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Wave Energy Assessment and Performance Estimation of State of the Art Wave Energy Converters in Italian Hotspots

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Abstract: This paper presents an assessment of offshore wave energy potential at the scale of the whole Mediterranean Sea. The offshore wave data were propagated, by means of numerical modeling, toward four Italian coastal areas, namely stretches of coast of Tuscany, Liguria, Sardinia and Sicily. For each area, the wave power and the monthly, seasonal and annual variability at water depths of 50 m and 15 m were analyzed and hotspots were located. The results show strong variability of the wave energy potential from point to point of the same area thus highlighting the need for spatially detailed analysis. The higher values of wave energy potential are located in the hotspots of Sardinia and Sicily, at 11.4 kW/m and 9.1 kW/m, respectively. The Tuscany and the Liguria hotspots are characterized, respectively, by 4.7 kW/m and 2.0 kW/m. In order to point out which state of the art WEC is best suited for the Italian areas, the performances of six different state of the art Wave Energy Converters (WECs) were evaluated. Finally, a comparison of the performances of each WEC in the selected Italian sites and in some European (EU) oceanic sites was conducted. The energy potential in the most energetic EU oceanic site, among those here investigated, is up to 38-times greater than the potentials in the studied Italian areas but the power output, of the best WEC technology, is no more than nine times greater.

Keywords: wave energy; Mediterranean Sea; offshore wave energy assessment; coastal wave energy assessment; wave energy hotspots; performances of wave energy converters

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1. Introduction

Due to the depletion of fossil fuel energy resources and the environmental impacts related to their use, the interest in the exploitation of renewable energy sources has been growing for many years and, in this context, the energy of the sea waves is emerging. The wave energy is the renewable energy source having the highest energy density and a global wave energy potential of 32,000 TWh/year is estimated to reach the world coastlines, a value close to the yearly mean world energy consumption [1]. Various Wave Energy Converters (WEC) have been proposed so far but these technologies have not yet reached the commercial level [2]. Among all the technical issues that impinge the development of WECs, resistance to extreme wave loads is one of the most challenging. If, on the one hand, the sea sites where the wave energy is relatively high offer higher energy potentials, on the other hand, the presence of high waves leads to heavy loads on the WECs, thus increasing the failure probability and so decreases the overall productivity. Seas with moderate wave climate, with respect to the oceanic conditions, such as the Mediterranean Sea or the North Sea might offer a good compromise for the exploitation of such kind of energy and act as test areas for prototypes in view of their development for the more energetic oceanic sites.

Studies on the assessment of wave energy potential in candidate sea sites for building pilot plants and the performance estimation of WECs in those sites are still needed in order to support the cost–benefit analysis of these technologies.

The siting of pilot plants for the exploitation of wave energy by means of WECs is a technical, economic and strategic problem. The assessment of wave conditions is necessary to estimate the wave energy resource available in the area of interest and to optimize the design of WECs for the specific wave climate. Due to non-technical factors [3] such as cost of investments for building, control, maintenance and energy transportation by submarine cables, nearshore areas are the candidate areas due to their proximity to the coast and harbors. However, once waves propagate toward the shore, part of their energy is dissipated due to frictional losses. At the same time, their interaction with the sea bottom and coast features like shoals, headlands and bays, induce refraction mechanisms that may lead the offshore wave energy to spread on a wider area or to focus on a smaller area. Considering the characteristics of the waves of the Mediterranean Sea, once the water depth is greater than about 15 m, the energy dissipation due to bottom friction or breaking is almost zero and the mentioned focusing mechanisms may lead to coastal areas where the wave energy potentials are higher than the related offshore values. Thus, the assessment of wave energy at coastal areas is pivotal in order to locate the hotspots for the exploitation of the wave energy resource.

The purpose of this work is the assessment of the energy potentials on the offshore of the whole Mediterranean Sea, the selection of the most promising Italian nearshore areas and the location of their hotspots, the evaluation of performances of state of the art WECs and comparisons between their energy productivity in Mediterranean hotspots and in EU oceanic hotspots.

The aims are to contribute to the present knowledge on energy assessment and selection of Italian sea sites for the exploitation of wave energy and to select some of the proposed WEC technologies that are most suited for the Mediterranean Sea climate. The content of this paper is of evident interest for the EU and Italian communities that are investing in this field as well as companies worldwide that are developing WEC technologies and thus need to optimize the device for specific wave climate in order to reach the level of commercial maturity.

The results of this study discover the exact place of some hotspots where thanks to focusing phenomena the wave energy potentials are higher than those in their surrounding areas. This finding would have not been achieved if numerical models with appropriate spatial resolution were not used; it suggests, to the research community, the need of such methodological approach. Moreover, this work proves that, although the energy potentials of the ocean sites are higher than those in the Mediterranean sites, this difference is drastically reduced in terms of the energy productivity potentials of existing WECs even though none of the tested technologies were optimized for the moderate wave climate. It suggests that, if the WEC technologies were optimized for moderate wave climate their production of energy would approach the values that characterize the oceanic sites. This latter result might contribute at the opening of a new market for WECs devices since, at present, they are under development just for the most energetic oceanic climates.

The paper contents are structured as follows. Section 2 provides a review of current state of research on each of the three topics, namely offshore assessment, nearshore assessment and performance estimation of WECs. Section 3 describes the wave data used for the offshore assessment, the methodology used for the nearshore wave propagation and a brief review of the state of the art WECs considered in this study. The assessment of the offshore and nearshore wave energy potential is presented in Section 4. Performance analyses of seven state of art WECs are discussed in Section 5. Conclusions are drawn in Section 6.

2. Review of the Current State of the Research Field

2.1. Assessment of the Offshore Potential

Traditionally, the assessment of the wave energy has been carried out for offshore deep water wave data [1,4–19], while, more recently, coastal areas have been investigated in order to locate hotspots [20–37]. At the oceanic global scale, the richest wave power areas are between 40° and 60° latitude of both hemispheres [10].

Concerning Europe, previous studies [1,4–11] proved that the maximum-yearly mean wave-energy values are on the western coast of Scotland and Ireland, where 70 kW/m are achieved [4,9]. In North America, the peaks are in Oregon, British Columbia and Alaska where it ranges from 40 kW/m to 60 kW/m. In the southern hemisphere, the highest values occur on the Pacific coasts of southern Chile (around 100 kW/m [4,9]), western South Africa (around 50 kW/m [4,9]), southwest and southern coasts of Australia [12] and New Zealand (around 100 kW/m [4,9]). It is worth noting that although the wave power values in the Northern and Southern Hemispheres are similar, the Southern inter annual variation is considerably lower [5,20] so it may foster the exploitation of the wave energy resource.

In the case of Mediterranean Sea, the first assessment of the offshore wave energy was developed in 1996 [13] pointing out wave power values close to 1 kW/m in the northern area of the Adriatic Sea, and 6 kW/m off the western area of Sardinia and Sicily Italian islands. In 2004, the interest on the Mediterranean Sea started to increase when a consortium of six companies published a wave power atlas [14], with spatial resolution of about 50 km, showing offshore wave potentials in the range between 0.75 kW/m in the northern area of the Adriatic Sea and 14.75 kW/m in the western area of Sardinia and Corsica islands [15]. In 2011, Vicinanza et al. [16], by using wave data collected by the Italian wave buoys network, obtained yearly mean values lower than 2 kW/m in the central Adriatic Sea and equal to 9.1 kW/m at the Alghero wave buoy on 100 m of water depth in the north west offshore facing the Sardinia island. In 2013, Liberti et al. [17] assessed the wave power through numerical simulation hindcasting of the whole Mediterranean Sea for the period 2001–2010, and their results show that the most energetic area is in the Western Mediterranean between the Balearic Islands and the western coast of Sardinia where it reaches values above 15 kW/m. Sierra et al. in 2014 [18] studied the wave energy resources around Menorca Island (Mediterranean Sea) finding yearly mean wave power close to 8.9 kW/m. In 2016, Besio et al. [19] followed the line opened by Liberti et al. [17] but increased the resolution of the atmospheric forcing from 1°/4° to 1°/10°, extending the range of the numerical simulation from 10 to 35 years (from 1 January 1979 to 31 December 2013) and decreasing the time step for the recording of wave characteristics to 1 h instead of 3 h. The Besio et al. [19] results are similar to those obtained by Liberti et al. [17]. In summary, these previous findings show that the offshore mean energy flux in the Mediterranean Sea has values between 1 kW/m and 2 kW/m in the central and northern area of the Adriatic Sea and between 10 kW/m and 20 kW/m in the offshore western area of the Sardinia and Corsica Islands.

2.2. Assessment of the Nearshore Potential

The assessment of the energy potential at coastal sites and the identification of the hotspots are frequently obtained by means of the propagation of offshore values toward the nearshore. Although direct measurements at coastal areas are possible, in practice, due to the need for detailed knowledge in terms of space resolution, the use of numerical modeling is imposed. Generally, the methodology is based on offshore wave data used as boundary conditions for the numerical modeling of nearshore wave propagation that can be calibrated and validated using coastal buoy measurements [21–24]. Some authors [25–31] propagated the most significant three or five wave cases representing winter/autumn average condition, a summer/spring average condition and a particularly energetic situation. Other authors [20,22,23,32–37] propagated the whole events in the time series of the offshore numerical model or the offshore wave buoy measurements and estimated the available nearshore wave power. For the Mediterranean nearshore, the wave power in the western side of Sicily has been estimated to be close to 8 kW/m by Iuppa et al. [23] and 5 kW/m by Monteforte et al. [32]. Iuppa et al. [23] also found a yearly mean wave power in the range 4–6 kW/m in the Strait of Sicily and 2–3 kW/m in its north and east sides. Along the north western Sardinia Island (Italy), Vicinanza et al. [33] pointed out values between 3.8 kW/m and 10.9 kW/m. For the western part of the Black Sea, Akpınar and Kömürcü [34] estimated values around 3 kW/m while on the Eastern

Mediterranean Sea, Ayat [22] in 2013 and Jadidoleslam et al. in 2016 [35] estimated values around 5 kW/m.

2.3. Performance Assessment of Wav Energy Converters

In order to evaluate the performance of wave energy converters, the commonly used methodology is based on the so-called scatter diagram of the wave resource and the power matrix of the WEC. The scatter diagram represents the occurrence of sea state as a function of the significant wave heights and energetic periods [30,33] while the power matrix gives the related power output from the specific WEC. The frequency of occurrence of the sea states with the highest wave power is generally very scarce and does not contribute much to the total energy. However, their consideration is essential in the investigation of WECs reliability and survivability [36]. The performance of a WEC is often evaluated in terms of yearly mean values of power output, energy production or as the ratio between energy production and the rated power of the WEC, the so called: capacity factor [38]. Following the latter methodology, many studies [38–45] compared the performances of different devices in the same site of interest.

O'Connor et al. [39] estimated the performance of the Pelamis and Wavestar devices, with different ratings of the devices, at six sites in Europe. The results of this study indicate that the Pelamis is appropriate for the highest energetic sites, while the Wavestar is suitable for all sites. The capacity factor of the Pelamis, the Wave Dragon and the AquaBuoy were obtained by Aoun et al. [40] on the Lebanon coast, Dunnet and Wallace [41] on the east coast of Canada, Bozzi et al. [38] on the Italian coast and Sierra et al. [18] on Menorca. These studies pointed out that for the Lebanon coast the capacity factors of all the three WECs is extremely low (around 5%). The Wave Dragon device operated with the highest efficiency, in the five analyzed areas in Canada with capacity factor larger than 20% while the same device has a capacity factor around 10% when tested in the Mediterranean area facing the Menorca coast. The Pelamis has the larger capacity factor (around 20%) in Alghero and Mazara del Vallo sites in Italy [38]. Mota and Pinto [42] estimated on the western coast of Portugal that the Wave Dragon has a capacity factor over 33% while the Pelamis and AWS have a capacity factor below 15%. In 2015, Iuppa et al. [43] compared the performance of three nearshore devices (Bref-SHB, B-HBA, B-OF) and seven offshore devices (F-2HB, F-HBA, F-3OF, F-OWC, AquaBuoy, Pelamis, and Wave Dragon). The results show a maximum capacity factor lower than 4% in two nearshore points selected on the western coast of Sicily. The Pelamis has the maximum capacity factor (7.15%) on an offshore point closed to Marettimo Island. The performance of Wave Dragon, Pontoon, OE, Wave Star, AWS, Wave Bob, Pelamis, Oceantec, Ceto, and AquaBuoy were tested by Rusu. and Onea [44] on the European continental coast and by Rusu and Onea [45] on the European coasts. The Sea Power and the SeabasedAB devices were also analyzed on the European coasts by Rusu and Onea [45]. In the first paper the European continental coast are divided in four zones (Northern Europe, Ireland and UK coasts, SW Europe, Mediterranean Sea and Black Sea. The Pontoon has the best capacity factor (values between 5.84% and 14.5%) on the Mediterranean Sea and Black Sea areas, while the Oceantec in the other areas. Rusu and Onea [45] analyzed the Iceland, Azores Islands, Madeira Archipelago and Canary Islands. The performance analyses divided the WEC system in two groups (device with rated power above 2470 kW and device with rated power below 1000 kW). In the first group the Wave Dragon has the larger capacity factor (values between 19.3% and 33.4%). Smaller differences are noticed at the second WEC group, with the exception of Ceto.

3. Materials and Methods

3.1. Assessment of the Offshore Potential

The present part of the study is based on numerical modeling wave hindcasting. The used wave hindcasting was provided by IFREMER (French Research Institute for Exploitation of the Sea) and was performed by the Prévimer model called MED 6MIN from June 2009 to December 2013, with a three-hour frequency [46]. The domain of wave hindcasting is the Mediterranean Sea from 6°W to

36.5°E of longitude and from 30°N to 46°N of latitude, with a resolution of 0.1° (that correspond to about 11 km in latitude and 8 km in longitude). The validation of the wave hindcasting was done by IFREMER on the basis of measurements from surface buoys and satellites [47]. The values of significant wave height and energy period were used to compute the deep water wave power corresponding to each sea state based on Equation (1):

$$P_w = \frac{1}{64}\frac{g^2}{\pi}\rho H_{mo}^2 T_{m-1,0} \ , \tag{1}$$

where ρ is the seawater density (1025 kg/m^3) and g is the gravitational acceleration (9.81 m/s). In addition, the yearly mean wave powers were computed in order to characterize the Mediterranean Sea (see Section 3).

3.2. Assessment of the Nearshore Potential and Hotspots Identification

The processes affecting the waves during their propagation towards the coastline can modify the offshore wave energy potential values, leading to reductions, due to energy dissipation or local enhancements due to focusing mechanisms. Numerical simulations were carried out to quantify these processes using the Spectral Wave (SW) module of the MIKE21 software package [48]. The SW is a third generation spectral wind–wave model based on unstructured mesh that allows the simulation of the non-linear wave–wave interaction, dissipation due to white-capping, dissipation due to bottom friction, dissipation due to depth-induced wave breaking, directional spreading, refraction and shoaling due to depth variations.

Offshore boundary conditions for the SW models were obtained from the wave hindcasting data of IFREMER–MED 6MIN model on water depths of about 100 m from June 2009 to December 2013. All 13,268 available values of significant wave height, peak period, mean wave direction and spreading factor were propagated with the fully spectral and quasi-stationary formulation. The JONSWAP fetch growth expression was used as initial condition with the classical parameters (σ_a = 0.07, σ_b = 0.09, γ = 3.3).

Four nearshore areas were investigated (see Figure 1): the area between La Spezia and Livorno, called Tuscany (domain sizes about 30 km × 130 km); the area between Monaco (France) and Imperia, here after called Liguria for brevity (domain sizes about 7 km × 75 km); the area between Stintino and Alghero, called Sardinia (domain sizes about 30 km × 70 km); and the area between San Vito Lo Capo and Mazara del Vallo, called Sicily (domain sizes about 65 km × 85 km).

Figure 1. Map of Italy showing the location of the analyzed areas.

These areas were selected taking into consideration technical aspects, such as the offshore resource availability, and non-technical aspects which, amongst others, are related to the interest of our research group for sitting a pilot plant.

The model meshes were characterized by a triangular grid size of about 1000 m in water depths over 50 m, 500 m in water depths between 50 m and 30 m, 300 m in water depths between 30 m and 20 m and 200 m from water depth of 20 m until the coast. Figure 2 shows, as an example, the mesh used for the Sicily area with resolution information (the total number of computational nodes was 13,256 and the total number of the elements was 25,506).

The nearshore wave power (P_w) was computed as in Equation (2)

$$P_w = \rho g \int_0^{2\pi} \int_0^{\infty} c_g(f,\theta) \times E(f,\theta) df d\theta, \tag{2}$$

where E is the energy density, c_g is the group celerity, f is the wave frequency and θ is the wave direction.

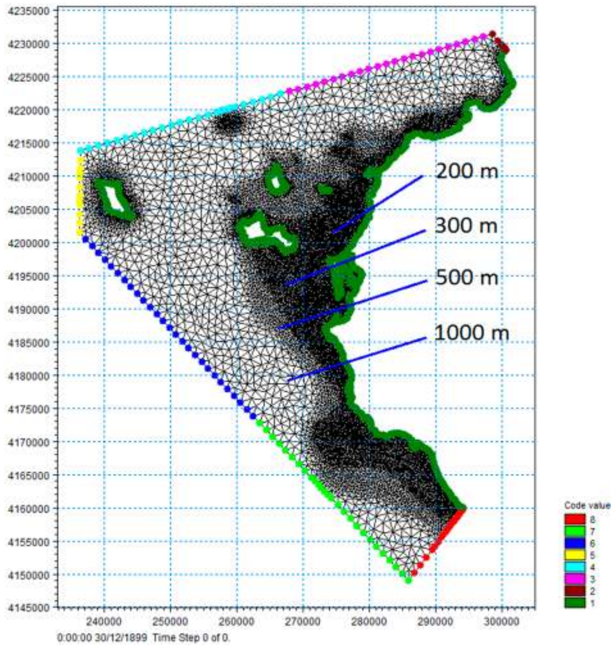


Figure 2. Sicily model mesh with grid resolution information.

The temporal wave power fluctuation was computed, following Cornett [6], as the coefficient of variation (COV) (Equation (3)), the seasonal variability index (SV) (Equation (4)), and the monthly variability index (MV) (Equation (5)):

$$COV(P) = \frac{\sigma(P(t))}{\mu(P(t))} = \frac{\left[\overline{\left(P - \overline{P}\right)^2}\right]^{0.5}}{\overline{P}}, \tag{3}$$

$$SV = \frac{P_{S1} - P_{S4}}{\overline{P}}, \tag{4}$$

$$MV = \frac{P_{M1} - P_{M4}}{\overline{P}}, \tag{5}$$

where σ is the standard deviation, μ is the mean and the over-bar means the time-averaging. In this work, COV is applied to the 3-h time series. P_{S1} is the mean wave power for the most energetic season (usually the winter, from December to February), P_{S4} is the mean wave power for the least energetic season (usually the summer, from June to August), the yearly mean power. P_{M1} is the mean wave power for the most energetic month and P_{M4} is the mean wave power for the least energetic month.

Relatively lower values of COV, SV, and MV mean a less varying wave power time series, which helps locate the most promising areas for wave energy harvesting.

For each area, the points at water depths of 50 m and 15 m were selected and the wave roses and the time series of the computed wave power values were extracted to describe the wave energy potential within the studied domain. Furthermore, the hotspot was highlighted as the point where the wave power is higher than the offshore value and higher than values in its neighborhood. These hotspot areas have the highest potential as prospective energy farm sites, as defined by Iglesias [27] in 2010 and by Rusu [30] in 2012, providing that the so-called non-technical factors are also favorable [49].

For each hotspot, scatter diagrams and energy diagrams were developed in terms of significant wave height and energetic period in order to visualize the occurrence of the different sea states and the contribution of the different sea states to the total annual wave energy.

3.3. Performance Assessment of Wave Energy Converters

Among all proposed WECs that have been presented in the open literature, in the present work, we have selected six (Table 1). More specifically, only those that were already tested in real sea state (at least as a scaled model with scale factor larger than 1:5) and that already published their power matrix as a measure of the actual performances [50–52] were considered. The selected WECs are: (i) AquaBuoy [49]; (ii) AWS [53]; (iii) Pelamis [54]; (iv) Wave Dragon [55]; (v) Oyster [56]; and (vi) Wave Star [57].

Table 1. Main features of the WECs considered in this study.

	Position	**Type**	**Power Take Off**	**Rated Power (kW)**	**Size**
AcquaBuoy	Offshore (>50 m)	Point absorber	hydraulic motor/ generator	250	diameter 6 m, draught 30 m
AWS	Offshore (>50 m)	Point absorber	linear generator	2000	43 m deep underwater
Pelamis	Offshore (>50 m)	Attenuator—Oscillating Body	hydraulic motor/ generator	750	diameter 3.5 m, length 150 m
Wave Dragon	Offshore (25–40 m)	Overtopping—floating	water turbine	7000	width 300 m, length 170 m
Oyster	Nearshore (≈15 m)	Oscillating Body—submerged	water turbine	800	width 18 m, height 12 m
Wave Star	Nearshore	Multi point absorber	hydraulic motor/ generator	600	Float diameter Ø5 m

The formula used to estimate the electricity production (P_e) of a WEC in a specific site is reported in Equation (6) [42]:

$$P_e = \sum_{i=1}^{nT} \sum_{j=1}^{nH} P_{ij} \times f_{ij}, \quad (6)$$

where nT is the number of period classes; nH is the number of significant wave height classes, and, for the i-th and j-th classes of period and wave height, is the power output of the device; and f is the occurrence frequency obtained in the selected location.

The performance of a WEC was evaluated in terms of capacity factor (C_f), defined in the Equation (7) as the ratio between the total electrical power produced and the rated power [43] and in terms of capture width (C_w), defined in the Equation (8) as the ratio between the electricity production (P_e) of a WEC (in kW) and the period averaged flux of energy transported by the waves (P_w) per meter of wave crest (kW/m) in each site [58].

$$C_f = \frac{P_e\,[\text{kW}]}{\text{Rated power}\,[\text{kW}]}, \quad (7)$$

$$c_w = \frac{P_e\,(\text{kW})}{P_w\,(\text{kW/m})} \quad [m] \quad (8)$$

The performances of AquaBuoy, Pelamis, AWS and Wave Dragon were evaluated in the most energetic points on the 50 m water depth between those selected in this work and compared with seven EU oceanic offshore locations whose scatter matrix were available in the open literature. These locations are: São Jorge in Azores Island [59], Madeira Island [29], Nazarè-Peniche and Sines-Aljezur in Portugal [42], Belmullet in Ireland [60], Ile d'Yeu in France [61], and Cornish Coast in United Kingdom [62].

The performances of the Oyster and Wave Star were evaluated in the four nearshore hotspots and compared with the nearshore location at Madeira Island [29].

4. Wave Energy Assessments

The spatial distribution of the offshore wave power for the whole Mediterranean Sea is shown in Figure 3 (mean values related to the used hindcasting period). The higher values (above 10 kW/m) are located in the Central Mediterranean and the maximum value, which reaches 16.4 kW/m, is located between Corsica Island, Sardinia Island and the Balearic Islands. In the Eastern Mediterranean Sea, the wave power values are between 6 and 9 kW/m. The lower values are located in the Adriatic Sea (below 2 kW/m).

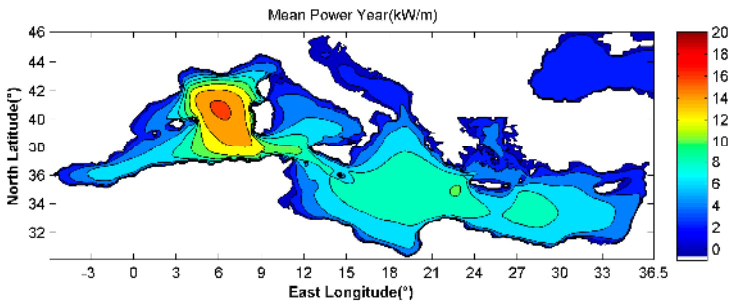
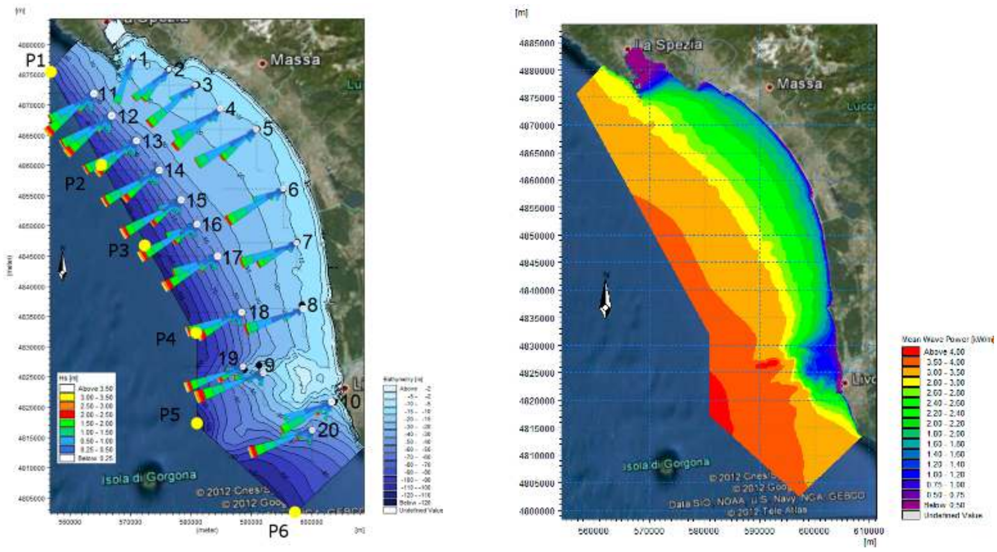


Figure 3. Yearly mean wave power spatial distributions (kW/m) during the analyzed hindcasted period.

Similar analyses, still based on numerical wave hindcasting as done in the present study, have been conducted by Liberti et al. [17] and Besio et al. [19]. It is worth noting that, although the length of the hindcasted periods used are very different, the results in terms of the spatial distribution and local magnitudes of the yearly mean wave power are almost identical among all the three studies.

The spatial distribution of the nearshore wave power at the four studied areas are depicted in Figures 4b, 5b, 6b and 7b, while Figures 4a, 5a, 6a and 7a show the location of the points (Pi) used as offshore boundary conditions and the location of points, on water depths of 50 m and 15 m, where the wave powers are plotted as wave roses and the maximum values are summarized in Table 2. Following Cornett [6], the coefficients that aim to describe the temporal fluctuation of the wave power were also computed (COV Equation (3), SV Equation (4) and MV Equation (5)).

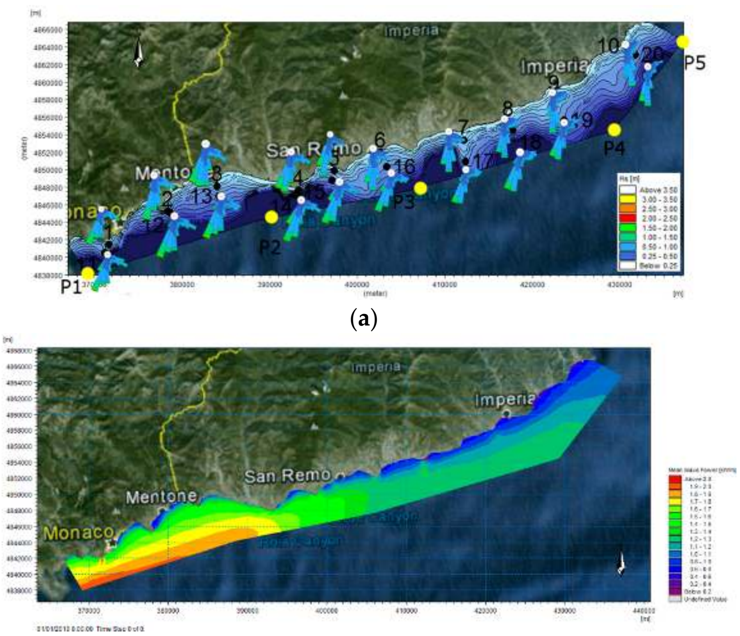
In the case of the Tuscany (Figure 4), the wave power decreases during the propagation toward the coastal waters except at a location in front of Livorno where it reaches values higher than those along the offshore boundary (Figure 4b). This is clearly related to wave focusing due to refraction processes that are triggered by the presence of the Meloria shoals (Figure 4a). This hotspot is located in 10 m of water depth (Table 2) about 1400 m shoreward of point 9. The mean wave power reaches 4.7 kW/m, a value about 25% larger than the value at the closer offshore boundary points P4 (3.6 kW/m) and P5 (3.9 kW/m). It is worth noting that at a distance of 1.5 km around this hotspot the wave power potentials dramatically decrease. This result motivates the necessity of high spatial resolution for the assessment of wave energy potentials in order to locate the most promising site for wave energy pilot plants. The COV values everywhere are lower than 1.7, the SV values everywhere are below 1 and the MV values are lower than 1.8 on water depths below 20 m.



(**a**) (**b**)

Figure 4. Tuscany: (**a**) bathymetry and extraction points; and (**b**) yearly mean wave power spatial distribution.

In the case of the Liguria area (Figure 5b), the highest values of wave power, on 15 m water depth, are located at point 1 where it reaches 1.9 kW/m, while in the case of 50 m of water depth the highest values are located at point 11 where it reaches 1.8 kW/m. Both points are located in front of Monaco (Figure 5a). The wave roses of these two points show that the main wave direction was S-SW. The French side of this nearshore area is characterized by high bathymetric gradients so that the transition from deep to shallow water is very sharp and as a consequence the waves propagate close to the coast without losing energy. The hotspot of this area is located only 210 m shoreward of point 1, on 10 m water depth, where the wave power reaches 2 kW/m (Table 2). The COV values are approximately equal to 1.8 in the whole area, the SV values everywhere are below 0.6 and the MV values are in the range 1.7–2.



(**a**)

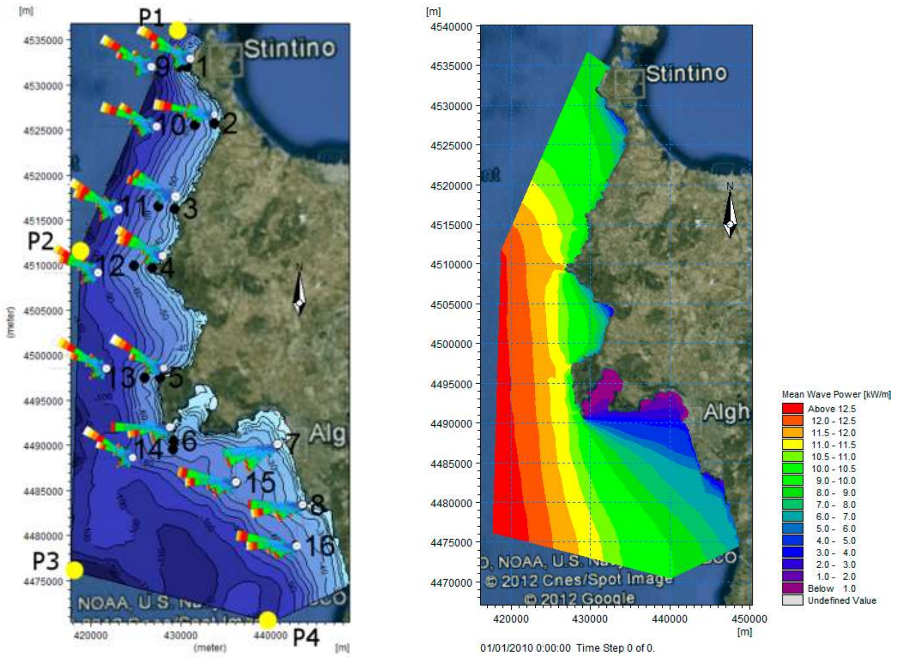
(**b**)

Figure 5. Liguria: (**a**) bathymetry and extraction points; and (**b**) yearly mean wave power spatial distribution.

Table 2. Location, mean wave power (P_w), COV, SV, and MV values related to the hotspots and the most energetic points among those selected on water depths of 50 m of the four nearshore areas investigated.

Latitude (WGS84-UTM32)	Longitude (WGS84-UTM32)	P_w (kW/m)	COV	SV	MV	Water Depth (m)
			Tuscany			
4,826,801	592,648	4.7	1.87	0.99	2.03	−10
4,826,150	587,255	3.8	1.84	0.96	2.02	−50
			Liguria			
4,841,692	371,620	2	1.93	0.69	1.9	−10
4,840,551	371,127	1.8	1.87	0.64	1.82	−50
			Sardinia			
4,509,652	426,722	11.4	2	1.49	1.72	−20
4,509,971	424,733	11.7	2	1.49	1.71	−50
			Sicily			
4,208,742	238,674	9.1	2.58	1.76	2.03	−15
4,209,477	238,355	8.6	2.55	1.76	1.99	−50

On the nearshore area along the Sardinia coast (depicted in Figure 6b), according to the results of the offshore assessment, the wave power values are much higher than those at the other nearshore areas. The northern part of this nearshore area is characterized by high bathymetric gradients and the focusing mechanisms induced by refraction effects occur near the headlands on the Argenteria area on the north of Capo Caccia. The maximum value of the mean wave power (Table 2) on 20 m of water depth reaches 11.4 kW/m (point 4) while in the case of 50 m water depth it reaches 11.7 kW/m (point 12). The wave roses of these two points show that the main wave direction was NW. Point 4 is also the hotspot of this area. The wave power potentials at this hotspot are more than two times larger than the potentials at the Tuscany hotspot and almost six times larger than the value at the hotspot on the Liguria coastal area. The COV values are above 1.8 across the whole area. The SV values are above 1.3 in the whole area: these values were 50% larger than those obtained in the Tuscany area. The MV values were lower than 1.8 and lower than those obtained in the Tuscany and Liguria areas.



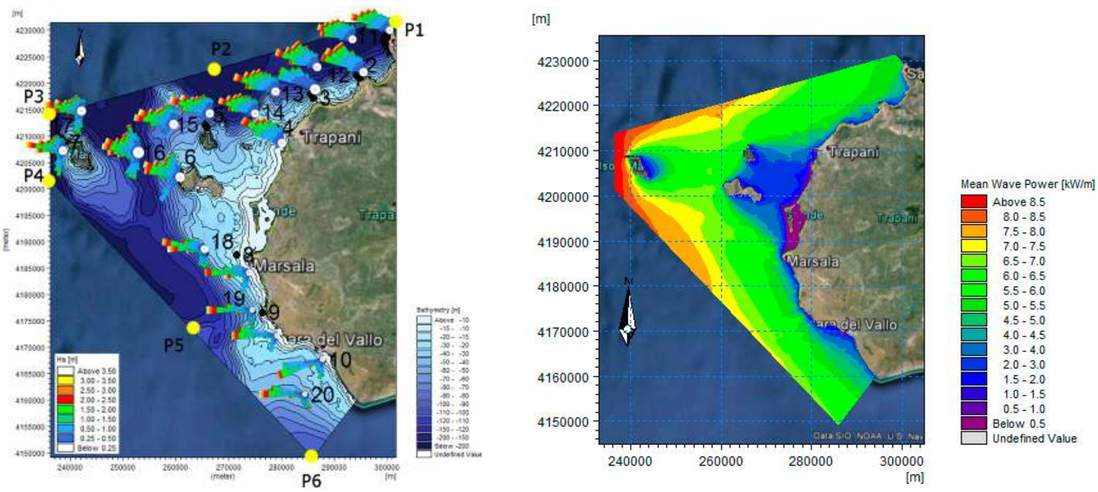
(**a**) (**b**)

Figure 6. Sardinia: (**a**) bathymetry and extraction points; and (**b**) yearly mean wave power spatial distribution.

Vicinanza et al. [33] studied the nearshore area along the NW of Sardinia. The nearshore simulation was performed with the MIKE 21 NSW model that was forced with wave data measured at the Alghero wave buoy (period 1989–2009). They reported the wave power at seven coastal points and found a largest value of 10.91 kW/m in front of Torre su Pittu bay (out of our domain).

In the case of the nearshore area at Sicily Region, the area between San Vito lo Capo and Mazara del Vallo was analyzed (Figure 7). The lowest energetic area is between Trapani and Marsala due to the protection of the Favignana and Levanzo Islands. The most energetic area is in front of the Marettimo Island. The maximum value at 15 m water depth reaches 9.1 kW/m (point 7) while at 50 m water depth it reaches 8.6 kW/m at point 17 (Table 2). Focusing mechanisms are identified on the NW coast of Marettimo Island and at Punta Mugnone area. The wave roses of these two points show that the most energetic wave direction is W and the secondary direction is S-SW. Point 7 is the hotspot of this whole area where the mean wave power reaches 9.1 kW/m, a value two times higher than that of the Tuscany hotspot, four and half times higher than that at the Liguria hotspot and just 20% less than that the value at Sardinia hotspot. The COV values were above 2 in the whole area, larger with respect to the other analyzed areas. The SV values and MV values were greater than 1.5.

The whole Sicily nearshore area has been analyzed by Iuppa et al. [23] and by Monteforte et al. [32]. Both of them identify the western part of Sicily as the area with the highest offshore wave energy potentials. Iuppa et al. [23] selected six sites characterized by high energy content between Terrasini and Mazara del Vallo and two sites near the islands of Favignana and Marettimo. Five of those sites are included in our domain. The differences in the predicted mean wave power obtained by our study and study by Iuppa et al. [23] are between 2% and 19%. Monteforte et al. [32] used the SWAN model to characterize the nearshore wave energy potential along the coastal stretch between Marsala and Mazara del Vallo. They highlight the presence of a hotspot relatively close to the coast on the north of Mazara del Vallo where the mean wave power value reaches 5.6 kW/m. The spatial resolution of our study did not identify this hotspot.



(**a**) (**b**)

Figure 7. Sicily: (**a**) bathymetry and extraction points; and (**b**) yearly mean wave power spatial distribution.

For each hotspot of the four analyzed coastal areas and for most energetic points on the water depth of 50 m, the scatter and energy diagrams are depicted in Figure 8. This analysis was carried out in order to highlight the occurrence of the different sea states and their contribution to the total annual wave energy.

At the Tuscany hotspot, the highest contribution to the total annual energy is given by the wave condition Hs = 2.5 m and Te = 7.5 s. This wave condition accounted for about 2.9 MWh/m (Figure 8a) and occurs 4.2% of the time. The same wave condition is also responsible for the highest contribution to the total energy at the most energetic point in 50 m water depth (point 19), where it accounts for about 2.5 MWh/m and occurs 3.5% of the time.

At the Liguria hotspot the highest contribution to the total annual energy value is given by the wave condition Hs = 1.5 m and Te = 5.5 s, that occurs for 6% of the time and accounts for about 2 MWh/m (Figure 8c). At point 14 at 50 m water depth the highest contribution to the total annual energy is about 1.5 MWh/m (Figure 8d) and is given by two different wave conditions. The first wave condition is characterized by Hs = 1 m and Te = 5 s while the second has Hs = 1.5 m and Te = 6.5 s. These combinations occurred for less than 6% of the time.

In addition, in the Sardinia costal area, two different wave conditions are responsible of the highest contribution to the total wave energy at the hotspot and at the most energetic point on 50 m of water depth. The first wave condition has Hs = 3 m, Te = 8.5 s while the second has Hs = 4 m, Te = 9.5 s. These combinations are present for less about 5% of the time. In the hotspot (point 4) this highest contribution to the annual energy is about 6.5 MWh/m (Figure 8e) while in the case of 50 m water depth (point 12) it is about 7 MWh/m (Figure 8f).

In the hotspot of the Sicily coastal area (Figure 8g), the maximum contribution to the total energy is given by Hs = 3 m, Te = 7.5 s and it reaches 4.7 MWh/m. At point 17, the most energetic point in 50 m of water depth, the maximum contribution is still given by the same wave condition and it accounts for 5.1 MWh/m. This wave condition occurs for the 3% of the time.

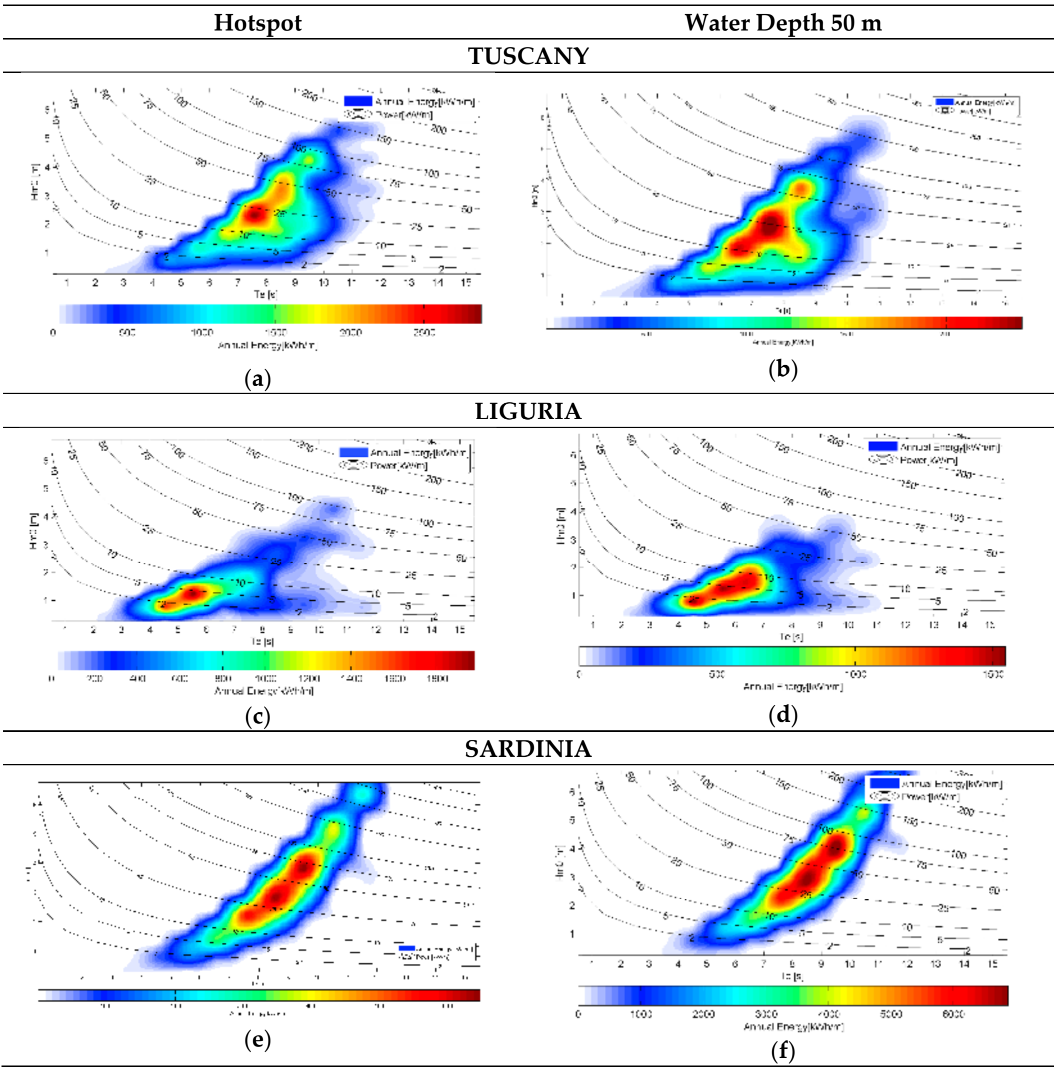


Figure 8. *Cont.*

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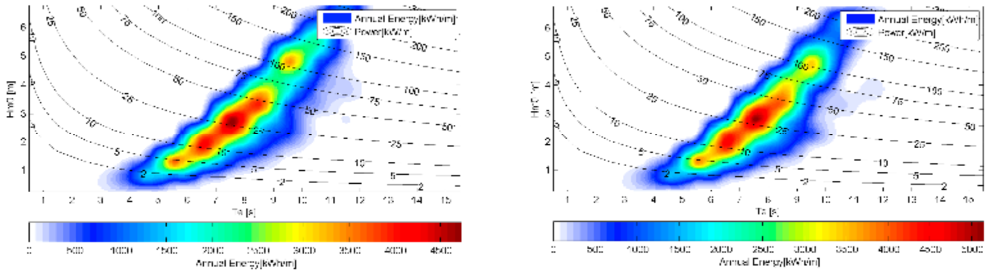

(**g**) (**h**)

Figure 8. Yearly mean wave power (kW/m) in terms of significant wave height (H_{m0}) and energy period (Te): (**a**) Tuscany hotspot; (**b**) point 19 Tuscany; (**c**) Liguria hotspot; (**d**) point 14 Liguria; (**e**) Sardinia hotspot; (**f**) point 12 Sardinia; (**g**) Sicily hotspot; and (**h**) point 17 Sicily. The color scale represents annual energy per meter of wave front (in KWh/m).

5. Performances of Wave Energy Converters

The performances of AquaBuoy (AB), Pelamis, AWS and Wave Dragon (WD) were evaluated by using the wave climate at the most energetic points on water depths of 50 m of the four coastal areas investigated (Table 2). Moreover, the WEC performances were also evaluated at the following EU oceanic sites in order to permit a relative comparison: Azores (Portugal), Madeira (Portugal), Nazarè-Peniche (Portugal), Sines-Aljezur (Portugal), Belmullet (Ireland), Ile d'Yeu (France), and Cornish Coast (UK) (see Table 3). The scatter matrices of these oceanic sites were found in the available literature [29,42,59–62].

The most energetic oceanic sites, among those selected in the present work, are located at the Azores and Madeira Islands (Portugal) and Belmullet (Ireland) where the energy flux is one order of magnitude higher than the values that characterize the Italian areas. However, it is worth noting that the energy potentials in the Italian areas in front of the Sardinia (11.4 kW/m) and Sicily (9.1 kW/m) islands are 22%–38% lower than the energy potentials in the oceanic areas at Sines-Aljezur (Portugal) and Ile d'Yeu (France).

Table 3. Location, depth, wave energy potentials in terms of mean power (P_w) and annual energy in the offshore and nearshore locations whose scatter matrix were found in literature.

	Location	Coordinates (WGS84-UTM32)	Depth (m)	P_w (kW/m)	Annual Energy (MWh/m)
Offshore	Azores (Portugal)	4291193/385315	43	73	639.5
	Madeira (Portugal)	3667766/371286	40	57.4	502.8
	Nazarè-Peniche (Portugal)	-	50	20.8	182.1
	Sines-Aljezur (Portugal)	-	50	14.8	129.3
	Belmullet (Ireland)	6028028/497403	72	50	438
	Ile d'Yeu (France)	5170879/544349	32	15	113.1
	Cornish Coast (UK)	5576508/309895	50	20	175.2
Nearshore	Madeira (Portugal)	3663184/374026	15	65.4	572.9

Table 4 shows the performance estimates for the four offshore devices. The highest value of capacity factor was obtained for the Wave Dragon (WD) at the area Nazarè-Peniche. This device is also the most suited for the Tuscany and Liguria sites where capacity factors reach 4.15% and 3.24% respectively. Instead, the Pelamis is the most suited in the cases of Sardinia and Sicily sites, with values of capacity factor 8.66% and 6.54%, respectively.

Table 4. Offshore locations: mean power output, capacity factor and capture width.

	Location	Mean Power Output (kW) "P_e"				Capacity Factor "C_f" (%)				Capture Width "C_w" (m)			
		AB	AWS	Pelamis	WD	AB	AWS	Pelamis	WD	AB	AWS	Pelamis	WD
Offshore	Tuscany	7.3	26.5	21.5	290.6	2.93	1.32	2.87	4.15	1.93	6.97	5.66	76.48
	Liguria	3.1	7.3	6.6	227	1.33	0.37	0.87	3.24	1.72	4.04	3.67	126.1
	Sardinia	21.1	99.2	64.9	540.4	8.44	4.96	8.66	7.72	1.81	8.49	5.56	46.26
	Sicily	14.5	64.7	49.1	419.4	5.81	3.23	6.54	5.99	1.7	7.55	5.73	48.99
	Azores (Portugal)	77.3	539.9	208.8	1967.5	29.97	26.69	27.83	28.11	1.06	7.4	2.86	26.95
	Madeira (Portugal)	45.5	413.8	118.6	1153.1	16.39	20.69	15.81	16.47	0.79	7.21	2.07	20.09
	Nazarè-Peniche (Portugal)	56.1	292	112.5	2779	22.44	14.6	15	39.7	2.7	14.05	5.41	133.69
	Sines-Aljezur (Portugal)	43.5	228	84	2324	17.4	11.4	11.2	33.2	2.95	15.44	5.69	157.41
	Belmullet (Ireland)	90.7	515.9	277.1	2159	37.96	25.8	36.94	30.84	1.81	10.32	5.54	43.18
	Ile d'Yeu (France)	53.2	367.9	120.8	1289.6	21.29	18.39	16.11	18.42	3.56	24.61	8.08	86.26
	Cornish Coast (UK)	51.3	250.9	172.3	1243.7	23.7	12.54	22.97	17.77	2.57	12.54	8.62	62.18

The capture width index was compared for the same device in the selected sites. The AquaBuoy (AB) and the AWS had the highest Cw in Ile d'Yeu (France), The Pelamis on the Cornish Coast (UK) and the Wave Dragon (WD) on the stretch of coast between Sines and Aljezur (Portugal). The Cw obtained for the Italian sites were very similar to those obtained in the most energetic site, Belmullet (Ireland). These values were greater than those obtained in the Azores and Madeira Islands except for the AWS device. In the case of Wave Dragon (WD) the Cw obtained for Tuscany area and mainly in Liguria was greater than those obtained in Sardinia and Sicily.

In the case of nearshore devices, the performances of the Oyster and Wave Star were evaluated by using the scattering matrices of the hotspots in the 4 Italian sites and compared with EU oceanic sites (Table 3) at Madeira Island [29]. Table 5 shows the performance estimates for the two nearshore devices.

Table 5. Nearshore locations: mean power output, capacity factor and capture width.

	Location	Mean Power Output (kW) "P_e"		Capacity Factor "C_f" (%)		Capture Width "C_w" (m)	
		Oyster	Wave Star	Oyster	Wave Star	Oyster	Wave Star
Nearshore	Tuscany	22.59	46.86	6.45	7.81	4.85	10.05
	Liguria	7.76	18.5	2.22	3.08	3.98	9.49
	Sardinia	48.51	96.59	13.86	16.1	4.27	8.49
	Sicily	41.72	91.23	11.92	15.2	4.56	9.98
	Madeira (Portugal)	129.2	257.3	36.97	42.88	1.98	3.9

The highest capacity factor was found at the Sardinia hotspot and was equal to 16.1% for the Wave Star. The lowest capacity factor was obtained at Liguria hotspot, with a value of 2.22% for the Oyster. In Madeira the capacity factor was equal to 42.9%, more than 2.5 times than that obtained in Sardinia but the mean wave power at Madeira is 5.5 times the value at the Sardinia hotspot.

The analysis of the C_W shows that Wave Star is the most suited for the Italian hotspots. It is worth noting that, in the case of the Tuscany site, the Wave Star capture width is more than two times the value at the Madeira site, thus proving that this device can convert a larger percentage of the Tuscany potential than the Madeira potential. However, considering that all the tested WECs have been optimized for oceanic wave climate and that the energy potentials at the oceanic sites are much higher than the potentials at the Italian sites, it is obvious that the mean power output at the oceanic sites is always higher than that at the Italian site. However, it is worth pointing out that, although the oceanic energy potentials are much higher, the mean power output at the Italian sites is quite close to the oceanic values.

A quantitative estimation of the relative WEC performances at the most energetic EU oceanic site (that is the Azores Islands site) and at the Italian sites is shown in Figure 9 (Tuscany), Figure 10 (Liguria), Figure 11 (Sardinia), and Figure 12 (Sicily).

The x-axis of the graphs is the relative power availability as defined in Equation (9):

$$P_W{}^* = \frac{P_{w,Azores}\,[kW/m]}{P_{w,Italian\,site}\,[kW/m]} \quad (9)$$

The y-axis of the graphs is the relative power output as defined in Equation (10):

$$P_e{}^* = \frac{P_{e,Azores}\,[kW]}{P_{e,Italian\,site}\,[kW]} \quad (10)$$

A similar analysis, but in terms of relative capture width, C_w* in Equation (11), as a function of the P_w*, is also reported.

$$C_w{}^* = \frac{C_{w,Azores}\,[m]}{C_{w,Italian\,site}\,[m]} \quad (11)$$

The points below the 45-degree line in the Figures 9–12 highlights the WECs that better exploits, in relative terms, the Italian potentials than the oceanic potentials.

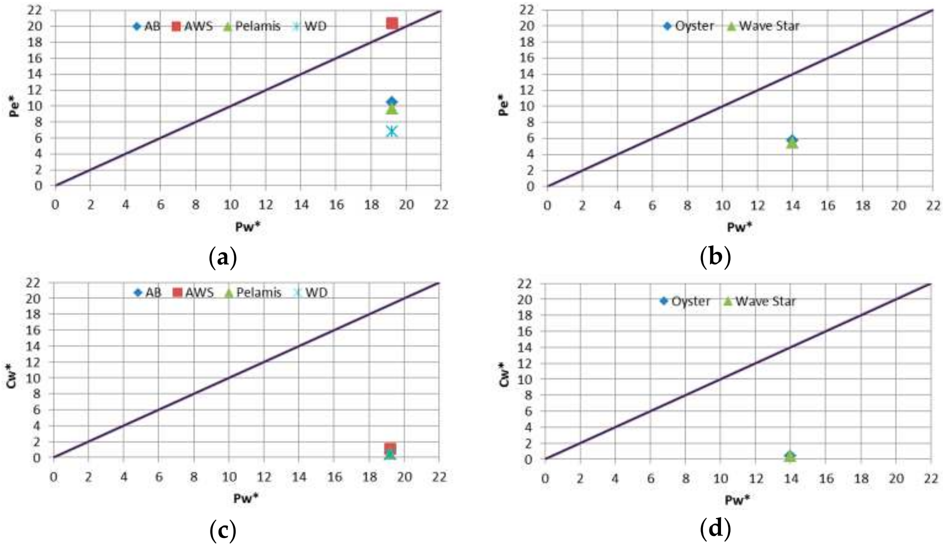

Figure 9. Comparison between the Tuscany site and the Azores site: (**a**) P_e* vs. P_w* offshore devices; (**b**) P_e* vs. P_w* nearshore devices; (**c**) C_w* vs. P_w* offshore devices; and (**d**) C_w* vs. P_w* nearshore devices.

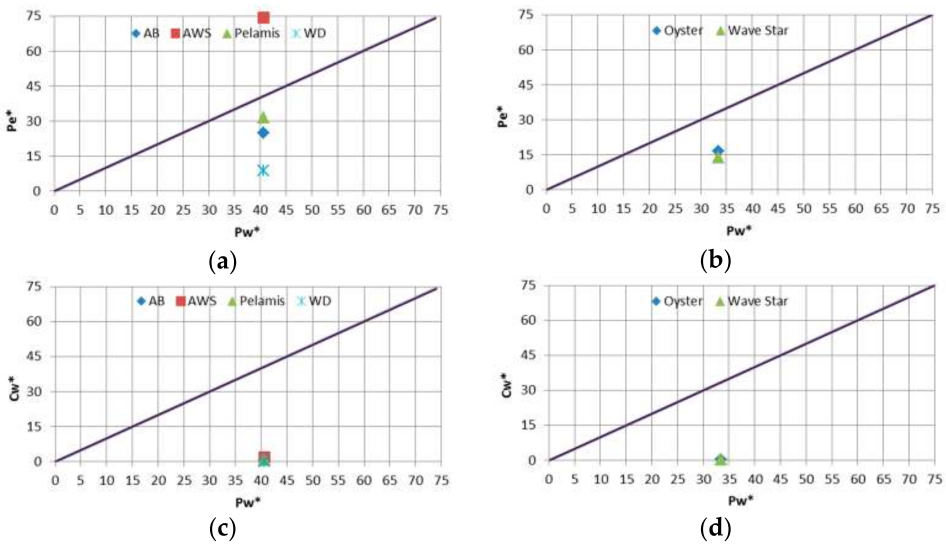

Figure 10. Comparison between the Liguria site and the Azores site (**a**) P_e* vs. P_w* offshore devices; (**b**) P_e* vs. P_w* nearshore devices; (**c**) C_w* vs. P_w* offshore devices; and (**d**) C_w* vs. P_w* nearshore devices.

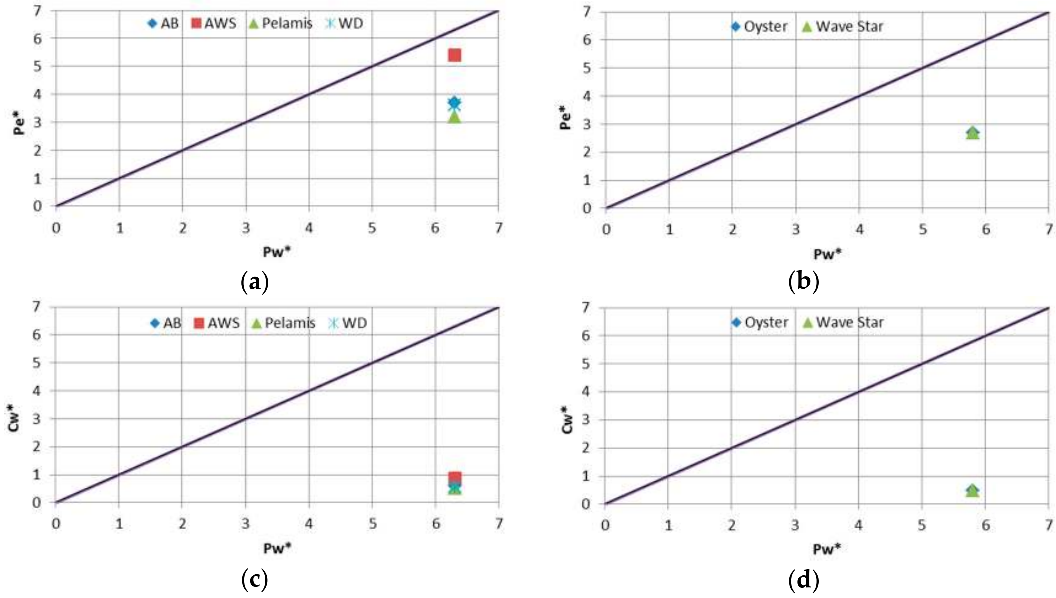

Figure 11. Comparison between the Sardinia site and the Azores site: (**a**) P_e* vs. P_w* offshore devices; (**b**) P_e* vs. P_w* nearshore devices; (**c**) C_w* vs. P_w* offshore devices; and (**d**) C_w* vs. P_w* nearshore devices.

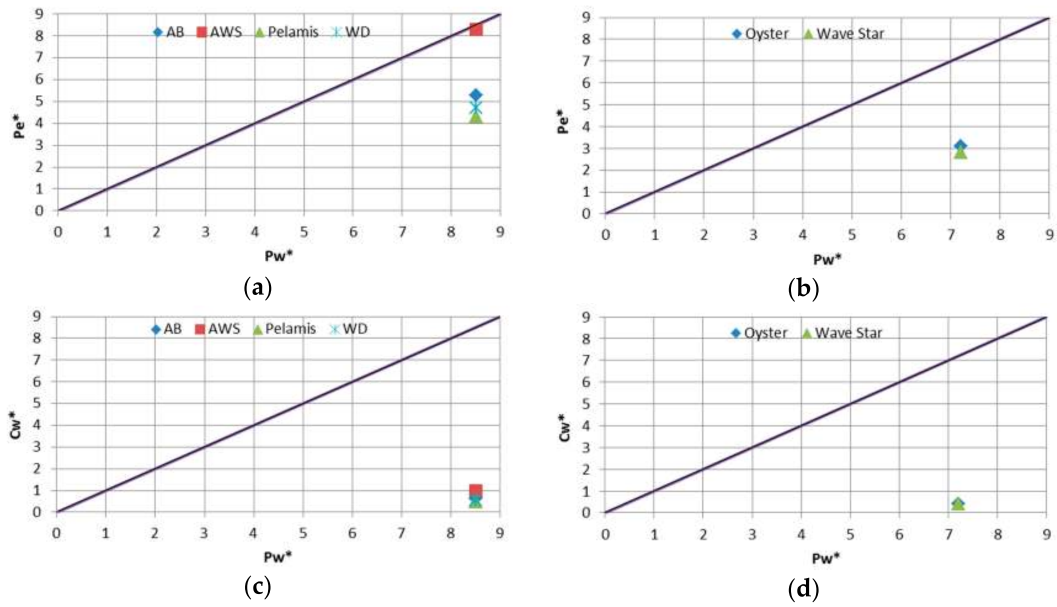

Figure 12. Comparison between the Sicily site and the Azores site: (**a**) P_e* vs. P_w* offshore devices; (**b**) P_e* vs. P_w* nearshore devices; (**c**) C_w* vs. P_w* offshore devices; and (**d**) C_w* vs. P_w* nearshore devices.

At the Tuscany offshore site (Figure 9a), the most suited device is the Wave Dragon, since, for a relative power availability around 20 (that is, Tuscany potentials are 20 times lower than the Azores potentials), it has the lower relative power output (just 6.8) among the tested offshore WECs. At the Tuscany hotspot (Figure 9b), all of the tested nearshore WECs had similar performance. Although the energy potential at the nearshore oceanic site is 14 times higher than in the Tuscany hotspot, the power output is just six times higher. It is also worth mentioning that the relative capture width, C_w*, for the offshore case is most of the times lower than 1 and in the case of Italian hotspots the C_w* is always lower than 1. It proves that the tested WECs technology can convert a larger part of the

Italian potentials than the EU oceanic site potentials. On the basis of this analysis, Table 6 summarizes the most suited offshore and nearshore WECs, among those tested, for each studied Italian sites.

Table 6. The most suited WECs for each Italian sites.

Location	Offshore WEC	Nearshore WEC
Tuscany	Wave Dragon	Wave Star
Liguria	Wave Dragon	Wave Star
Sardinia	Pelamis	Wave Star
Sicily	Pelamis	Wave Star

6. Conclusions

The assessment of wave energy potential in the offshore of the whole Mediterranean Sea confirms that the most energetic offshore area is located between Corsica, Sardinia and Balearic Islands. In this area, the maximum yearly mean wave power reaches 16.4 kW/m. This assessment was carried out using a numerical simulation hindcasted period substantially lower than those used in 2013 by Liberti et al. [17] and in 2016 by Besio et al. [19], nevertheless their values of the maximum yearly mean power in this area are equal to our value. This potential is related to an offshore area that is too far from the continental borders and so, in practice, the interest for its exploitation is lowered due to unfavorable economic reasons.

In general, a favorable condition that can facilitate the exploitation of wave energy potentials is the proximity of a harbor and coastal sites where the produced energy can be transferred and used. Such condition can lower the maintenance, monitoring, and energy transport costs. It is why an assessment was performed of the nearshore potentials in front of the Tuscany, Liguria, Sardinia and Sicily regions. This nearshore assessment also permitted the location of hotspots, i.e., the areas where the wave power has the maximum value in their surroundings and, sometime, the local wave power is also higher than the offshore values. The Liguria hotspot is just 1 km from the closer harbor while it is 10 km for the Sicily and Tuscany hotspots and 40 km for Sardinia hotspot.

Among all the four hotspots of this work, the most energetic is the one near the headlands of the Argenteria (Sardinia region) on water depth of 20 m where the total mean annual energy reaches 100 MWh/m. The second most energetic hotspot is located NW of the Marettimo Island in front of Punta Mugnone (Sicily region) in 15 m of water depth where the total mean annual energy is 80 MWh/m and the wave conditions with 7 s < $T_{m-1,0}$ < 8 s and 2 m < H_{m0} < 3 m is responsible of the major contribution equal to 4.7 MWh/m. The Tuscany hotspot is located at the Meloria shoals in water depth of 10 m where the wave conditions 7 s < $T_{m-1,0}$ < 8 s and 2 m < H_{m0} < 3 m bring most of the energy for a contribution of 2.9 MWh/m while the total mean annual value reaches 41 MWh/m. In the case of the Liguria area, the hotspot is located in front of Monaco at a water depth of 10 m, the total annual energy reaches the very limited value of 18 MWh/m and most of the energy is carried by wave conditions 5 s < $T_{m-1,0}$ < 6.5 s and 1 m < H_{m0} < 1.5 m that account for 2 MWh/m.

The performance assessment of the state of the art WECs, here investigated, demonstrates that the offshore devices most suited for the Italian areas, in terms of capacity factor when installed in 50 m water depth, are the Wave Dragon for the Tuscany and Liguria and the Pelamis for Sardinia and Sicily. However, in each studied offshore site, the highest mean power output as well as the maximum capture width is always guaranteed by the Wave Dragon. In the case of the hotspots, the most suited device is always the Wave Star in terms of higher values of capacity factor, capture width and mean power output and, moreover, the highest capture width is obtained in the case of Tuscany area.

The comparison between the performance estimates of the studied WECs, in the most energetic oceanic site here considered (i.e., the Azores Island) and in the Italian sites, demonstrated that the capacity factor in the Italian sites is always lower than those obtained in the ocean, as expected, since all the devices are developed for the oceanic wave climate. However, the capture width values in the Italian sites are larger than those obtained in the Azores except for the AWS device in the

Tuscany and Liguria sites. This demonstrates that the studied WECs technologies convert a higher percentage of the potential wave energy when installed in the Italian sites than in the oceanic sites. In fact, the oceanic energy potential is up to 38-times greater than the potentials in the studied Italian areas but the power output, from the most suited WEC technology, is no more than nine times greater. These differences lead to the conclusion that, although the oceanic potentials can be much higher than the Mediterranean potentials, the tested WECs are not able to convert a large part of the oceanic energy. In other words, the harvesting of the wave energy in the Mediterranean Sea is facilitated by the fact that the energy potential is related to wave conditions that can be more efficiently harvested by the state of the art technologies.

Considering that the performance assessment of the WECs in Italian sites has shown lower capacity factors but higher capture widths in comparison to values in oceanic sites it is believed that if these technologies are properly downscaled for the Italian sites the values of their power output might be close to the values in the oceanic sites. This assumption seems to be confirmed by the work of Bozzi et al. [38].

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