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Power Production Performance of Different Wave Energy Converters in the Southwestern Black Sea

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***Abstract*—**This study aims to investigate the amount of energy (economic wave energy potential) that can be obtained from the existing wave energy converters in the high wave energy potential region of the Black Sea in terms of wave energy potential and their performance at different depths in the region. The data needed for this purpose were obtained using the calibrated nested layered SWAN wave modeling program version 41.01AB, which was forced with Climate Forecast System Reanalysis (CFSR) winds from 1979 to 2009. The wave dataset at a time interval of 2 hours was accumulated for a sub-grid domain for around Karaburun beach in Arnavutkoy, a district of Istanbul city. The annual sea state characteristic matrices for the five different depths along with a vertical line to the coastline were calculated for 31 years. According to the power matrices of different wave energy converter systems and characteristic matrices for each possible installation depth, the probability distribution tables of the specified mean wave period or wave energy period and significant wave height were calculated. Then, by using the relationship between these distribution tables, according to the present wave climate, the energy that the wave energy converter systems at each depth can produce was determined. Thus, the economically feasible potential of the relevant coastal zone was revealed, and the effect of different depths on energy converter systems is presented. The Oceantic at 50, 75 and 100 m depths and Oyster at 5 and 25 m depths presents the best performance. In the 31-year long period 1998 the most and 1989 is the least dynamic year.

***Keywords*—**Annual power production, Black Sea, efficiency, power production performance, wave energy converter.

I. Introduction

GLOBAL concerns about anthropogenic greenhouse gas abatement have led to emissions and the need to assist in more sustainable development, both in the expansion of renewable energy investments and in the creation of renewable energy directives for the share of future carbon-free energy. In 2015, the United Nations Framework Convention on Climate Change formulated the Paris Climate Agreement in which the commitment to reduce global warming to below 2 degrees was adopted [6]. Since electricity production constitutes 25% of greenhouse gas emissions worldwide, the transition to renewable energy production is accepted as a critical component to achieve this goal [7]. Therefore, all countries of the world are trying to find ways to produce more sustainable, high quality and environmentally friendly energy. So, with Turkey a young populated country, which is one of the world's fastest growing economies, is not an exception. Turkey's population is expected to grow significantly over the next few decades. Along with this growth and Turkey's 2023 development plans to achieve these goals will certainly need more energy. In order to achieve the goal of the renewable energy sources in electricity production share to be at least 30% in 2023 [8], the production of renewable energy resources must be increased; on the other hand, new resources should be put into operation. Wave energy is a technology that attracts considerable investment. Technologies that will benefit from a largely unused wave energy source have the potential to contribute in reductions of greenhouse gas concentrations and be as important part of the future global energy mix. However, the progress from pre-commercial, full-scale prototype tests to the commercialization of Wave Energy Converters (WEC) is relatively slow. This is partly due to the variability of the wave energy sources and the subsequent financial risks of potential production performance over the expected life of the projects. Therefore, analyzing both inter and intra annual performance of WEC technologies is very important before establishing a WEC farm [1].

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II. Study Area and Dataset

The needed wave data to detect the energy presence of the south-west coast of the Black Sea were generated using a layered nested wave hindcast model calibrated and validated with the data of the measuring stations, corresponding to each sub-domain [2], [3]. In this layered network system, firstly waves are generated on a regular computational domain covering the entire Black Sea, then calculations are made on a finer regular domain covering the western part of the Black Sea with boundary conditions taken from the previous regular domain which covered all the Black Sea. Finally, with the boundary conditions provided by this fine domain, a long-term wave database is created in a high-resolution local sub-domain area (Fig. 1) focusing on the shores of Karaburun (SD3). To provide all the data needed for determining, the wave climate and wave energy flux of the desired locations, the significant wave height, wave peak period and wave energy period parameters are taken from this database accumulated for 31 years between 1979-2009 at 2-hour time resolution and 0.005^o spatial resolution.

Five different depths (5 m, 25 m, 50 m, 75 m and 100 m) were selected along a line perpendicular to the shoreline in the Karaburun sub-domain SD3. The coordinate and depth information of the selected locations are shown in Table I.

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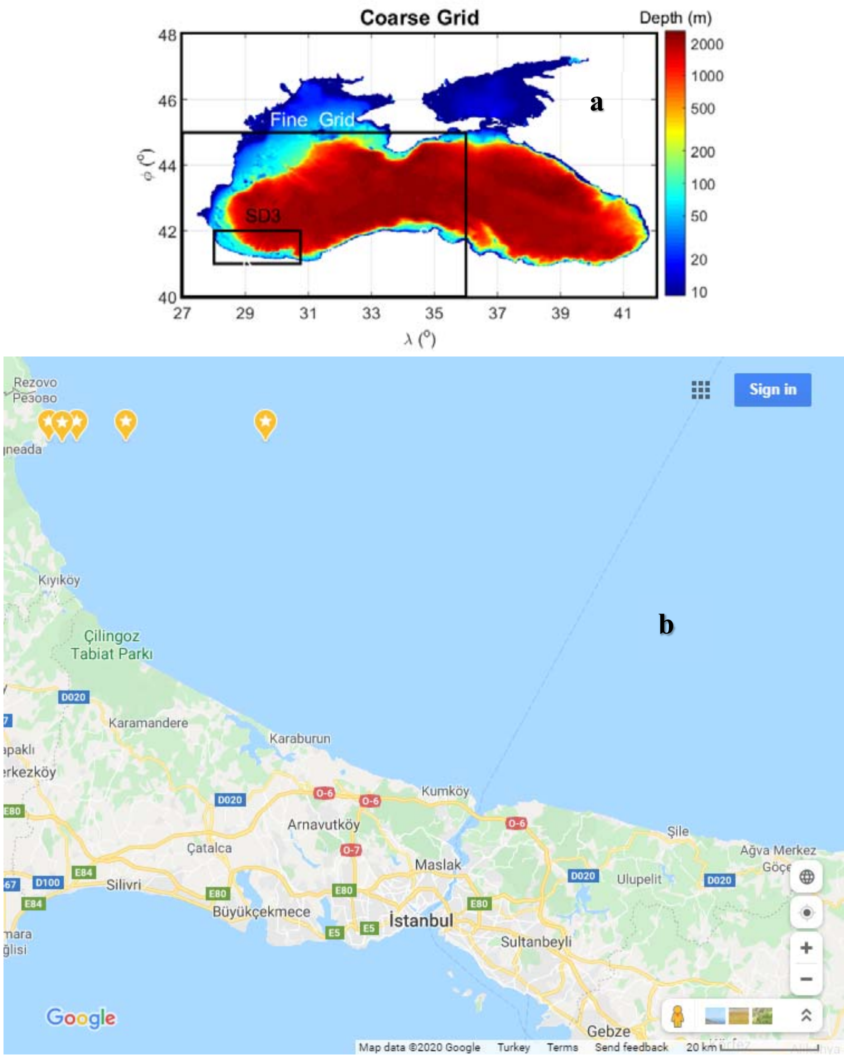

Fig. 1 The bathymetry map of the entire Black Sea and the layered nested grids (a) and the yellow points numbered from left to right are the five selected locations in SD3 sub-domain

TABLE I
THE COORDINATE AND DEPTH INFORMATION OF THE CURRENTLY SELECTED FIVE LOCATIONS

Locations	Xp (o)	Yp (o)	Depth (m)
Location 1	28.0625	41.8913	4.0949
Location 2	28.0938	41.8913	25.1939
Location 3	28.1250	41.8913	54.2750
Location 4	28.2437	41.8913	74.7855
Location 5	28.5688	41.8913	99.4807

III. WEC SYSTEMS (WECS)

In this study, 15 different WEC technologies, AquaBuoy, AWS, Langlee, OE Buoy, Pelamis, Pontoon, SeaPower, Wavebob, Heave buoy, Oceantec, Oyster, Oyster2, Seabased, SSG, WaveDragon and Wave Star were selected. These WEC systems are characterized by different working principles at different depths. The main characteristics of the WEC systems which are considered in this study are given in Table II.

IV. POTENTIAL ANNUAL ENERGY PRODUCTION AND PERFORMANCE

The power generation of a WEC in a field is a result of combining the power matrix of the device with the present wave climate characteristic matrix of the respective region [4]. The potential annual power production (in MWh) for each of the WEC devices at each station is calculated according to (1) [1]:

$$E_0 = \sum_{i=1}^{nT} \sum_{i=1}^{nH} p_{ij} * P_{ij} \qquad (1)$$

In (1), ρij represents each sea wave state (characteristic matrix), and Pij shows the electric power efficiency for the same cell in the power matrix of the WEC system. The annual or monthly wave power of different WEC systems depends on the nominal power (P_m) of the same system. The production performance is the ratio of power production (E_0) to the nominal power (P_m) of the device as in (2) [1]:

$$R_h = \frac{E_0}{P_m} \tag{2}$$

The ratio (R_h) is expressed in (Wh/W).

V. Results and Discussion

The average annual R_h values of the Wave Energy Conversion Systems for 5 different stations are presented in Fig. 2. According to this figure, the R_h values are plotted for the considered 35 WEC-Station combinations. The largest power production can be achieved with Oceantec-500 technology, R_h = 1916 Wh/W at maximum water depth (100 m), followed by Oyster-290 with 1483 Wh/W at 25 m depth. In the study area, Oceantec and Oyster have the potential to generate almost three times more energy than other WEC systems. At 100, 75 and 50 m depths, Oceantec-500 and at 25 and 5 m depths Oyster-290 and Seabased-15 are the technologies which provide the highest R_h values.

Fig. 3 shows the annual R_h values in a 31-year time period for 7 different WEC systems operating at 5 and 25 m depths. The Oyster WEC system has higher R_h values in comparison with the other 6 installable systems in location 1 and Location 2. The highest value is 1988 Wh/W in 1998 at Location 2. At this depth, the lowest energy production (300 Wh/W) is achieved by the Wave Star. The Heave Buoy and Wave Dragon WECs show almost the same performance throughout the time period.

Fig. 4 presents annual Rh values of 31 years for 11 different WECs operating approximately at 50, 75 and 100 m water depths. In these systems, it is observed that Oceantec has a better performance in comparison with the other systems at all the three different depths. Rh value for Oceantec was determined to be the lowest in 1989 and highest in 1998. It is worth to say that the changes of the Rh values for the other 10 WECs except Seabased AB present at least 500 Wh/W and they show parallelism with each other during 1979-2009 period.

TABLE II
MAIN CHARACTERISTICS OF THE CONSIDERED WAVE ENERGY CONVERSION TECHNOLOGIES [1], [5]

WEC System	Nominal Power [kW]	Classifications	Installation Depth [m]	Power Matrix Resolution [Hs × Te]
Aqua Buoy	250	Point Absorber	Offshore (50-60)	0.5m × 1.0s
AWS	2470	Point Absorber	Offshore (100)	0.5m × 0.5s
Heave buoy	2192	Bottom-Fixed	Shallow Water	0.5m × 1.0s
Langlee	1665	Oscillating Surge Transducer	Offshore	0.5m × 1.0s
Oceantec	500	Absorber	Offshore (50-100)	0.5m × 1.0s
OE Buoy	2880	Point Absorber	Offshore (> 100)	0.5m × 1.0s
Oyster 2	3332	Point Absorber	Offshore (< 50)	0.5m × 1.0s
Oyster	290	Terminator	Near Shore ((10-25)	0.5m × 1.0s
Pelamis	750	Absorber	Offshore (50-70)	0.5m × 0.5s
Pontoon	3619	Point Absorber	Offshore (>100)	0.5m × 1.0s
Seabased AB	15	Absorber	30-50	0.5m × 1.0s
SSG	20000	Terminator	Foreshore	0.5m × 0.5s
Wave Bob	1000	Point Absorber	Offshore (>50)	0.5m × 0.5s
Wave Dragon	7000	Terminator	Near Offshore (> 20)	0.5m × 0.5s
Wave Star	2709	Point Absorber	Near Shore (30-50)	0.5m × 1.0s

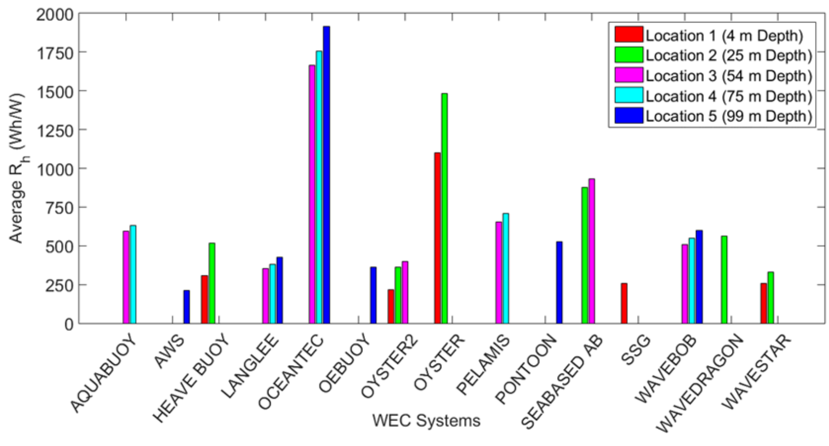

Fig. 2 Average annual R_h values of 15 different WECs at 5 different locations

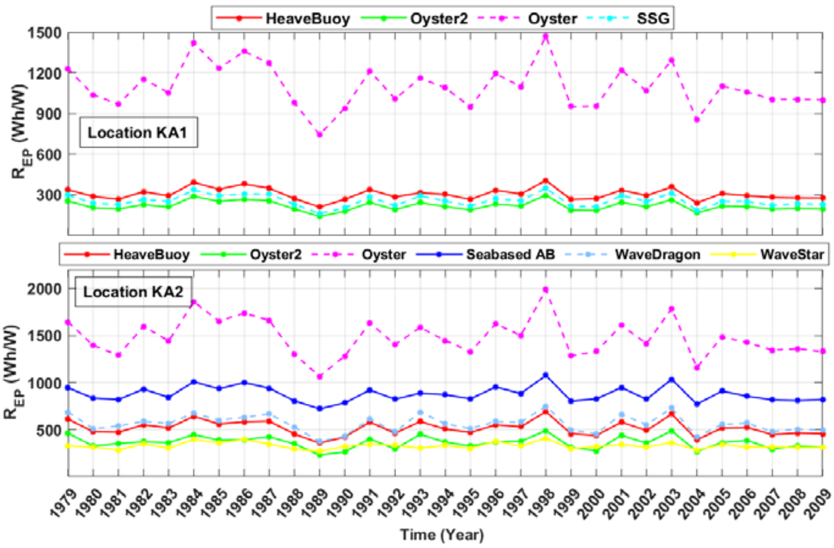

Fig. 3 Annual R_h values of 7 different WECs in Location 1 (5 m depth) and Location 2 (25 m depth)

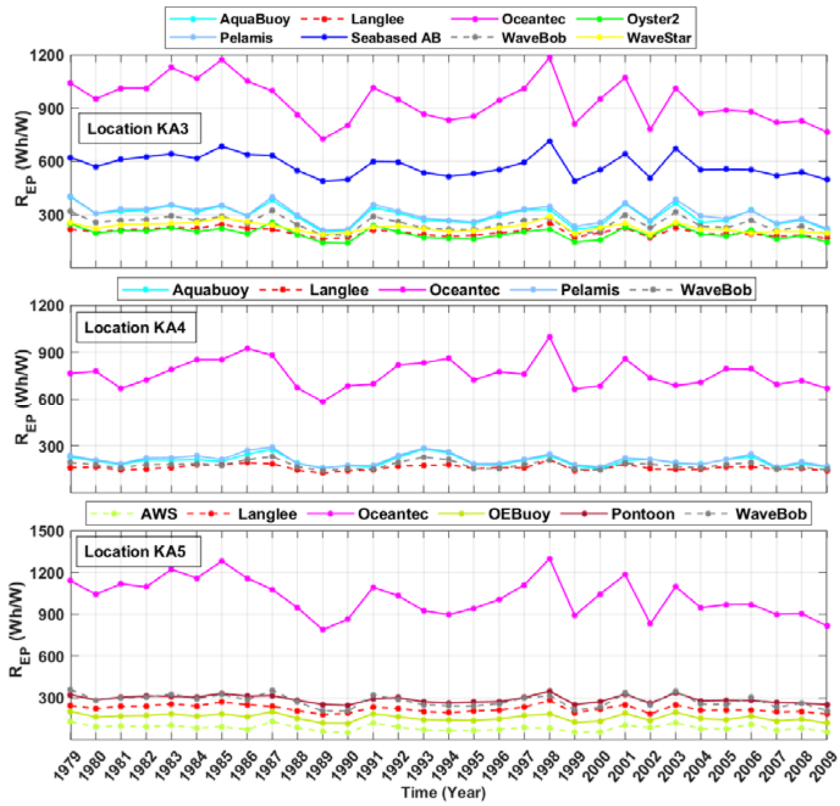

Fig. 4 Annual R_h values of 5 different WECs in location 3 (50 m depth), location 4 (75 m depth) and Location 5 (100 m depth)

VI. Conclusion

The establishment of a wave farm in the coastal area should be based primarily on a comprehensive analysis of the energy production that existing technologies can provide in different areas of interest. In this study, a total of 15 technologies at 5 different water depths forming 35 different WEC-Location combinations were analyzed. The characteristic matrices were obtained from the database with the desired resolution level (the same as the power matrix of the considered device) and the energy output (R_h) of the WECs per installed power unit was calculated. The technology that provides the highest R_h values is the Oceantec-500 at a water depth of 100 m. As the water depth decreases (100-5m) energy production decreased as well. In the study area, the Oceantec-500 is the technology that provides the highest production performance (R_h values) in its installation depth range (50-100 m). Oyster presents the best performance at 5 and 25 m depths. It is also worth to say that 1998 is the most and 1989 is the least dynamic year. However, the final decision on the choice of WEC technologies and location to build a wave farm in the coastal area should be based on a comprehensive knowledge of potential factors such as installation and operating costs as well as other environmental factors.

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