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Wave energy assessment in the Mediterranean Sea

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ABSTRACT: The aim of the paper is to analyze the Mediterranean's wave resource, in order to determine the optimal locations for wave energy converters (WECs) deployment in the region. A preliminary estimation of the available wave resource in the Mediterranean Sea provided eight potential locations. The areas that demonstrated the highest wave resource were distinguished for a more detailed analysis. Further parameters were taken into consideration for the analysis such as the bathymetry and the distance from the shore. For each selected location, an assessment of the wave energy that could be produced by three different WECs was performed, namely Pelamis, WaveDragon and AquaBuoy. The power matrices were used in order to estimate the mean annual energy production in the selected areas, for each WEC.

1 INTRODUCTION

The natural world is filled with an abundance of renewable energy sources, as is wind, wave, tidal, biomass, osmotic, and more. Wave energy presents an ample source, which is estimated at 2 TW on a global scale (Besio et al., 2016). Researchers have dealt not only with the wave resource of the ocean, but also with siting and efficacy of a diversity of renewable energy systems given the area of interest.

Liberti et al., (2013) using data from the WAM Cycle 4.5.3 model, presented some remarkable results for the average annual wave power resource (energy flux) of areas such as Menorca 10.90 kW/m, Hyères 6.47 kW/m, Ajaccio 8.44 kW/m, Ras Al Hilal 6.59 kW/m, Ras Angela 9.25 kW/m, Alghero ~12 kW/m and Manzara del Vallo 6–7 kW/m. (Besio et al., 2016), based on 35 years of data (01/01/1979–31/12/2013) using the WavewatchIII wave model, provided the following wave power resource results for 4 areas of interest: Alghero 9.49 kW/m, Manzara del Vallo 5.58 kW/m, Annaba 9.10 kW/m, and Benghazi 5.97 kW/m. In a broader analysis taking into account several extended areas of the Mediterranean (Archambeau et al., 2016), by use of the numerical model SWAN, the following results were obtained: Italy 6–15 kW/m, southern Aegean 7–12 kW/m while for the northern Aegean 4–7 kW/m, France 4–7 kW/m, Spain 8–15 kW/m, Libya 6–11 kW/m and finally Tunisia up to 12 kW/m.

Lavidas & Venugopal (2017) utilized the formulations of WAM III and IV cycles to calibrate a SWAN model that was used for the Aegean Sea, in order to evaluate its results with in-situ measurements and accurately depict the spatial distribution of wave resource in the examined region. The analysis of the 35-year long dataset (1980-2014) demonstrated that the areas in the Aegean, with the highest wave power resource, are found in the E and W coasts of Crete Isl. (≃8 kW/m), as well as in specific areas of the Cyclades complex (5–6.5 kW/m). Following simulations for the three energy converters in these sites, the maximum annual energy output was found to occur offshore E Crete Isl., Kithnos Isl., and Paros Isl., with the WECs having the potential to produce energy in the range of 0.39–1.28 GWh for the Pelamis, 5.92–11.51 GWh for the Wave Dragon and 0.12–0.24 for the AquaBuoy.

According to Guillou & Chapalain, (2018), who studied the area of W Bretagne in France taking into account the seasonal and annual variability of the wave power resource, the latter was estimated at 40 kW/m. They then calculated the annual energy produced by each of the three wave energy converters (WEC) under study, namely Pelamis, Wave Dragon, and AquaBuoy, for the same time span (2004–2011), as being approximately 1.03 GWh, 13.1 GWh, and 0.39 GWh respectively.

In Kardakaris et al., (2021), the complementarity and synergy of the wave and offshore wind power resource of the Greek Seas has been studied based on 20 years of the ERA5 dataset. Several locations have been identified where the complementarity or the synergy index between the examined resources take high values. Finally, in Soukissian & Karathanasi, (2021), the joint assessment of wave power

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resource and sea-state direction was performed based on both measured and reanalysis data for several locations in the Mediterranean Sea including Mykonos, Santorini and Zakynthos islands, and the Gulf of Lion.

2 WAVE POTENTIAL EVALUATION

The mean wave energy is the sum of the potential energy of water molecules due to their vertical oscillation and the kinetic energy due to their rotational motion. The potential wave energy is given by the formula:

$$\overline{E_P} = \rho g \frac{d^2}{2} + \rho g \frac{H^2}{16}, \quad (1)$$

where d is the water depth, g is the acceleration of gravity, ρ is the density of sea water and H is the wave height. The kinetic energy is:

$$\overline{E_K} = \rho g \frac{H^2}{16}, \quad (2)$$

and the total wave energy is provided as:

$$\overline{E} = \overline{E_\mathrm{P}} + \overline{E_\mathrm{K}} = \rho g \frac{d^2}{2} + \rho g \frac{H^2}{8}. \quad (3)$$

Wave power is usually described as the energy transmitted across a wavelength, on a level perpendicular to the directional motion of the wave, which is then multiplied by the wave group velocity c_g. The relation that expresses the wave power is the following:

$$P = c_g E = nc \frac{1}{8} \rho g H^2, \quad (4)$$

where

$$n = \frac{1}{2}\left[1 + \frac{2kd}{\sinh(2kd)}\right], \quad (5)$$

$$c = \frac{\lambda}{T} = \frac{\omega}{k} = \sqrt{\frac{g}{k}\tanh(kd)}, \quad (6)$$

where $k=2\pi/\lambda$ is the wave number, and ω is the angular frequency. When d approaches infinity, $n \rightarrow 1/2$ and $c=(g/k)^{1/2}$, and the wave power formula becomes:

$$P = nc \frac{1}{8} \rho g H^2 = \frac{1}{32\pi} \rho g^2 H^2 T, \quad (7)$$

while for shallow water, the formula becomes:

$$P = \frac{1}{8} \rho H^2 \sqrt{d} \sqrt[3]{g}, \quad (8)$$

However, estimating the wave power resource in real sea conditions is a more complicated issue. A realistic sea state does not consist of simple harmonic waves and therefore the factor of chance needs to be included. In fact the sea consists of a group of waves with different characteristics (frequencies, wavelengths, propagation directions) and its description is achieved through a distribution function of spectral energy density $S(f,\theta)$. For practical reasons it is common to use only certain spectral parameters such as the significant wave height H_S, the mean energy period T_e, the spectral peak period T_P and the average wave direction. For deep waters, the wave energy flux per unit of wave-crest length is given by the formula:

$$P = \frac{\rho g^2}{64\pi} \mathrm{H}_\mathrm{S}^2 T_e. \quad (9)$$

The significant wave height and the energy period are defined as functions of the zero m_0 and negative first order spectral moment m_{-1}, i.e.,

$$H_S = 4\sqrt{m_0}, \quad (10)$$

and

$$T_e = \frac{m_0}{m_{-1}}, \quad (11)$$

where in general:

$$m_n = \int_0^{2\pi} \int_0^{\infty} f^n S(f,\theta) df d\theta. \quad (12)$$

3 METHODOLOGY

3.1 *Site selection and data*

The data initially used in the implementation of the study were the significant wave height and the energy period provided by the ERA 5 reanalysis for the Mediterranean, from 2016 until 2020. The coordinates used as the Mediterranean region borders were from -6 W to 36.5° E and 30° S to 46° N.

The ERA 5 model is a set of data analysis (reanalysis) that combines satellite observations and numerical model results, which utilizes data assimilation to correct, optimize and produce more reliable data. The wave measurements and data generated have in spatial resolution of 0.5°X0.5° and a temporal resolution of one hour.

The use of ERA 5 datasets contributed to a preliminary assessment of the wave potential of the Mediterranean as a whole, in order to find the optimal areas for further analysis.

The areas selected are Ajaccio (AJ), Alghero (AL), Annaba (AN), Benghazi (BE), Kasos (KA), Hyères (HY), Manzara del Vallo (MV), Menorca (ME). See also Table 1 in section 4. These selected areas were studied to a greater extent using data with temporal coverage of 5 years (2015-2019) and with the more refined resolution of 1/24°, that was acquired from the Copernicus-CMEMS website. The wave model used to generate and collect data in the Mediterranean Sea is based on the WAM Cycle 4.6.2 numerical model. This modelling method, calculates a forecasting part of the wave spectrum in distributed frequencies, which is later corrected by use of significant wave height measurements, as recorded by a satellite system. The numerical model provides one instantaneous value per hour and takes into account one dimension, that of the sea surface. The spatial resolution creates a mesh of 0.042° x 0.042°,in the WGS 84 coordinate system (EPSG 4326). Each grid point contains a value for the significant wave height, its direction, and its period, with measurements recorded once per hour, for the duration of 5 years.

A new wave potential estimation was formulated for the 8 selected areas that were identified after analysis with ERA 5 data and calculations of their mean annual, seasonal and monthly potential. The selected areas were analysed on a 1°x1° spatial scale. For the annual distribution, the mean wave energy flux of the total 5 years of data in each region is presented. Similarly, with respect to the seasonal distribution of the wave potential, the data is divided into the 4 seasons (winter, spring, summer, autumn) where it corresponds, and a mean value is given for each season, from the 5 years in total, while for the monthly distribution a mean value for the wave potential of each month (12) in each area, is given taking into account the data for the same time period. The analysis and estimation of the wave potential was based on the formulas and equations mentioned in the previous section.

The mean wave energy flux for each grid point and for all sea-states in a given time period is calculated by the formula:

$$\bar{P} = \frac{\sum_{i=1}^{N} P_i}{N}, \tag{13}$$

where N is the total number of sea-states and P_i, is the wave energy flux for the i-th sea state.

3.2 *WEC power output*

Regarding the selection of the WEC installation locations in each area, it was necessary to take into account the water depth, in order to ensure the correct mooring of the WEC, as well as the distance from the shore for financial reasons, since as the distance from shore gets greater, the cost of energy transmission is increased. With respect to bathymetry, data from the EMODnet website was used, for each of the 8 sites. The final selection of the installation points was made considering where the largest wave potential of the area is, but also given an average depth of 50 m. At the 8 final selected points, the Pelamis, WaveDragon and AquaBuoy wave energy converters were installed. Each WEC provides a Power Matrix, displaying the output for each combination of significant wave height and energy period. In Figures 1, 2, and 3 the power matrices for the three WECs under study Pelamis, WaveDragon, and AquaBuoy are presented.

With the help of the power matrices, the mean energy E they produce was calculated on an annual and seasonal basis. Moreover, in order to better capture and evaluate the performance of the three WECs, their total operating hours and the total energy produced in the period of 5 years were also calculated, as well as each capacity factor CF, i.e.:

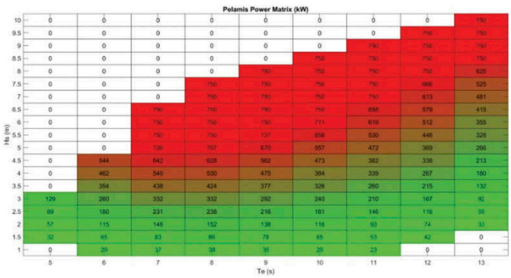

Figure 1. Pelamis power matrix (kW).

Figure 2. WaveDragon power matrix (kW).

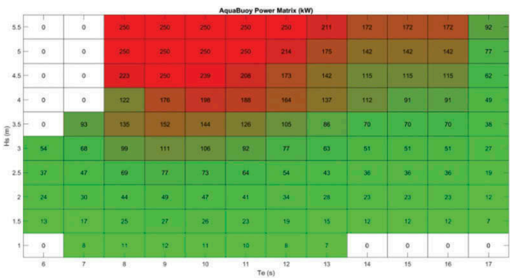

Figure 3. AquaBuoy power matrix (kW).

$$CF = \frac{P_A}{P_M}, \tag{14}$$

where P_A is the actual power output for a particular time period and P_M is the power output based on the maximum installed capacity for the same time period.

4 NUMERICAL RESULTS

4.1 *Available wave resource*

In the following sections, more detailed results for the Alghero location will be provided. In Figures 4, 5 and 6, the seasonal and annual wave power resource and the corresponding wave rose are respectively presented.

The highest resource is available during the winter period, with the mean wave energy flux being estimated at 20 kW/m throughout the study area. The wave energy flux shows a decrease during spring with an average value of 14 kW/m, while this reduction continues during the summer, when the minimum mean wave energy flux of the area is observed at 3 kW/m. Finally, during autumn, there is a progressive increase of the wave power resource at 10-11 kW/m.

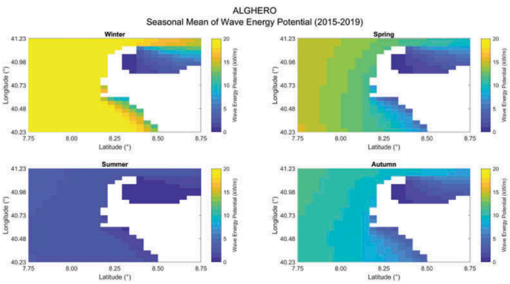

Figure 4. Seasonal wave power resource at Alghero.

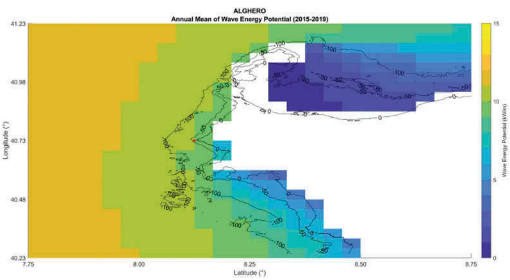

Figure 5. Annual wave power resource at Alghero.

The mean annual wave power resource is estimated at 11 kW/m. The location of the WEC was selected to meet the high energetic wave conditions, as well as the specifications and requirements of the WEC for anchoring at depths of approximately 50 m. This point in the extended study area is found at the coordinates 8.125°E and 40.729°N and a depth of 46 m while its potential is estimated at 10–11 kW/m.

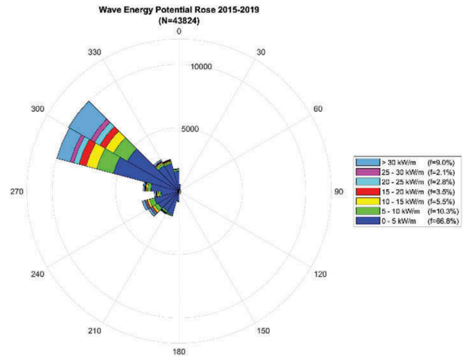

Figure 6. Annual wave energy flux rose at Alghero.

From Figure 6, it is observed that the prevailing sea-state direction was between 285° and 315°. The majority of the waves (57%) have heights up to 1 m, while the most common energy period ranges between 4-6 s (38%). In Figure 7, the frequency table of the significant wave height and energy period dur ing the 5 years period is shown for Alghero. The combination with the highest frequency is the same one emerging for the individual seasonal distribution, having a rate of 14.43%.

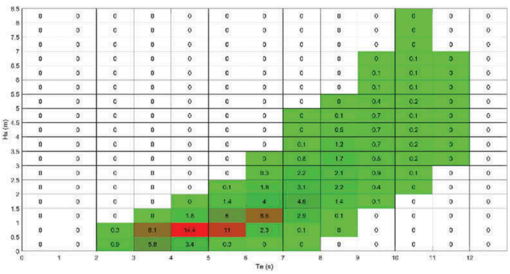

Figure 7. Annual frequency table of H_S and T_e at Alghero.

In the following Table 1, the locations, their coordinates and water depths, as well as the mean annual wave potential are presented.

Among the particular locations (that meet the necessary conditions of depth and high wave potential for the WEC installation), the study area that stands out from the results is Alghero. Alghero has the highest power resource (11 kW/m) of all examined locations. Then follow the areas Ajaccio, Annaba, Manzara del Vallo and Menorca with 9 kW/m, Benghazi with 7 kW/m, Hyères with 6 kW/m and finally Kasos with 5 kW/m.

Table 1. Mean annual wave power resource at the examined locations.

Location	Coordinates (°) E	N	Water depth (m)	Mean annual wave power resource (kW/m)
AJ	8.54	41.85	57	9
AL	8.12	40.73	46	11
AN	7.37	37.15	50	9
BE	20.04	32.27	48	7
KA	27.04	35.44	54	5
HY	6.25	42.99	59	6
MV	11.79	37.48	40	9
ME	4.04	40.10	62	9

In general, the analysis showed that the predominant wave class recorded in all study areas had a significant wave height between 0.25–0.75 m and energy period in the range of 3.5 to 4.5 s.

4.2 *Energy output*

In Table 2, the energy produced by each of the examined WECs is presented in a seasonal and annual basis. It can be seen that winter presents the highest energy efficiency in all regions (only Alghero is shown here). Moreover, the WECs seem to perform better during spring followed by autumn, with the minimum resource being available during summer. Exceptions to the seasonal power efficiency distribution present the areas of Kasos and Menorca where the declining power output ranking is as follows: winter, autumn, spring, and summer. Considering the mean annual power it is observed that the areas that are most efficient in declining order are: For Pelamis: Alghero, Manzara del Vallo, Menorca, Annaba, Ajaccio, Benghazi, Hyères, and Kasos; For Wave-Dragon: Alghero, Annaba, Ajaccio, Manzara del Vallo, Menorca, Benghazi, Hyères, and Kasos; For AquaBuoy: Alghero, Annaba, Ajaccio, Menorca, Manzara del Vallo, Benghazi, Hyères, and Kasos. Evidently, the area with the highest power output for each WEC is Alghero. In contrast, the areas with the lowest power output are Benghazi, Hyères and Kasos.

A way to evaluate the energy output of each WEC by region, is to calculate the mean annual wave energy produced. However, it is not possible to compare the efficiency between the WECs yet, as their rated power and wavelength range utilized differ significantly.

The WEC suitability comparison for each area, towards the selection of the ideal one, is accomplished using Table 3 that imparts the operating hours of each WEC as well as their capacity factor. Table 3, presents the percentage of the working hours for each WEC, during the 5 years of study (in total 43824 hours). In every region, the WEC with the longest working period was WaveDragon with rates that ranged at 50.07-63.74%. AquaBuoy was the WEC with the lowest working period, and rates that range at 16.82-35.99%. Finally, Pelamis was between the two with a working rate during the 5 years approximately ranging at 36.53-46.63%, except for Kasos Isl., where it proved less efficient, with a working rate of 31.82%. The power produced by the three WECs operating for a period of 5 years at their rated power is respectively: Pelamis 32.868GWh, WaveDragon 258.5616 GWh and AquaBuoy 10.956 GWh.

After calculating the power produced during 5 years for each WEC in the 8 study areas, the capacity factor for each case was calculated. From the capacity factor it is then observed that the ideal WEC for energy production in any area is the WaveDragon. The Pelamis follows in efficiency, and finally the AquaBuoy, in all the cases considered.

Table 2. Mean seasonal and annual wave energy production at the examined locations.

Area	WEC	Mean seasonal wave energy (GWh) W	S	S	A	Mean annual wave energy (GWh)
AJ	PE	0.212	0.141	0.052	0.124	0.536
	WD	2.455	1.684	0.674	1.485	6.344
	AB	0.062	0.038	0.012	0.033	0.146
AL	PE	0.268	0.173	0.063	0.157	0.660
	WD	3.008	1.957	0.754	1.784	7.460
	AB	0.080	0.047	0.015	0.043	0.184
AN	PE	0.272	0.145	0.035	0.135	0.577
	WD	3.120	1.803	0.589	1.682	7.075
	AB	0.082	0.040	0.008	0.038	0.163
BE	PE	0.216	0.078	0.023	0.062	0.388
	WD	2.500	1.058	0.440	0.909	4.996
	AB	0.063	0.019	0.004	0.015	0.103
KA	PE	0.154	0.046	0.038	0.048	0.288
	WD	1.528	0.624	0.634	0.636	3.444
	AB	0.033	0.008	0.005	0.008	0.054
HY	PE	0.135	0.090	0.027	0.085	0.343
	WD	1.473	1.053	0.389	0.975	3.934
	AB	0.029	0.018	0.004	0.017	0.070
MV	PE	0.261	0.176	0.031	0.137	0.615
	WD	2.538	1.809	0.441	1.453	6.305
	AB	0.062	0.040	0.006	0.029	0.138
ME	PE	0.281	0.140	0.049	0.148	0.599
	WD	2.751	1.488	0.570	1.578	6.217
	AB	0.071	0.033	0.010	0.034	0.142

Table 3. Percentage of operating hours and capacity factor for the examined locations and WECs.

Area	WEC	Percentage of operating hours (%)	*CF*
AJ	PE	43.32	0.082
	WD	50.07	0.123
	AB	32.88	0.067
AL	PE	45.63	0.100
	WD	53.41	0.144
	AB	35.20	0.084
AN	PE	46.63	0.088
	WD	56.01	0.137
	AB	35.99	0.074
BE	PE	36.53	0.059
	WD	55.71	0.097
	AB	25.76	0.047
KA	PE	31.82	0.044
	WD	60.29	0.067
	AB	16.82	0.025
HY	PE	39.41	0.052
	WD	51.33	0.076
	AB	26.48	0.032
MV	PE	45.61	0.094
	WD	63.74	0.122
	AB	32.24	0.063
ME	PE	39.27	0.091
	WD	50.45	0.120
	AB	28.55	0.065

5 CONCLUSIONS

Among the selected locations, that meet the necessary depth and wave potential conditions for WEC placement, the study areas that present the highest wave power resource are Alghero (11 kW/m), Ajaccio, Annaba, Manzara del Vallo and Menorca (9 kW/m), Benghazi (7 kW/m), Hyères (6 kW/m), and finally Kasos (5 kW/m).

Once the WECs are installed, it is observed that the classification of the studied areas according to their annual mean wave power resource coincides with the classification according to WEC efficiency, indicating a positive correlation between the wave resource and WEC efficiency. This is mainly due to the uniformity of the waves that have in their majority significant wave height in the range of 0.25 - 0.75 m, and energy period in the range of 3.5 - 4.5 s, in all areas.

The WEC that performs best according to the capacity factor in all studied areas, is the WaveDragon. However, it is advised that in any case the optimal WEC is chosen by also considering the weighted cost of electricity (LCOE). Therefore, it is important to calculate the capital (CAPEX) and operating costs (OPEX), in comparison to the energy value delivered over the lifecycle of the chosen WEC.

In general, this study demonstrated that the wave power resource in the Mediterranean does not seem very efficient when utilizing the three technologically mature wave devices that were examined. Possibly, future devices will be able to harness waves of shorter height and period, and therefore yield higher percentages of power, thus making the Mediterranean suitable for investment in wave energy exploitation.

Overall, regarding the applicability of WECs in low energy seas (such as the Mediterranean and the Black Sea), the very recent review of Foteinis, (2022) and the references included therein provide a lot of relevant information. For the Mediterranean mild wave climate, survivability seems to be not an important issue, while in order to secure profitability downscaling of WECs is a promising solution, (Bozzi et al., 2018). Moreover, for the identification of the most promising technologies for particular sites high quality measured wave data are required. As is also concluded in (Foteinis, 2022), the selection of a particular WEC (technology, capacity and geometry) is highly site dependent; for the Mediterranean Sea a downscaling ratio of 0.25 provided the optimal CFs, (Bozzi et al., 2018).

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