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Dimensionless Normalized Wave Power in the Hot-spot Areas of the Black Sea

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Abstract. The main objective of this study is to identify and compare wave power sources in the high potential areas in nearshore and shallow water regions of the Black Sea. To achieve the goal, 23 locations were selected on two parallel lines around 5 m (10 sites) and around 25 m (13 sites) depth along the shoreline. The data needed to do the required analyzes at these locations were produced by using the calibrated nested layered 31-year wave hindcast SWAN model, which is operated between 1979-2009 with CFSR winds. The wave data were collected at a 2-hour time resolution for the sub-grid domains (SD3, SD2, and SD1) developed for the vicinity of Karaburun, Filyos, and Sinop coasts. HeaveBuoy, Oyster, Seabased AB, WaveDragon, WaveStar, Oyster2, and SSG, the most common known wave energy converters, were evaluated in the analysis. To ensure a more comprehensive analysis of the geographic variation of the predicted electrical power for each considered wave energy converter system, dimensionless normalized wave power and efficiency index were calculated separately for each wave energy converter devices at each location. From the results, it is recognized that generally, all the WEC systems performances are decreasing from Karaburun to Sinop while FB1 (13 m depth) the lowest, and KA2 (25 m depth) has the highest wave power capability. The most and the least energetic years were 1998 and 1989, repectively.

1 Introduction

In order to regulate greenhouse gases, we need to replace fossil fuels with clean energy. The extraction of ocean wave energy, which is a vast clean energy resource, became a challenging problem in the 21st century. It has been exploring to commercialize ocean wave energy, almost everywhere around the world. As the WECs (Wave Energy Converter Systems) cost a lot to make or install, a lot of projects are in progress to bring ocean wave energy commercially. Because of that, a detailed investigation of the desired geographical locations is highly required. The geographical location of Turkey, in which the three sides are surrounded by sea, makes it a potential area for the production of energy from waves. WEC systems are some developed technologies for installation in both coastal and open sea areas. The primary purpose of this research work is to investigate seven different WECs which their installation depth range is between 5-30 meters on two parallel lines (first line depth is around 5 m and the second line depth is about 25 m) to the shoreline of the south-west of the Black Sea. The dimensionless normalized wave power (P_{En}) is calculated, and the comparison of WECs power production performance and the energy capacity of the locations are discussed.

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2 Study Area and Wave Data

The long-term (31-year) estimations of wave parameters along the south-west coast of the Black Sea were produced spatially for all the study area by our previous research works [1-3] This data set uses the CFSR winds and the nested grid system, which focuses on 3 sub-domains (Karaburun, Filyos, and Sinop) in the south-west of the Black Sea, the coarse grid, fine grid, and each sub-grid domains were generated using the third generation numerical wave prediction model SWAN version 41.01AB, which was calibrated separately and subsequently verified by wave measurements which were not used in the calibration. The detailed information on the calibration and verification of the coarse grid can be found in [1]. Furthermore, although an article on the detailed calibration and verification of the nested grid system is published [4], the initial findings are presented in a conference paper [5]. Therefore, all the wave parameters needed for each location of this study are extracted from the specified data set in a period of 31 years at a time resolution of 2 hours. For the forcing of the SWAN model, the CFSR winds [6] at 10 m above the surface of water with a spatial resolution of 0.3125°, and a time resolution of 1 hr were used. The bathymetry and nested domains are shown in Fig.1

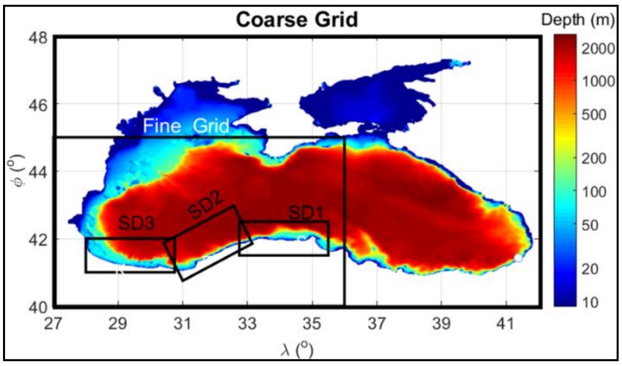

Fig. 1: The bathymetry map of Black Sea, The coarse grid, Fine grid and sub-domains (SD3, SD2 & SD1)

In Karaburun (SD3), Filyos (SD2), and Sinop (SD1) 13 lines perpendicular to the coastline were chosen for our present TUBITAK project on every line, five different depths were selected (5, 25, 50, 75, and 100m). In this paper, the (P_{En}) of 7 different WECs was calculated for 62 locations. Only the details of 23 locations are presented in Table 1; the rest of the locations will be presented in the presentation. In Fig. 2, there are 13 lines perpendicular to the coastline from left to right on three lines (KD, FC, and SB); the slopes of bathymetry are changed suddenly so, the 5 m depth does not exist. Because of that, there are only 10 locations on the first and 13 locations on the second parallel line to the shoreline.

Table1. The coordinates and depth of the chosen locations in the study area, the first two letters in location names represent the ID of perpendicular lines to the coastline.

ID on Map	Location Name	Xp (°)	Yp (°)	Depth (m)
1	KA1	28.0625	41.8913	4.1
2	KA2	28.0938	41.8913	25.2
3	KB1	28.1938	41.5696	7.0
4	KB2	28.2125	41.5696	25.9
5	KC1	28.7813	41.3174	12.7
6	KC2	28.7875	41.3217	22.3
-	-	-	-	-
7	KD2	29.5000	41.2087	26.4
8	KE1	30.3188	41.2043	7.2
9	KE2	30.3188	41.2174	25.9
10	FA1	31.0033	41.0860	14.0
11	FA2	31.0035	41.0982	24.6
12	FB1	31.3727	41.1907	13.0
13	FB2	31.3504	41.2051	23.9
-	-	-	-	-
14	FC2	31.8416	41.5057	26.9
15	FD1	32.5268	41.8124	15.7
16	FD2	32.5193	41.8147	30.9
17	SA1	33.0438	41.9348	11.5
18	SA2	33.0313	41.9435	24.5
-	-	-	-	-
19	SB2	33.9375	41.9870	27.0
20	SC1	34.9125	42.0348	14.0
21	SC2	34.9063	42.0478	25.9
22	SD1	35.1688	41.8522	13.0
23	SD2	35.1975	41.8609	26.2

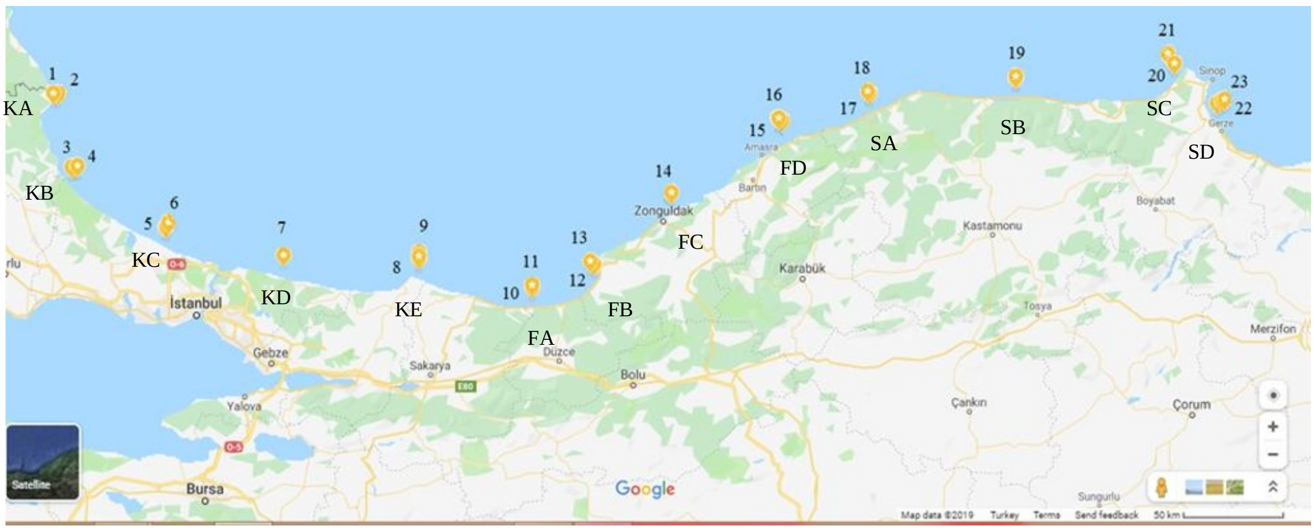

Fig. 2: The yellow points numbered from left to right are the 23 selected locations in SD3, SD2 and SD1 sub-domains.

3 Calculating annual energy production

One of the fundamental objectives of numerical modeling is the estimation of the mean annual energy production of WEC systems. "*It is directly used in the calculation of the levelized cost of energy, which is the primary economic determinant of competitiveness of wave energy"* [7]. There are three different methods for representation of the wave energy resource, scatter table (the traditional way), abridged set of spectral wave data, and extensive set of spectral wave data for detailed information refer to [7]. Some necessary details of the seven WEC systems which can work in the depth range of (4-30 m depth) are given in Table 2.

Table 2. Some essential characteristics of the considered wave energy converter technologies [8 -12].

WEC System	Nominal Power [kW]	Classifications	Power Matrix Resolution [m× sec]
HeaveBuoy	2192	Bottom-Fixed	0.5×1.0 [$H_s \times T_{mean}$]
Oyster	290	Terminator	0.5×1.0 [$H_s \times T_e$]
Seabased AB	15	Absorber	0.5×1.0 [$H_s \times T_{peak}$]
SSG	20000	Terminator	0.5×0.5 [$H_s \times T_e$]
WaveDragon	7000	Terminator	0.5×0.5 [$H_s \times T_e$]
WaveStar	2709	Point Absorber	0.5×1.0 [$H_s \times T_e$]
Oyster 2	3332	Point Absorber	0.5×1.0 [$H_s \times T_e$]

From 1979 to 2009, the annual total energy is calculated for every year and every location separately, using the following equation [7].

$$E_0 = T\sum_{i=1}^{N} P_i \cdot f_i \qquad (1)$$

Where

$$\sum_{i=1}^{N} f_i = 1 \qquad (2)$$

In the above equations, f_i represents each sea wave state (characteristic matrix), and P_i shows the electric power efficiency for the same cell in the power matrix of the WEC system, and T is the total length of a year 8760 hr or 8784 hr. The characteristic matrix is the probability of the occurrence of sea states, and its total is equal to one [7].

In this study, for the calculation of annual total energy, a combination of scatter table (characteristic matrix) and the power matrix of the WEC system is used. As an example, Table 3, the power matrix of oyster, and Table 4, the scatter table of location KA2 (25 m depth) for 1979, are presented.

Table 3. The power matrix of Oyster, H_s represents significant wave height, and T_e represents the wave energy period [10].

H_s (m)	T_e (s) 5	6	7	8	9	10	11	12	13
0.5	0	0	0	0	0	0	1	3	3
1.0	20	30	38	42	44	44	45	47	45
1.5	80	85	92	97	102	103	104	100	104
2.0	140	147	152	158	155	155	160	161	156
2.5	192	197	208	202	203	209	211	201	204
3.0	241	237	237	241	243	230	236	231	235
3.5	0	271	272	269	268	267	270	260	260
4.0	0	291	290	290	280	287	276	278	277
4.5	0	291	290	290	280	287	276	278	277
5.0	0	0	290	290	280	287	276	278	277
5.5	0	0	290	290	280	287	276	278	277
6.0	0	0	290	290	280	287	276	278	277

Table 4. The annual characteristic matrix of the sea state at location KA2 (25 m depth) for 1979. H_s represents the significant wave height, and T_e represents the wave energy period.

H_s (m)	T_e (s) 5	6	7	8	9	10	11	12	13
0.5	371	33	4	4	2	0	0	0	0
1.0	517	411	122	10	1	0	0	0	0
1.5	13	152	241	67	1	0	0	0	0
2.0	0	2	62	194	118	13	0	0	0
2.5	0	0	0	2	88	71	51	5	0
3.0	0	0	0	0	0	0	0	5	4
3.5	0	0	0	0	0	0	0	0	0
4.0	0	0	0	0	0	0	0	0	0
4.5	0	0	0	0	0	0	0	0	0
5.0	0	0	0	0	0	0	0	0	0
5.5	0	0	0	0	0	0	0	0	0
6.0	0	0	0	0	0	0	0	0	0

4 Results

Providing a more detailed illustration of the geographical variations of estimated wave electric power for each considered WEC system, the P_{En} was calculated for every WEC system in 23 different geographic locations with a depth range of 5 m to 30 m. Thus, Fig.3 and Fig.4 illustrate the annual expected energy and dimensionless normalized wave electric power provided by Oyster, Oyster2, SSG, HeaveBuoy, Seabased AB, WaveStar, and WaveDragon. The P_{En} is calculated with the following equation [10].

$$P_{En} = \frac{P_E}{P_{E,max}} \times 100 \qquad (3)$$

in which P_E is the estimated wave electric power in the respective location for the considered device, and P_{Emax} is the maximum annual power of the same device in all the locations which the same device can work in the period of 31 years (1979-2009).

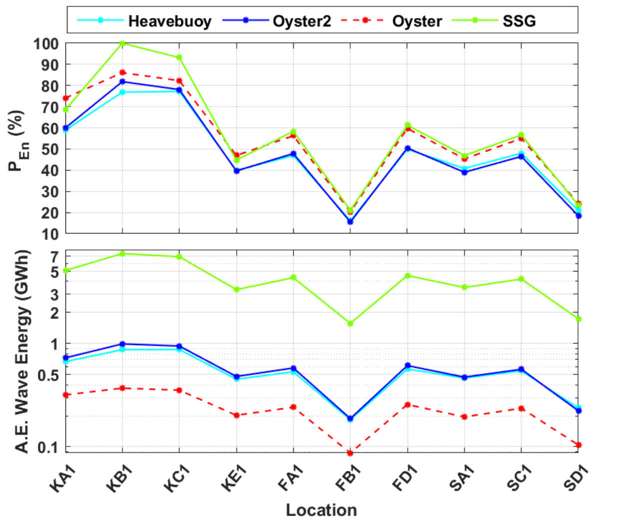

Fig. 3. On the top P_{En} (%) and on the bottom, the annual expected mean wave power (GWh) of Oyster, Oyster2, SSG, and HeaveBuoy at 10 different locations on a line of about 5 m depth parallel to the coastline.

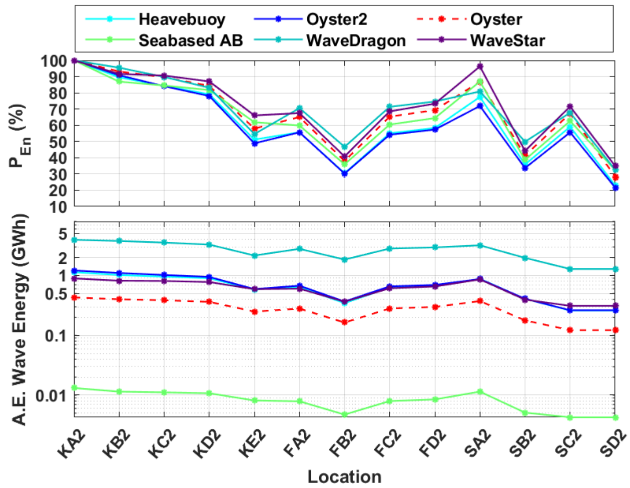

Fig. 4. On the top P_{En} and on the bottom, the annual expected mean wave power (GWh) of Oyster, Oyster2, Seabased AB, WaveStar, HeaveBuoy, and WaveDragon at 13 different locations on a line of around 25 m depth parallel to the coastline.

In order to have a clearer picture of the variations of power production of WEC systems in the time period, the efficiency index E_i (%) and the annual expected wave power (GWh) of 7 different WEC systems were graphed at location KA2 (the most enegetic location) in Fig. 5, as an example. These graphs are drawn for all other locations as well; some more examples will be presented in the presentation. The E_i is the ratio of P_E and the maximum annual wave energy ($P_{ET,max}$) during the 31-year longterm dataset and the higher E_i represents the better performance of the device.

$$E_i = \frac{P_E}{P_{ET,max}} \times 100 \qquad (4)$$

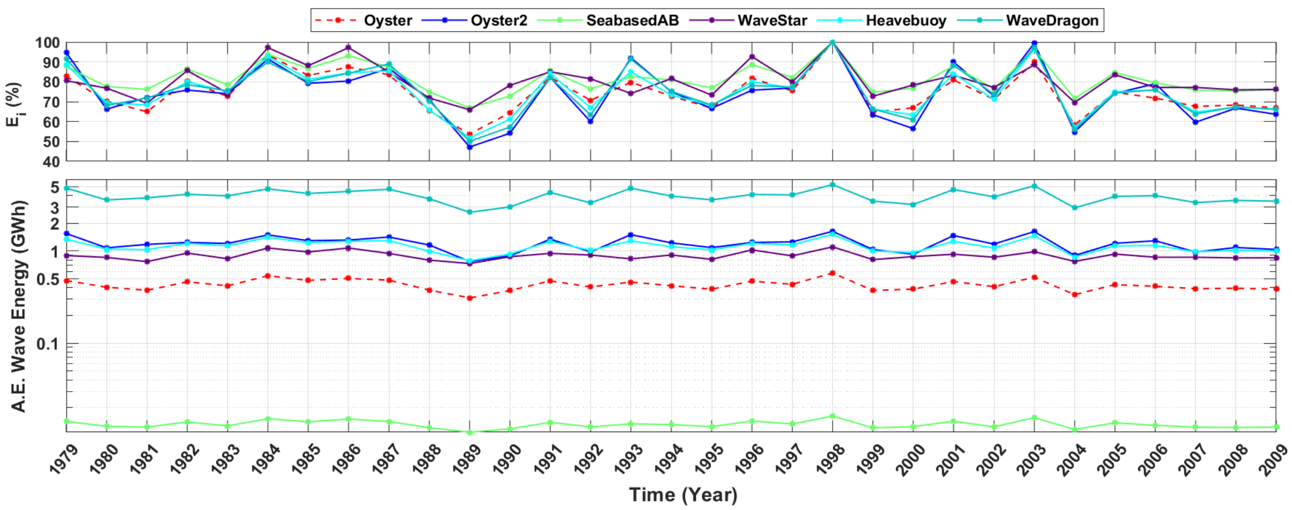

Fig. 5. On the top E_i (%) and on the bottom annual expected wave power (GWh) of Oyster, Oyster2, Seabased AB, WaveStar, HeaveBuoy and WaveDragon only in total time (1979-2009) at KA2 (25m depth)

In Fig.3 and Fig.4, we can see that all the WEC systems' performances in both lines (5 m and 25 m) are relatively decreasing from Karaburun to Sinop. In Fig.3, the WEC systems in which their installation depth is around 5 m, all the devices produce the highest P_{En} at KB1 and KC1, but the lowest P_{En} is at FB1 and SD1. In Fig.4, the highest wave power and P_{En} value are at KA2 and SA2. One of the reasons that SA2 has a high wave energy capacity is the long wave fetch, which starts from Odessa coasts and ends in Sinop coasts. Fig. 5 shows that 1998 is the most dynamic year for all devices, and 1989 is the calmest year in the aforementioned time period (1979-2009). In Fig. 5 at KA2 WaveDragon, the highest and Seabased AB produce the lowest wave energy.

5 Conclusion

In this work, the evaluation of wave conditions in the southwestern coasts of the Black Sea in a time interval from 1979-2009 by calculating the normalized wave, electric power and efficiency index was performed. On this basis, the performance of 7 different WEC systems were evaluated in their installation depth range (5-30 m depth). The results show that a correct identification of high energetic geographical locations is essential. It's vital to have ideas about the expected wave energy in different places in the interested area and also have ideas on the comparison between different wave energy converting technologies. The computational strategy is based on the SWAN model for the nearshore wave transformation. Three computational phases were defined for the SWAN simulations; the first one was a coarse grid covering all the Black Sea. The second one was a fine grid covering all the southwestern coasts of the Black Sea and three sub-domains (Karaburun, Filyos, and Sinop). The 62 point-data was extracted from the sub-domains data set. Then, the characteristic matrices of sea states (defined by significant wave height and peak period, mean period or energy period) were generated. Using the power matrices of WECs and the Characteristic matrices of the sea states, the annual total energy was calculated for every WEC system and every location, separately. The normalized wave energy and efficiency index were calculated in each location for every device, and a detailed comparison between these machines and geographical areas were made.

The wave energy analysis in the southwest of Black Sea shows that at the considered locations the highest values of P_{En}, E_i and the highest wave power for areas with (5-15 m depth, find Fig.3) is obtained from SSG especially at location KB1 (13 m depth), and the lowest P_{En} values are reported by Oyster2 and the density of wave power get their maximum value at location KB1 (100%, 7.45 GWh for SSG) and decreasing from Karaburun to Filyos gradually. Generally, the locations with a depth range of (20-30 m, find Fig. 4) are more energetic as it was expected. The highest P_{En} values are given by WaveStar and WaveDragon where the Oyster2 gives the lowest P_{En} values. All the devices show their best performance at location KA2 and SA2 respectively for WaveStar (100% and 97%). The wave density is again decreasing from Karaburun to Sinop. FB1 and SD1 from the first and FB2 and SD2 are the calmest sites in the study area. 1998 and 2003 are the most and 1989 is the least dynamic years in the 31-year period. The results of this study are not enough to decide the best machine-location combination so, many other parameters should be investigated as the WECs capacity factor, device survivability, installation, maintenance and mooring costs, potential environmental conflicts, grid connection points, permitting requirements, shipping traffic and other sea applications as well.

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