

Fig. 6. Monthly averaged values of the wind speed (m/s) based on the ECMWF data (time period: January 1999 - December 2007).

The maximum mean wind speed is registered during December at the location P20 with 7.47m/s, followed by the location P13 with 7.41m/s. May can be considered the less energetic month with the locations P11, P12 and P21 registering a mean wind speed around 2.76m/s while the lowest value is reported in July by the location P5 with almost 2.14m/s.

Based on the annual mean wind speed values, it was noted that more energetic conditions occur more frequent in the western side of the sea with the points P13, P14, P19 and P20 registering values higher than 5.6m/s. A much lower value of 3.11m/s is registered by the location P5, which is followed by the location P17 with 3.5m/s.

Figure 7 ilustrates the monthly mean wind speed values based on the NCEP data. December is the most energetic month with the locations P13 and P14 registering wind speeds higher than 7.13m/s. During the summer season, the locations P13 and P14 are more energetic in April and September with mean wind speed values close to 4.8m/s.

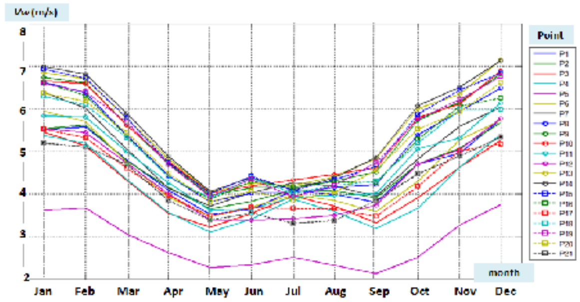

Fig. 7. Monthly averaged values of the wind speed (m/s) based on the NCEP data (time period: January 1999 - December 2007).

From all the locations, the point P5 registers much lower wind speed conditions which do not exceed 3.75m/s in the winter time and 2.5m/s during summer season.

The mean power output based on the Vestas 3.0 characteristics is presented in Figure 8. By considering the ECMWF data (Figure 8.a) it can be noticed that a maximum value of 1600kW is registered in the north-west part of the sea (in the offshore area) while for the east sector a power output of 900kW is indicated.

The NCEP data (Figure 8.b) indicate a much lower power output with a maximum 1400kW for the central part of the sea, 1100kW for the west sector and 900kW for the east area of the basin.

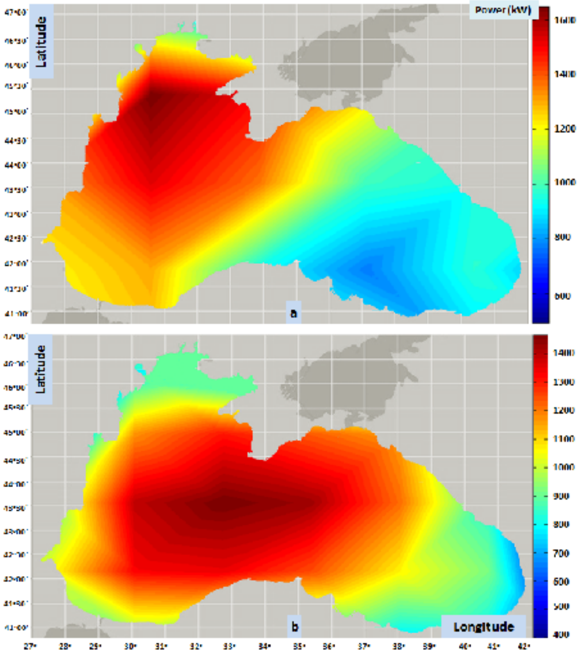

Fig. 8. Mean power output (kW) of the Vestas 3.0 wind turbine based on: a) ECMWF data, b) NCEP data. Time period: January 1999-December 2007.

3 Discussion of the Results

Since one of the purposes of the present study is to identify the most suitable areas for implementing wind farms in the Black Sea basin, it is useful to compare the severity of the regional wind conditions with the one from locations where offshore wind farms are known to operate.

From the previous results it was highlighted the fact that the western part of the sea is more energetic. As a consequence, only the locations A2 and P12 located in this area were considered for the next analysis. In Hasager et al. [24] some offshore wind farm projects which are currently developed in Europe are presented in detail. From these, a number of nine locations were considered for analysis. These are: Tunø Knob, Rødsand I, Anholt O, Lillgrund, Utgrunden II, Bockstigen, Breitling, Baltic Eagle and Aldergrund GAP.

The analysis is based on two years (January 2010-December 2011) of satellite data provided by AVISO, being focused on the evaluations of the Vestas 3.0 power output of the above considered points. Figure 9 presents this analysis in terms of the total time period and winter season, which was also noted to be more energetic for the Black Sea region.

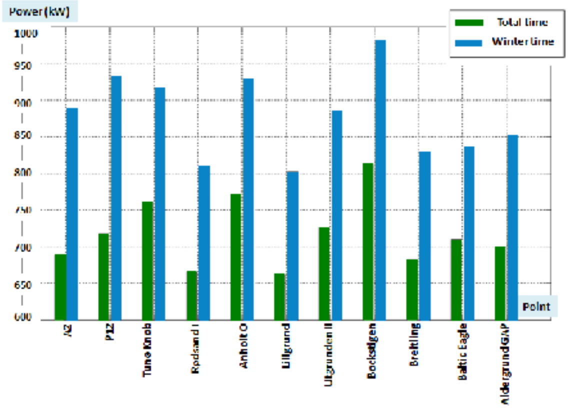

Fig. 9. Mean power output (kW) of the Vestas 3.0 wind turbine based on satellite data (time interval: January 2010-December 2011)

For the total time period the reference point A2 indicates a mean power out of 690kW while for the point P12 this is around 720kW. These values are higher than the one indicated by locations like: Rodsand I (665kW), where a 166MW wind farm operates since 2003; Lillgrund (660kW), where a 110MW wind farm capacity operates since 2007; and Breitling (685kW), where another wind capacity operates since 2008 with only one turbine installed (2.5MW).

For this period, the following offshore locations present higher values: Tunø Knob (760kW), with an installed wind capacity of 5MW; Anholt O (770kW), with a planed capacity of 200MW since 2012; and Bockstigen (815kW), where a 3MW wind farm operates since 1998.

During the winter time the power output of the point P12 registers almost 935kW, which is higher than the one reported at the offshore wind farm locations, except for the Bockstigen site where a maximum output of 980kW is registered. Also the location A2, with an output of 890kW, can be considered more energetic than locations like Rødsand I, with 810kW, Lillgrund, with 800kW, and Aldergrund GAP, with a power output of 850kW.

4 Conclusions

In the present work, the wind climate in the Black Sea area has been evaluated based on 13 years (1999 - 2011) of data coming from weather stations, satellite measurements and reanalysis wind models. A general assessment of the wind conditions is made by considering 21 grid points equally distributed along the Black Sea basin while a more detailed analysis is carried out for the western side of the basin using data in situ measured data from 11 in-situ stations.

The results coming from the meteorological dataset indicate an annual mean wind speed values in the range of 2-8.5m/s, with more energetic wind conditions encountered in the location A2.

From the analysis of the satellite data and of those provided by the numerical models resulted that more energetic wind conditions are registered during the winter season, especially in the western sector of the sea.

To give a more practical evaluation of the wind potential, the power curves and the characteristics of the Vestas 3.0 wind turbine have been used to express the local wind conditions in terms of theoretical power output (kW) at a 80m height.

The power outputs from the points A2 and P12 are similar or even higher than those registered in several offshore wind farm locations, especially during the winter time when the point P12 registers an output of almost 935kW.

Based on the results presented in this work, it may be concluded that the western sector of the Black Sea is a viable candidate to implement offshore wind farms projects which could diversify the regional energy portfolio.

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