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EVALUATION OF THE OFFSHORE WIND ENERGY POTENTIAL IN THE ROMANIAN COASTAL ENVIRONMENT OF THE BLACK SEA

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ABSTRACT

The present work is focused on the analysis of the offshore wind energy potential in the Romanian coastal areas at the Black Sea. A direct comparison of these conditions with those reported in similar sites, where wind parks are planned to be developed, is also performed. In order to cover large marine areas, the wind conditions are evaluated by considering the AVISO satellite measurements, which correspond to the time interval 2010-2015. This data set is completed by 15-year of reanalysis wind data (2000-2014) coming from the European Centre for Medium-Range Weather Forecasts. Since the turbine rotors operate at higher levels, the main wind parameters were translated to a 80 m height (above sea level), the results being defined in terms of spatial maps or statistical parameters. From the comparison with the offshore wind parks, it is possible to identify what type of project is more appropriate in terms of number of turbines, water depth or distance from the shore. Based on the direct comparisons carried out with the wind conditions of the sites located in the Northern, Baltic or Mediterranean seas, it was noticed that the local conditions seem to present similar values, while in some cases the energy potential is even more significant.

Keywords: *Romanian coastal environment, wind energy potential, nearshore-offshore, satellite measurements, reanalysis data*

INTRODUCTION

The renewable energy market is a dynamic environment, where changes and opportunities may occur every day. Wind industry can be considered one of the most interesting sectors, if we take into account that the wind resources are available on a global scale, the energy content in the air masses being more consistent in mountain or marine regions. Moreover, the success reported during the last decades in this field may be linked to the fact that most of the wind turbines are based on the Danish concept, which involves a rotor with three blades operating at 80 m height above the ground [1].

The progress registered by the European offshore wind industry is obvious, starting with 5 MW in 1993, reaching 532 MW in 2003 and a cumulative capacity of almost 50000 MW at the end of 2012. One of the main trends is to develop projects in deep water areas which involve new offshore foundations such as jackets or tripods, being also taken into account the floating platforms. The main players involved in this field are France, Spain, United Kingdom, Sweden and Netherland, where the average water depth considered for installation is around 25-30 m. Judjing after the percentage, many the projects are located in the North Sea (62%), being followed by the Baltic Sea and Atlantic Ocean with 21% and 9%, respectively [2]. Also, it must be pointed out that there are plans to develop similar projects in enclosed seas, such as the Mediterranean Sea especially in the northwestern part of the basin in the vicinity of the Sardinia Island [3].

The Black Sea can be considered another important basin in terms of the wind energy. This aspect is highlighted by the intense storm events encountered in this area, which combined with the local wave conditions [4, 5] contributed to severe marine hazards. During the recent years, the northwestern part of the sea started to gain more attention in terms of these natural resources. Thisarea seems to have a better potential in the vicinity of the Romanian and Ukrainian coastal environments [6-8].

In this context, the main objective of the present work is to identify how the wind resources from the Romanian coastal areas may vary according to the geographical locations or with the distance from the shore, and also to estimate the configuration of a wind project which could operate in this environment.

MATERIALS AND METHODS

Target area

Figure 1 illustrates the target area which is located in the northwestern part of the Black Sea, more precisely in the vicinity of the Romanian sector. In order to assess the local wind conditions of the entire coastal area, twelve reference points were defined for three different water regions, nearshore (NP), offshore (OP) and deep water (DW). The NP group points, was defined close to the shoreline in water depths between 4-12 m, being followed by the OP points, which were selected to define the wind conditions from the central part of the area for depths 46-86 m, the point OP1 being defined by much higher value. In the vicinity of the continental shelf-edge the DW points were defined, with the corresponding depths: DW1-214 m; DW2-311 m; DW3-158 m and DW4-103 m, respectively.

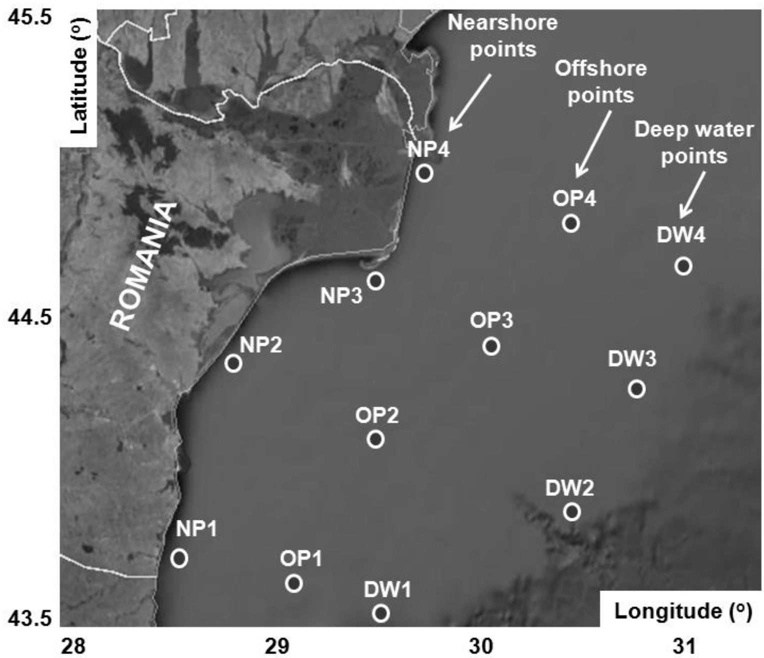


Fig. 1. The Romanian coastal area and the spatial distribution of the reference points, where: a) NP1-NP4 → nearshore points; b) OP1-OP4 → offshore points; c) DW1-DW4 → deep water points. Figure processed from Google Earth (2015)

Wind data

For the present work the altimeter measurements coming from the AVISO multi-mission project [9] were considered. Throughout the Ssalto/Duacs system data from various altimeter missions (such as: Cryosat-2, Jason-1&2 or *ERS*-1 & 2) are collected in order to obtain a consistent database of various parameters, among them being the wind conditions in the marine areas. The benefit of this data is that they represent real measurements available on a global scale, while a weak point can be considered the accuracy of these measurements in the vicinity of the shoreline which is influenced by the land-water interface. The AVISO measurements were processed for the interval September 2009-August 2015, being defined by one measurement per day which indicates only the wind speed.

Another important source of data is the ERA-Interim project maintained by the European Centre for Medium-Range Weather Forecasts (ECMWF), which is considered to be a reanalysis database. This was started in 2006, connecting the previous ERA-40 project (1957-2002) and the next state of the art reanalysis model, which cover the interval 1979 and continue with data in real time. The improvement in the model, involves a 4-dimensional variational analysis, a bias correction for satellite data, and methods how the biases and changes in the observing systems are computed. The ERA-Interim atmospheric model is defined by the following spatial resolutions: a) 60 vertical levels, with the top one at 0.1 hPa; b) T255 spherical - harmonic representation; c) reduced Gaussian grid with 79 km spacing [10]. In this case, the wind data (wind speed and direction) corresponding to the Romanian sector were processed for the 15-year interval January 2000-August 2014 considering values reported for a 6 hour time step (00-06-12-18 UTC).

RESULTS

The initial data sets (for AVISO and ECMWF) are reported at 10 m. In order to highlight the wind conditions at 80 m height, where most of the wind turbines operate, the two databases were adjusted at this height throughout the following logarithmic law [11]:

$$U_{80} = U_{10} * \ln\left(\frac{H_{80}}{z_0}\right) \Big/ \ln\left(\frac{H_{10}}{z_0}\right) \quad (1)$$

where: U_{80} - represent the wind speed at 80 m height (H_{80}); U_{10} - indicate the wind conditions at 10 m (H_{10}), while z_0=0.2 mm is the roughness factor of the sea surface (neutral conditions) [12].

Figure 2 provides an overview of the wind conditions in the target area according to the ECMWF data set. At this point, must be mentioned that the analysis will be focused on the following time intervals: a) summer time (April-September); b) winter time (October-March). The distribution of the average values is illustrated in Figure 2a, where can be observed that the wind conditions may vary between the two intervals, according to the water depth and to the geographical locations.

From the analysis of the summer time it can be noticed that the points NP present values in the interval 4.63-5.11 m/s, more energetic conditions being reported by the points OP (5.61-6.01 m/s) and by the DW points (5.78-5.96 m/s). In general, more consistent conditions are observed on the extremity of the target area, especially in the northern part as can be observed from the points NP4, OP4 and DW4, respectively. Regarding the winter time, can be observed a smooth transition of the values between the NP group and the OP points, while from the comparison of the wind conditions from the central part with the ones from DW points can be observed little differences. In this case a maximum of 8.29 m/s is reported by OP4, being followed by DW4 with 8.24 m/s, while a minimum of 7.57 m/s is accounted by OP1.

Since the point NP4 is located in a water depth which is suitable for the development of an offshore wind park, in Figure 2b is presented in more details the distribution of the values by wind classes according to the two main seasons. From this distribution can be mentioned that most of the values are grouped in the range of 3-12 m/s, with the mention that during the summer time the interval 3-9 m/s appears to be more important, compared with the winter season when only the wind speeds located between 6-9 m/s is more consistent.

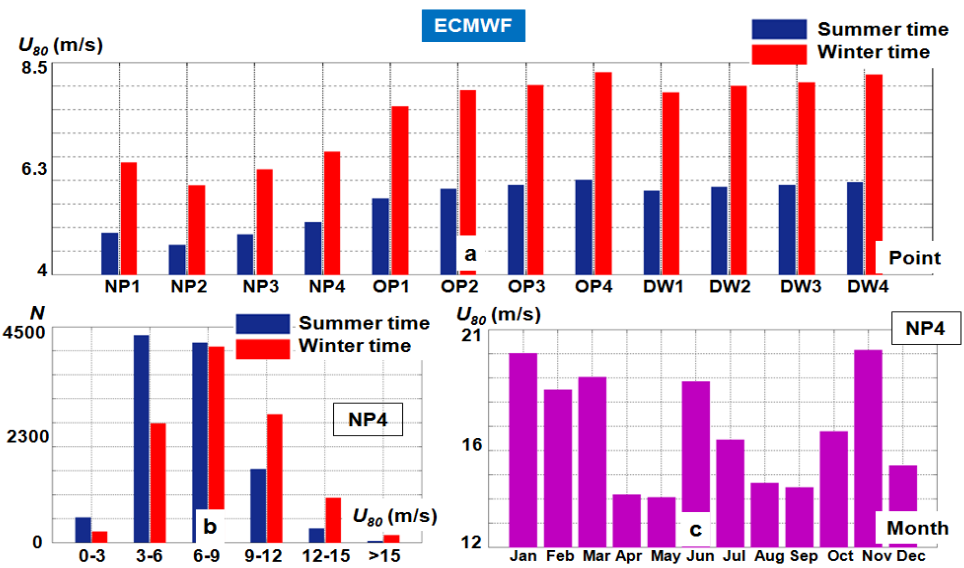


Fig. 2. Distribution of the wind conditions for the 15-year interval 2000-2014 according to the ECMWF dataset. Results available for: a) average values for summer and winter time; b) *U80* histogram of the point NP4 reported in the summer and winter time; c) monthly maximum values reported by the point NP4

The distribution of the maximum values is highlighted in Figure 2c, which indicates that the storms reported during the winter time represent a common event, during which can be observed a maximum of 20.1 m/s in November. During the summer time, these values are around 14 m/s being reported some peaks in June (18.9 m/s) and July (16.4 m/s), respectively.

A complete analysis of the wind conditions is presented in Table 1, considering various statistical parameters. As a first step, the performances of a typical offshore wind turbine to produce electricity considering the local wind resources are estimated. The first value (3 m/s) is usually indicated throughout the cut-in value and indicates the lower value of the power curve of a turbine at which the turbine will start to generate electricity which is profitable from an economical point of view. From the reference points can be observed that in the points NP can be expected that a wind turbine to operate in approximately 78 % during the summer time, while a maximum of 90.4% can be expected in NP4 during winter. For the rest of the points can be mention maximum values of 93.6% (OP4) and 93.5% (DW4), values which were reported during the winter period.

Another important value for the wind turbines is the rated wind speed which indicates the values from which the generator will perform on a full capacity. This value may start from 12.5 m/s and may reach 15 m/s, as in the case of the Vestas V90–3MW. Compared to the previous results, can be observed that this time the values are much smaller indicating for the point OP4 a maximum of 2.71% (summer time) and 12.6% (in winter), while a minimum of 0.3% is reported by NP2 during the summer season.

In terms of the maximum values, can be mentioned the following values: NP1-NP4 (16.3 – 18.9 m/s → summer time ↔ 18.1-20.1 m/s → winter time); OP1-OP4 (20.4-22.2 m/s ↔22-23.5 m/s) and DW1-DW4 (20.8-22.5 m/s↔22.7-23.7 m/s). The standard deviation index reporteda maximumaximum of 3.01 m/s for the point OP4 (summer time) and close to 3.6 m/s for the points OP2-OP4 or DW1-DW4.

Table 1. Statistical analysis of the wind conditions illustrated by the ECMWF dataset, for the 15-year interval 2000-2014 structured on summer (ST) and winter time (WT), respectively

Results	**Period**	**Points**											
		NP1	NP2	NP3	NP4	**OP1**	**OP2**	**OP3**	**OP4**	DW1	DW2	DW3	DW4
≥3 m/s (%)	ST	78.1	76	77.7	79.7	82.6	83.7	83.2	83.4	83.5	83.9	83.8	83.2
	WT	88.4	86.9	89	90.4	91.4	92.3	92.7	93.6	92.1	92.5	93.1	93.5
≥12.5 m/s	ST	0.516	0.304	0.442	0.672	1.84	2.44	2.62	2.71	2.23	2.38	2.47	2.48
	WT	3.57	1.9	2.37	3.37	9.46	11.1	11.3	12.6	11.2	11.6	11.6	12.3
Maxim	ST	17.2	16.3	17	18.9	20.4	20.7	22.2	21.1	20.8	21.7	22.5	21.2

(m/s)	WT	18.9	18.1	19.5	20.1	22	23.3	23.5	22.6	22.9	23.7	23.3	22.7
Std	ST	2.37	2.23	2.36	2.49	2.77	2.89	2.95	3.01	2.86	2.9	2.92	2.98
(m/s)	WT	3.01	2.74	2.82	2.92	3.5	3.57	3.56	3.58	3.6	3.57	3.54	3.56

Figure 3 presents the directional distribution of the wind conditions based on the ECMWF dataset, reported to the two main seasons (summer and winter). During the summer time can be observed that all the points indicate the northeast and southwest directions as being more important, with the mention that in the case of the points NP4 and DW4 the values are equally distributed along the northern sector. Regarding the winter season, can be mentioned that the structure of the wind field is significantly different revealing only the north and north-eastern sector as the windiest directions. From the distribution of the wind classes, can be observed that during the winter time the conditions reported above 9 m/s are more consistent.

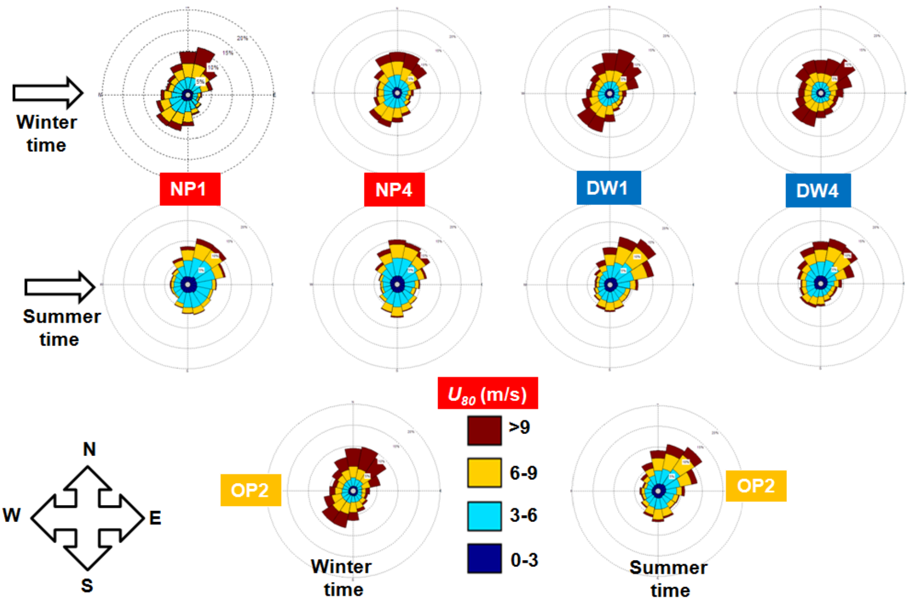


Fig. 3. Wind roses reported to the reference points NP1, OP2 and DW4 for the summer and the winter seasons. Analysis based on the ECMWF data set for the interval 2000-2014

Going to the satellite measurements, Figure 4 presents the evolution of the wind in the reference points considered based on the AVISO dataset. From the analysis of the mean values (Figure 4a) can be observed little variations between the values regardless the distance from the shore or the geographical distribution. During the summer time the values are in the interval 3.74-3.81 m/s, where the point DW1 reports the smallest one compared to NP4 which account for the highest value. In the winter, the reference points presents values in the ranges: NP1-NP4 →5.93-6.04 m/s;

OP1-OP4 → 5.91-6.07 m/s and DW1-DW4 → 5.89-6.06 m/s. Compared to the wind histogram indicated by the ECMWF data for the point NP4, can be observed that the satellite measurements present much lower wind conditions, which are mainly around the 3-6 m/s regardless of the season considered. In terms of the monthly maximum values reported by NP4, can be mentioned that his time the second part of the year (August-December) seems to be more energetic from this point of view, with a maximum of 16 m/s in October. During the summer time, September presents a value of 15.5 m/s compared to 7.6 m/s in July.

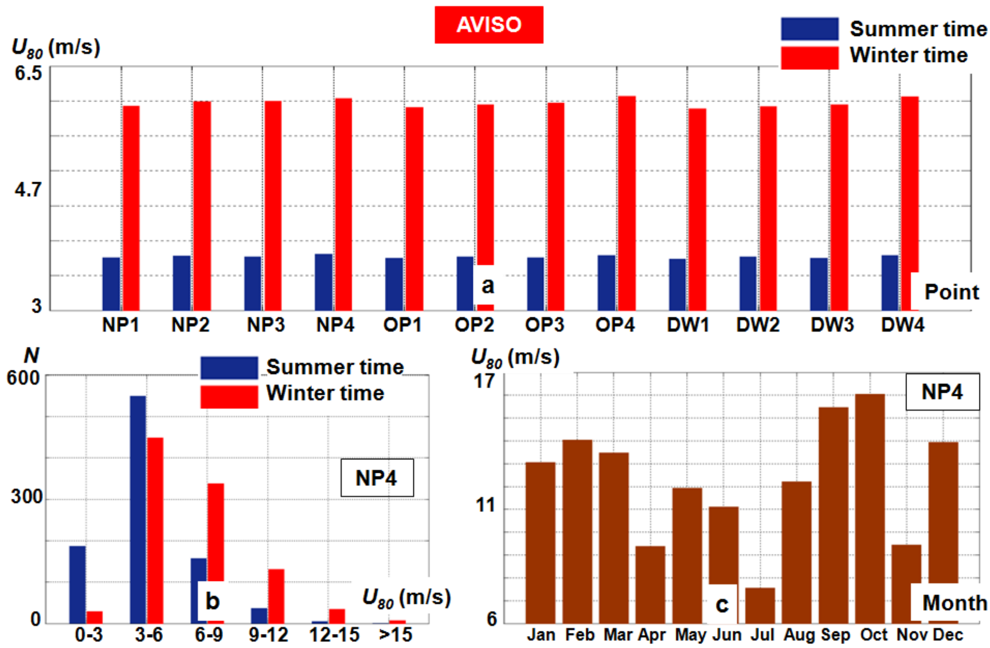


Fig. 4. Distribution of the wind conditions for the interval September 2009-August 2015, as reflected by the AVISO dataset. Results available for: a) average values for summer and winter time; b) *U80* histogram for the point NP4 reported to the summer and winter time, respectively; c) monthly maximum values corresponding to the point NP4

A detailed analysis of the wind conditions is presented in Table 2 taking into account the AVISO satellite measurements. From the analysis of the NP points, can be observed that the points located on the northern part seem to present more energetic characteristics indicating during the winter time a maximum of 83.2% for conditions ≥3 m/s, while a 4.8% is reported by the point NP2 for the values ≥12.5 m/s for the same time interval. As regards now the summer time, the remaining points may register values in the range: 52.6-54.7% (≥3 m/s) and 0.28-0.63% (≥12.5 m/s), respectively. The maximum value and standard deviation are also presented in this table, from which can be noticed a maximum of 19.7 m/s for the first parameter and a minimum of 2.33 m/s for the second one.

Table 2. Statistical analysis of the wind conditions illustrated by the AVISO measurements, for the interval September 2009-August 2015 structured in summer (ST) and winter time (WT), respectively

Results	Period	Points											
		NP1	NP2	NP3	NP4	**OP1**	**OP2**	**OP3**	**OP4**	DW1	DW2	DW3	DW4
≥3 m/s (%)	ST	52.1	52.3	52.6	53.3	52.6	53.2	53	53.9	52.8	53.9	54.7	54
	WT	82.1	81.6	82.5	83.2	82.8	83.2	83.4	84.7	83.4	84.6	85.3	84.9
≥12.5 m/s	ST	0.73	0.63	0.62	0.64	0.62	0.63	0.62	0.56	0.52	0.28	0.41	0.56
	WT	4.69	4.8	4.4	4.26	4.29	4.2	3.88	4.4	4.19	4.11	3.28	4.4
Maxim (m/s)	ST	17.4	17.9	18.2	18.4	17.3	17.8	18.1	18.6	17.2	17.8	18.1	18.5
	WT	18.8	19	19.1	19.1	18.8	19	19	19.7	18.8	18.9	19	19.6
Std (m/s)	ST	2.47	2.49	2.46	2.47	2.43	2.41	2.39	2.41	2.39	2.35	2.33	2.4
	WT	3.21	3.23	3.19	3.18	3.14	3.11	3.1	3.15	3.1	3.07	3.02	3.13

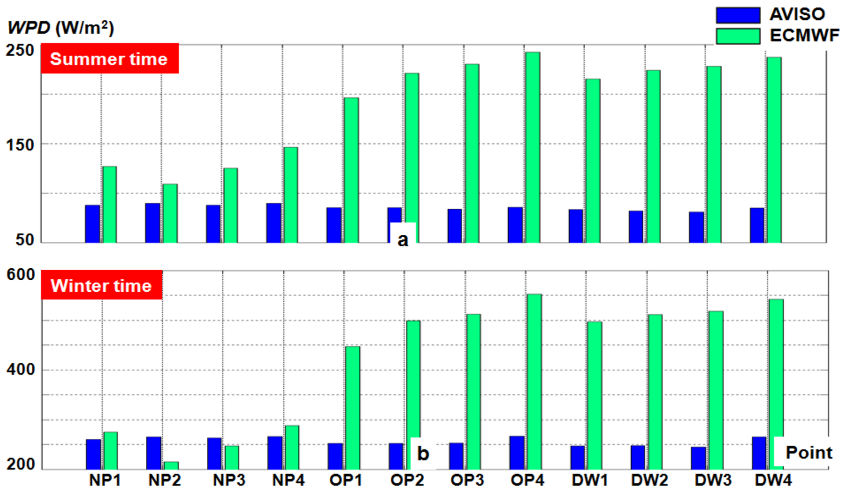
The wind power density - *WPD* (in W/m^2), represent another parameter, which could be used to assess the potential of a particular site. This can be defined as:

$$WPD = \frac{1}{2}\rho U_{80}{}^{3} \qquad (2)$$

where ρ is the air density (1.22 kg/m^3).

Figure 5 presents a direct comparison between the two data sets, considering the distribution of this parameter for the summer and winter time. Can be mentioned that the ECMWF values are much higher, with the exception of the winter time when the points NP2 and NP3 present more consistent values for the AVISO data. During the summer time (Figure 5a) there is a constant distribution of the values in the interval 82-90 W/m^2 compared to the ECMWF values which may vary in the ranges: NP1-NP2 → 109-146 W/m^2; OP1-OP4 → 196-242 W/m^2; DW1-DW4 → 215-237 W/m^2. Regarding the wintertime, from the AVISO values can be mentioned the point OP4 with 267 W/m^2, compared to 552 W/m^2 reported for the same point by the ECMWF.

Another objective of the present work is to evaluate the wind conditions from the marine areas, already taken into account to develop offshore wind farms. Several projects are presented in Table 3 [13], from which can be mentioned that from Denmark and Germany was considered one project, three projects are from Sweden, while from France were selected two. The expected configuration of the farms is provided in the table, a minimum capacity of 10 MW being expected for the MISTRAL project (France) while a maximum of 640 MW is estimated for the Kriegers Flak II project (Sweden) to be developed over an area of 63 km^2. The depth ranges may vary significantly from 10 m in the case of Storgrundet (Sweden) and reaching a maximum of 94 m in the case of the VertiMED project (France) which is only in the early stage of planning.



Fi. 5. Distribution of the wind power density (W/m^2) based on the AVISO and ECMWF dataset, where the results correspond to: a) summer time; b) winter time. Results reported only for the interval September 2009-August 2015

Other important parameters taken into account are the CO_2 reduced per year (in tonnes) or the homes supplied with electricity, which as expected is much higher in the case of the Kriegers Flak II - Sweden (453283 homes).

Since the AVISO project provides real measurements of the wind resources, which are frequently used to calibrate numerical models, as a further step the wind conditions of these offshore sites will be compared with the similar ones reported in the vicinity of the Romanian environment. Such an analysis is performed in Figure 6, from which can be observed that during the summer time the point NP4 presents a similar distribution of the *U80* parameter with the project Storgrundet (Sweden) and exceeds the project Petlandskär (Sweden) with almost 0.27 m/s. During the winter time, the offshore sites present much higher values, being reported the following differences: Kriegers Flak (DK) → 0.52 m/s, Storgrundet (SE) → 0.35 m/s and VertiMED (FR) → 0.42 m/s. The values reported by the *WPD* parameter are significantly higher in the case of the offshore sites, from which can be highlighted the projects from France, whicha maximum registers a maximum of 120 W/m^2 in summer and 361 W/m^2 during winter.

Table 3. Characteristics of the offshore wind project (planned or authorized) taken into account [13]

Project	Country	Project capacity (MW)	Turbine capacity (MW)	Status	Area (km^2)	Depth range (m)	CO_2 reduced per year (tonnes)	Homes provided annually
Kriegers Flak	Denmark	590-610	3-10	Early planning	4	15-30	873144	432036
Arkona-Becken Südost	Germany	385	6-7	Consent authorized	39	21-28	551083	272678
Kriegers Flak II	Sweden	640	5	Consent authorized	63	20-40	916086	453283
Storgrundet	Sweden	210-265	3-6	Consent authorized	67	10-25	379317	187688
Petlandskär	Sweden	60	3	Stand by	5	-	85883	42495
MISTRAL	France	10	-	Consent authorized	-	60-70	14314	7083
VertiMED	France	26	2.6	Early planning	14	81-94	37216	18415

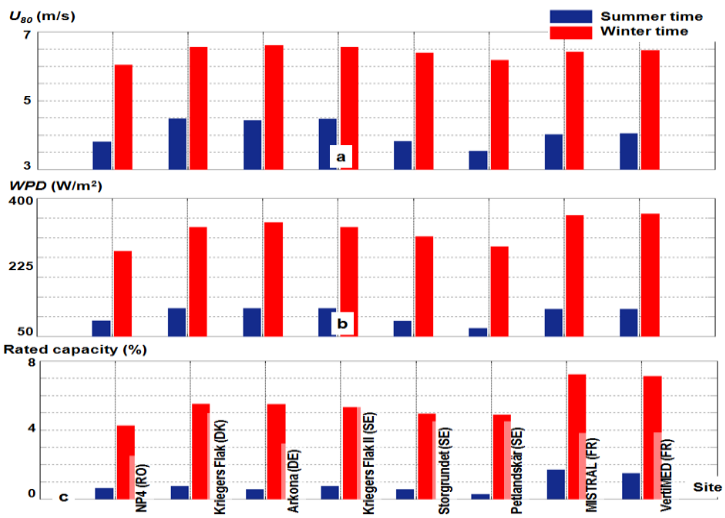


Figure 6. Comparisons of the wind conditions from the point NP4 with the similar ones in the vicinity of some planned offshore wind projects during the summer and winter time, respectively. Results based on the AVISO measurements for the interval September 2009-August 2015, where: a) mean values of the *U80* parameter; b) mean values of the *WPD* parameter; c) rated capacity

In terms of the rated capacity (Figure 6c), we can notice that the differences reported between the point NP4 and the group sites Kriegers Flak (DK) - Petlandskär (SE) are not so high, since in this case is reported a maximum of 0.74% during summer and 5.5% in winter, respectively. The MISTRAL and VertiMED projects may report a maximum of 7.22% during the winter time, while 1.7% is accounted by the summer season.

CONCLUSIONS

In this work a general analysis of the wind conditions in the Romanian coastal environments was carried out by considering different sources of data, from which can be mentioned the ECMWF data available for the 15-year interval 2000-2014 and the AVISO satellite measurements, which correspond to the time interval 2010-2015. Following these results, can be mentioned that both data sets (AVISO and ECMWF) indicate the northern part of the target area as being more important in terms of the wind energy potential. In general, it was noticed that the satellite measurements reveal smaller variations in relationship with the point position, regardless of the water depth. The ECMWF data presents lower wind conditions for the NP points defined in the vicinity of the coastline, while smaller variations are noticed in relationship with the OP and the DW points. From the comparisons with the offshore sites, where is expected to be developed wind projects, it was noticed that the point NP4 seems to present very similar features with two projects from Sweden, where one of the project is already authorized, being rated to develop a wind farm with a maximum capacity of 265 MW. Finally, it has to be also highlighted that, since wave energy is also relevant in the target area, hybrid energy farms obtained by co-locating the wind and wave farms can also be considered and such approaches can play an active role also in the coastal protection [14, 15].

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