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ASSESSMENT OF THE ENERGY POTENTIAL OF THE WAVES IN THE BLACK SEA

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ABSTRACT

The present work aims to evaluate the energy potential of the waves from the Black Sea offshore area, taking into account eight reference points along the sea perimeter, and at the same time evaluating the performance of five wave energy converters (WECs) in these points. The study has shown that the most promising areas are those located in the west and south of the sea, where the wave parameters are the highest, and among the WECs analyzed the best in these areas have proved to be Wave Dragon and Oceantec.

Keywords: ERA-Interim, WECs performance, capture width, capacity factor, wave parameters

1. INTRODUCTION

The increased global energy demand is a direct result of the population growth, the global economic expansion and the rising of population living standards, along with concerns on reducing the fossil fuel reserves, increasing the environment pollution, accompanied by the global climate change, and the desire to ensure a sustainable development. All these aspects put the mankind to face an increasing need to use the renewable energy resources [6], [9]. Among these, the ocean energy, in particular the wave energy, is available in huge quantities, mainly in the coastal areas. Thus, the electricity generated by the use of the wave energy could play an important role in meeting the energy demand, stimulating the economic growth of the coastal regions and protecting the environment [21]. The energy policy promoted by the UN at global level and by the European Parliament at EU level focuses on the use of renewable energy sources and the reduction of greenhouse gas emissions [3].

From this perspective, in 2008, the European Parliament adopted the Energy-Climate Change Package, which has as main objectives that by 2020 the share of the renewable energy sources in the EU's total energy consumption should increase by 20% (8.5% in 2005) and the greenhouse gas emissions to be reduced by 20% as compared to 1990 levels. For 2030, the targets are more ambitious: increasing the share of renewable energy sources to 27% and reducing the greenhouse gas emissions by 40 % [24].

In Romania, the renewable energy provided 17.5% in 2006 and 20% in 2008 in the national energy consumption. In the energy policy of our country, an important role has the strategy for capitalizing in renewable energy sources, approved by GD 1535/2003.

Based on the above mentioned aspects, the work aims to evaluate the energy potential of the waves in the Black Sea coastal environment. For this, the authors have considered 8 reference points, disposed along the sea perimeter. Finally, the performances of some state of the art wave energy converters have been assessed in these locations.

2. LITERATURE REVIEW

Waves formed under the action of winds, which transfer their energy to the superficial water layers. Given that the winds occur as a result of different warming of the water from the planetary ocean and the dry surface, the wave energy represents in fact an indirect form of the solar energy. The wave parameters (height, length, period) depend on the magnitude of the wave surface on which the wind acts, as well as on the duration and the speed of the wind [1]. In turn, the wave parameters along with the water density, in which the waves form, determine their energy potential [4, 5]. The greatest potential of the waves are in the regions with latitudes between 40^0 and 60^0 north and south, where the winds are the strongest [2].

Thus, on the western coasts of Europe, the mean wave power is around 50 kW/m and can reach, in storm conditions, even up to 1000 kW/m. For the oceans, the average wave power is 10-100 kW/m [12], [25].

Among the richest nations as regarding the potential for the wave energy is the UK and northern Scotland [23]. Studying the energy potential of the waves in 15 sites located near the continental coastal areas, sites from both the northern hemisphere and the southern hemisphere, Rusu et al. [19, 20] have observed that the highest values are reached in the offshore sites of the Europe (over 75 KW/m). Then, there follow, in order, the sites from the South African coastal area (with a maximum of 54 KW/m), the coastal area of the western Australia, located in the Indian Ocean, the sites from South America and Central America, where near the Chilean coast the potential of the waves exceeds 60 KW/m and moderate values have been observed near the coast of the Asia [7], [8]. For most the sites, the wave power values are higher in the winter than in the total time of the year. The available global wave energy potential is about 2 TW, of which 320 GW in the EU. From this potential, about 10-12% could be used, as a result of factors such as the oceans' hard environment, energy conversion losses, costs [13].

The wave potential can be exploited by capturing and converting it into electricity. There are a significant number of patents for the wave energy recovery devices, but only a small number of them are commercially viable [22].

Most of the tested prototypes considered to be technologically advanced, generate a small amount of energy. Most of these consist of WECs devices of low capacity (rated power below 50 KW) and only a smaller number with higher capacity [20].

The performance study of 10 WECs devices, of which 5 with power over 2500 KW and 5 with rated power below 1000 KW, has showed that, among the systems with a rated output of more than 2500 KW, the Wave Dragon system shows the best performance in terms of power, power factor and capture width, and of those with a nominal power of less than 1000 KW, the Oceantec system is the most performing [10, 11].

3. METHODS AND MATERIALS

The methodology used consists in selecting the reference points on the Black Sea surface, generating the wave parameters using the ERA-Interim project, calculating the wave energy and WEC performance.

3.1 Reference points

The assessment of the energy potential for the chosen sea coasts is done so that they cover most of the sea's perimeter. The points have been chosen in the coastal area, considering that a real interest in extracting the wave energy is mainly in these areas. In these areas, the wave power can reach important values. The points selected are represented in Fig. 1 and their main characteristics are given in Table 1.

As it can be seen from Fig. 1, on the west side of the sea, there are 4 points, 3 points in the northwest (P1, P2, P3) and one point in the southwest (P8). On the eastern side, there are 3 points, one point in the northeast (P4) and 2 points in the southeast (P5, P6), and in the south is located only one point (P7). All points are located in depth zones, ranging from 12 m (P2) to 160 m (P6), and the distance from the shore has a minimum value of 3.39 km (P6) and the highest being 44.1 km (P1) (Table 1). All these can be considered, in general, convenient distances for the location of the WECs. At long distances from the shore, the waves exploitation projects are less attractive because the initial investments can be too large.

Fig. 1. Locations of the 8 reference points (map from Google Earth)

Table 1. The main characteristics of the reference points considered (coordinates and depths)

Point	Location (Long-Lat)	Depth (m)	Distance to shore (Km)
P1	29.216126^0 N 44.102196^0 E	49	44.1
P2	46.033629^0 N 31.216067^0 E	12	37.25
P3	44.574716^0 N 33.269680^0 E	92	8.75
P4	44.613734^0 N 37.626428^0 E	63	5.86
P5	41.672164^0 N 41.573516^0 E	90	4.68
P6	41.041593^0 N 39.734089^0 E	160	3.39
P7	42.168191^0 N 35.006004^0 E	92	8.43
P8	41.439795^0 N 29.097933^0 E	94	20.76

3.2 WAVE PARAMETERS IN THE REFERENCE POINTS

In order to determine the wave parameters corresponding to the 8 reference points selected in the Black Sea, the ERA-Interim project was used.

It is known that one of the most comprehensive environmental databases is produced by the European Centre for Medium-range Weather Forecasts (ECMWF), of which the ERA-Interim project is a set of high-quality re-analysis data that can describe various marine environmental parameters [19]. By processing the ERA-Interim data set, the significant height of wave, H_S, and mean wave period, T_m, were obtained over a 5-year period, ranging from January 2013 to August 2017. The data were obtained for the total time, as well as for the season of winter, associated in the northern hemisphere with the time interval of October-March.
Depending on the mean wave period, T_m, the energetic period of the waves, T_e, was calculated with the relationship:

$$T_e = 1.269\ T_m \tag{1}$$

The values of the wave parameters H_S and the energetic period of waves T_e for the eight reference points selected are illustrated in Fig. 2 and Fig. 3.

In Figure 2, the distribution of the H_S parameter is structured over the total time and for the winter season. From the data analysis, it is observed that the higher values are met in the winter, for all 8 reference points, with increases ranging from 16% (P8) to 29% (P4). For the total time, the values for the H_S range from 0.313 m (P5) to 1.024 m (P3) and in winter from 0.373 m (P5) to 1.214 m (P3), the highest values being reached in the points from the western part of the Black Sea (P1, P3, P8) and the point P7 in the southern area, while the lowest values are reached in the points located near the east coast (P4, P5). The parameter T_e (Fig. 2) shows small variations between values recorded in the total year time and the winter interval, the highest values being reached in the points where the H_S has the highest values (P1, P3, P7, P8), and the minimum values in the points from the eastern part of the sea (P4, P5).

Another important parameter is the wave power, P_W, which, for large water depths, is calculated with the relationship:

$$P_w = \frac{\rho \cdot g^2}{64\pi} T_e \cdot H_s^2 \tag{2}$$

where P_W [Kw/m] is the energy flow, expressed in watts per meter of the wave crest length, ρ=1025 kg/m^3 is the see water density, g=9.81 m/s^2 is the gravitational acceleration.

The values calculated for P_W in the 8 selected reference points are shown in Fig. 4.

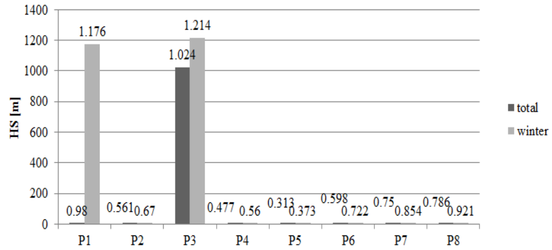


Fig. 2. The average H_S values corresponding to the total and winter time for the 5-year interval from January 2013 to August 2017

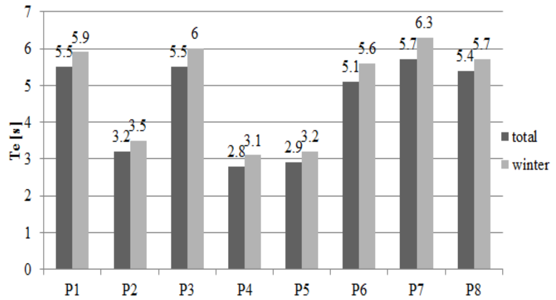


Fig. 3. The average T_e values corresponding to the total and winter time, for the 5-year interval from January 2013 to August 2017

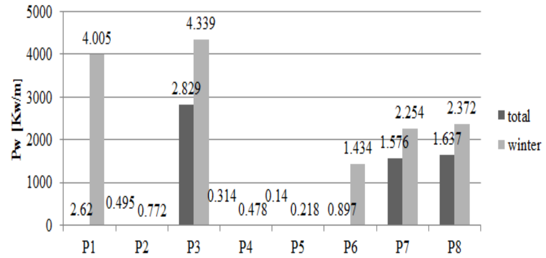


Fig. 4. Wave power corresponding to the total year time and the winter time for the 5-year interval from January 2013 to August 2017

As expected, the points with the highest wave power are those that have the highest H_S and T_e, i.e. the points P1, P3, P7, P8, while the points P4 and P5 and P2 show very low values for this parameter. Thus, the differences between the selected points appeared more clearly.

3.3 WAVE ENERGY CONVERTERS (WECs)

From the wave measurements analysis, the theoretical energy can be identified for different periods of time, but the electrical energy that may be obtained depends on the characteristics of each WEC system. The WEC systems allow for extracting the wave energy by harnessing their potential and kinetic energy. These are several principles for this convertion of the wave energy [16]. Moreover, by reporting the installation area to the shoreline they can be: shoreline systems, shallow water and deep water wave energy converters, the latter presenting the best energy performance, but also the highest instalation and operational costs.

Taking into account the operating principle of these systems, they can be placed in three distinct categories: point absorbers, attenuators and terminators [15]. The point absorber system is similar to a buoy, in which the active part moves on a vertical axis [17]. The attenuator systems are floating systems (semi-immersion), located parallel to the wave propagation direction of the incident waves, which gradually absorb some of their energy as they propagate. The terminator systems are oriented parallel to the wave crests and have as operating principle of capturing or reflecting the waves [18]. Table 2 presents the main features of the WEC systems considered in the present study, including the WECs from all the three categories above mentioned.

Table 2 Technical specifications of the WEC systems considered in the present work [14]

Category	Device type	Dimension	***RP* [kW]**
Point absorber	ABWave Bob Seabed	20 m 3 m	1000 15
Atenuator	Pelamis Oceantec	150 m 52 m	750 500
Terminator	Wave Dragon	-	5900

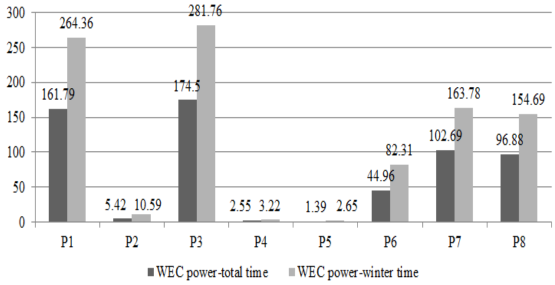
The variety of the WEC devices in the study, with power between 15 kW and 5900 kW, makes it possible to identify the performance of these systems in order to assess which system is most suitable for the 8 reference points from the Black Sea. *RP* is the nominal power, defined as the maximum value reported in the manufacturer's power matrix.

For the period January 2013 - August 2017, it is generated an average power over the total (total) and winter time (October-March) with the ERA-Interim project for the WECs systems shown in Table 2.

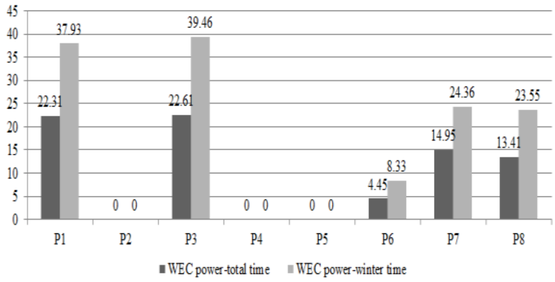
The calculation is based on the association of the power matrix of the WECs with the environmental matrix obtained for each combination of significant wave height (H_s) and energy period (T_e) in the considered point. It can be expressed as:

$$PE = \frac{1}{100} \sum_{n=1}^{nT} \sum_{j=1}^{nH} p_{ij} \cdot P_{ij} \tag{3}$$

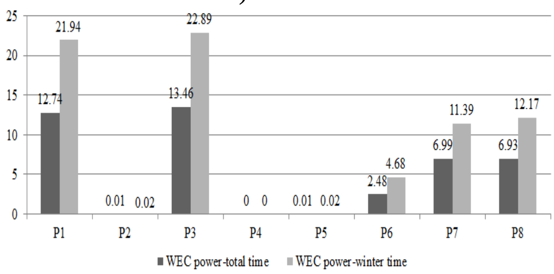
where: p_{ij} is the percentage corresponding to the cell defined by line i and column j in the environmental matrix; p_{ij} is related to the bivariate distribution of the sea states and includes the bin defined by column j and line i, whereas P_{ij} is the expected power output, defined in the power matrix of each WEC, for the same cell defined by column j and line i.



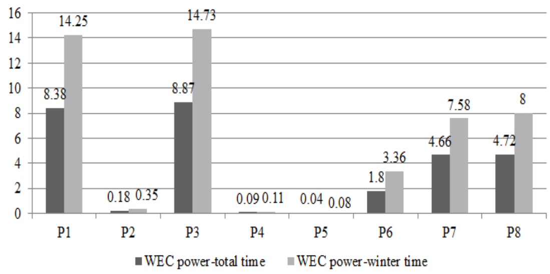
a) Wave Dragon



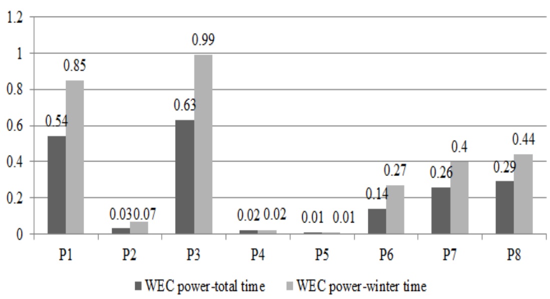
b) Oceantec



c) Pelamis



d) Wave Bob



e) SeabasedAB

Fig. 5. Mean power (KW) provided per day by WEC systems taken in the study on total and winter time

For the same period, using the ERA-Interim data, the capacity factors (C_f) have been calculated. This represents, in fact, an efficiency factor (%), which expresses, to some extent, the maximum system power that was used. Another parameter evaluated is the capture width C_W (m), which expresses how many meters of a wave length covers the respective WEC system.

Calculations are made using the following formulas:

$$C_f = 100\frac{PE}{RP} \quad (4)$$

$$C_w = 100\frac{PE}{Pw} \quad (5)$$

where P_w is calculated with relationship (2).

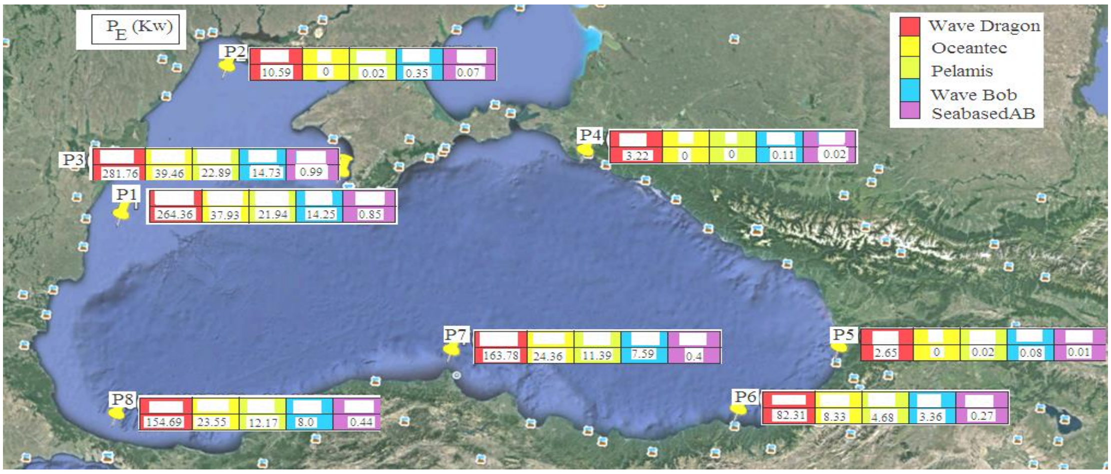
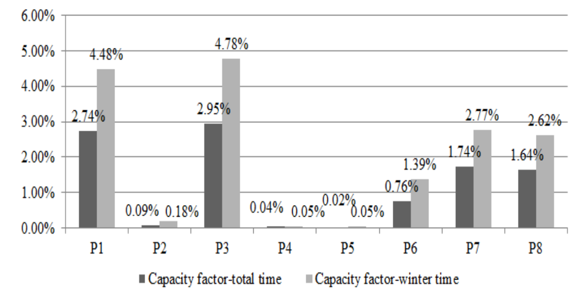
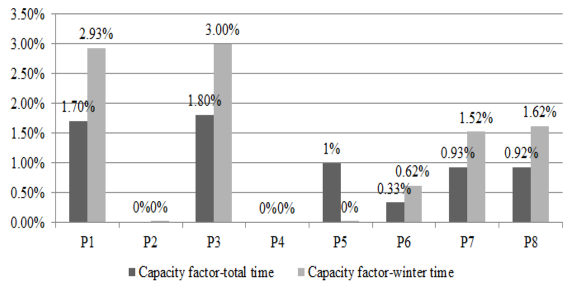


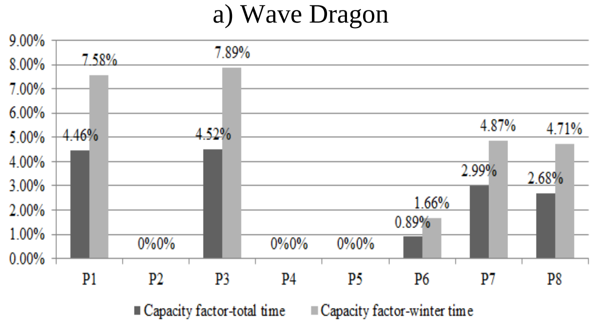
Fig. 6. The electric power output (kW) expected from the WECs in the references points considered. The mean values correspond to the 5-year interval from January 2013 to August 2017, where the first and second lines of each table indicate the WEC performance during the total and winter times, respectively



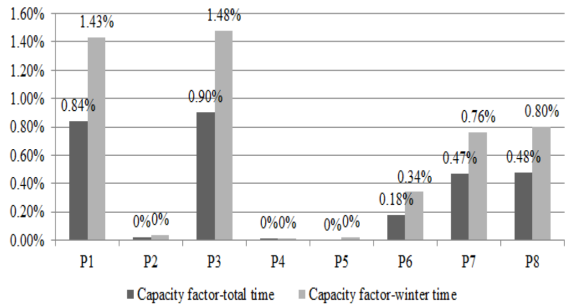
a) Wave Dragon



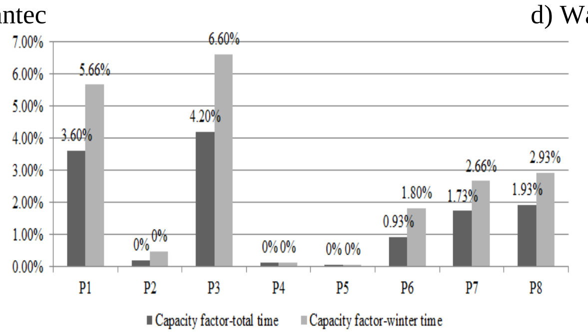
c) Pelamis



b) Oceantec



d) Wave Bob



e) SeabasedAB

Fig. 7. The capacity factors (%) of the WECs systems taken in the study for total and winter time

The results of the expected electrical power (kW/day) to be generated by the five WECs systems considered in the present study by wave energy recovery, in the 8 reference points in the Black Sea are shown in Fig. 5. The results are structured over the total time and winter season. As shown in Fig. 5, the most promising reference points are P1 and P3, located in the western side of the Black Sea and the points P7, P8, which are in the south and southwest of the sea, while the lowest expectations are in the points P4 and P5 situated on the east coast, both for total and winter time, respectively. The values for the winter time are in all cases higher than for the total time.

The performance of the five WECs considered, from the point of view of the produced electric power, is different. The most powerful system is the Wave Dragon, followed by Oceanec, Pelamis, Wave Bob, and the least performing is the SeabasedAB system (see Fig. 6).

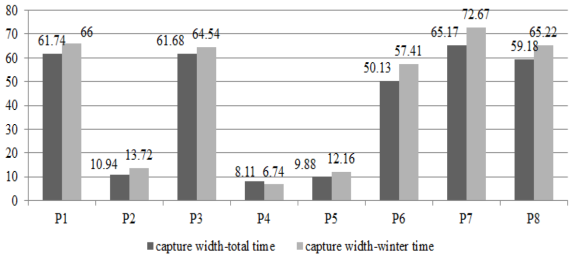
The power expected to be produced by the Wave Dragon is about 7 times higher than that produced by the Oceantec system, about 12 times that of the Pelamis system and about 20 times greater than the expected power of the Wave Bob system.

For the capacity factor, the values obtained for the five WECs systems considered in the study are presented in Fig.7.

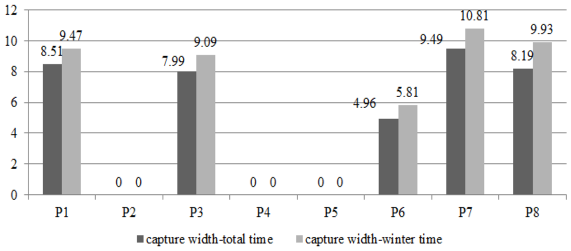
From Fig. 7, it can be noticed that the capacity factor is very small for all five WECs systems. The maximum value obtained is 4.52% for the total time and 7.89% for the winter time for the Oceantec system, followed in order by the systems SeabasedAB with the maximum values of 4.2% for the total time and 6.6% for the winter time, Wave Dragon with 2.95% for total time and 4.78% for winter time, Pelamis with 1.8% for total time and 3% for winter time and the last being Wave Bob with 0.8% for total time and 1.48% for winter time.

If one refers to the selected points, the highest values for the capacity factor were obtained, as expected, for the following points P1, P3, P7, P8, higher during the winter than the total time.

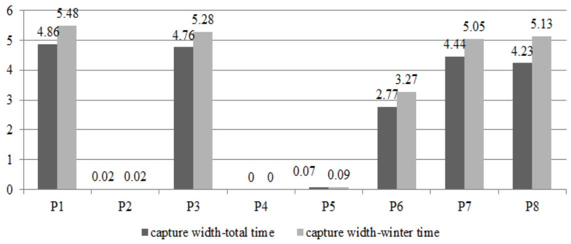
For the capture width of WECs, the results are shown in Fig. 8, where there are very large differences for the capture width for the WECs systems considered in the study, from tens of meters (Wave Dragon) to less than 0.3 m (SeabasedAB). For most of the WECs, the same order for the capture width and the expected power output are observed, meaning the highest values have been obtained for the Wave Dragon, followed in order by Oceantec, Pelamis, Wave Bob and the smallest values for the SeabasedAB system. From the structure of the results for the total time and winter time, it is found that, in general, the values for the winter time are higher than for the total time. If one refers now to the selected reference points, the highest values of the capture width were obtained for the points P1, P3, P7 and P8, in all cases. Thus, 66.0 m for P1, 72.6 m for P7, for the Wave Dragon system and at larger distance from the other WECs. 9.7 m for P1 and 10.81 m for P7 for the Oceantec system, 5.48 m for P1 and 5.13 m for P8 for the Pelamis system and 0.23 m for P3 and 0.19 m for P8 with the SeabasedAB system, values for the winter time. The smallest values are for the points P4, P5 and P2.



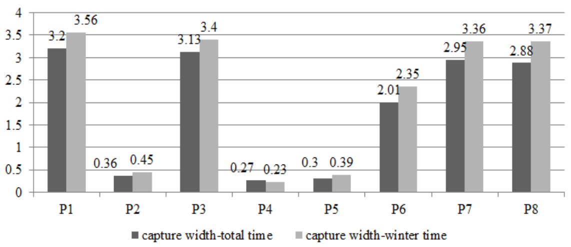
a) Wave Dragon



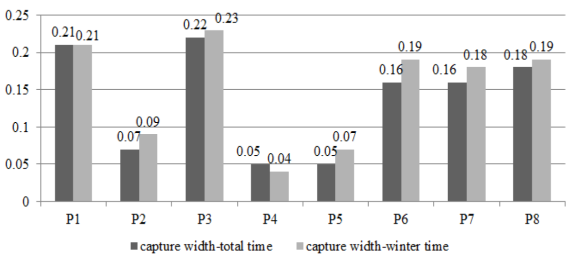
b) Oceantec



c) Pelamis



d) Wave Bob



e) SeabasedAB

Fig. 8. The capture width of the WECs systems considered in the study for total and winter time

CONCLUSIONS

Waves of the oceans and seas are an important renewable energy source that can significantly contribute to the global energy security, reducing the environmental pollution and increasing the energy independence of many countries.

From this perspective, in this work, an assessment of the wave potential in the Black Sea was done, taking into account 8 reference points along its coast (west, northwest, east, southeast and south), at different distances from the shore (3.39-44.1 km) and different depths of the water (12-160 m). By their geographic position, the selected reference points have different values for the wave parameters, allowing, thus, testing the five chosen WECs systems under different wave conditions. The wave parameters were determined taking into account the data generated by the ERA-Interim project. From the wave parameter analysis, it has been found that they have higher values in the winter than in the total time.

In order to appreciate the performance of the WEC systems, five different devices belonging to the three categories in terms of their operating principle, were considered, of which a system with high nominal power (5900 KW, Wave Dragon), another one with the nominal power of 1000 KW (Wave Bob) and the other three with nominal power less than 1000 KW (Pelamis, Oceantec, SeabasedAB). From these systems, the Wave Dragon presents the best performance in terms of expected power output and capture width, far away from the other studied systems, but ranks on the third place for the capacity factor, comparable to other WECs. Pelamis, Oceantec and Wave Bob systems show some variation between the expected power output, while the SeabasedAB system records the smallest power in the range of 0.01-0.54 kW (total time) and 0.01-0.99 kW (winter time). At the same order, it is situated the capture width for these four systems. Some change is recorded for the capacity factor, meaning that the SeabasedAB system is no longer on the last place, but on the second place after the Oceantec, followed by the Pelamis and Wave Bob systems.

The results obtained in the present study indicate that, for the Black Sea, the best WECs are Wave Dragon with high nominal power and Oceantec with nominal power equal to or less than 1000 KW.

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