Designing a point-absorber wave energy converter for the Mediterranean Sea

This work aims to assess the potential for wave energy production in the Italian seas by the deployment of arrays of heaving point absorbers, specifically optimized for mild climates. We model a single-body WEC, consisting of a cylindrical heaving buoy, attached to a linear electric generator placed on the seabed. The model includes both hydrodynamic and electromechanical forces. The results show that the best buoy-generator configuration at the selected sites (Alghero and Mazara del Vallo) is given by a 6 to 10 kW device and with a buoy with diameter between 4 and 5 m. This device can be brought to resonance, increasing the performances, by adding a submerged sphere. These results are encouraging and enlarge the perspective on wave energy production in the Italian seas.

DOI: 10.12910/EAI2015-052

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Introduction

Among renewable energy resources, wave energy represents a large and viable source of power supply, which deserves serious attention [1]. Although it represents only a small portion of wind energy, which in turn is only a small fraction of solar energy, the energy of surface ocean waves is more predictable, persistent and spatially concentrated [2]. The enormous wave power potential, together with the technical advantages of wave energy conversion has stimulated the interest of governments and energy companies since the oil crisis of 1973. Nowadays, a number of full-scale wave energy devices have been deployed in real sea conditions and several others are at the end of their development phase [3]. Most of them have been installed off the western coasts of continents in moderate to high latitudes. At present only few attempts have been made to exploit wave energy in the Mediterranean Sea.

The aim of this paper is to present recent research on point-absorber wave energy converters (WEC) specifically designed for mild climates, such as the one of the Italian seas. The paper, which resumes the work of two research groups, is organized as follows: first, the wave resource along the Italian coasts is characterized. Then, we present a preliminary work on the downscaling of existing devices – designed for Atlantic conditions – to make them suitable for the Mediterranean wave climate. In the following section a point-absorber wave energy converter, directly driven by a linear generator, is modelled and optimized for the Mediterranean Sea conditions. Finally, the effect of WEC interactions on energy absorption is investigated and advice is provided for the design of small wave energy farms in the Italian offshore areas.

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	Site	Depth (m)	Distance from shore (km)	Wave record length (y)	Missing data (%)	Average annual wave power (kW/m)	CV of average monthly wave power (%)	I	II	III	IV
1	Alghero	95	5.2	18.8	9%	9.1	48%	38%	25%	11%	26%
2	Mazara del Vallo	75	13	18.8	15%	4.7	59%	42%	27%	8%	23%
3	Ponza	100	1.44	17.7	10%	3.7	50%	37%	23%	11%	28%
4	La Spezia	92	15.6	18.8	13%	3.5	36%	33%	23%	14%	30%
5	Crotone	100	1.22	17.5	7%	2.9	56%	47%	23%	4%	26%
6	Monopoli	65	6.02	17.7	9%	2.1	55%	43%	24%	11%	22%
7	Catania	100	5.1	18.8	9%	1.9	63%	43%	28%	6%	24%
8	Ortona	60	10	17.7	12%	1.9	66%	46%	22%	9%	23%

Note: CV, coefficient of variation.

TABLE 1 Main features and statistics of the study sites. Columns I, II, III and IV represent the percentage of the annual wave energy in the months of December-February, March-May, June-August and September-November, respectively
Source: [4]

Wave resource characterization in the Italian seas

Wave energy exploitation starts with the characterization of the wave energy resource. Resource assessments allow to select the most promising locations for wave farms, design wave energy converters and estimate the production of energy and its possible costs. For these purposes it is crucial to know the amount of resource available, its monthly distribution and its composition in terms of sea states. In the present work, the wave energy resource of the most promising locations off the Italian coasts has been characterized. Table 1 reports the main features and wave energy statistics of these locations, sorted by decreasing wave power potential. More details are provided in Bozzi *et al.* [4].

The most energetic sites (1-4 in Tab. 1) are located in the Tyrrhenian Sea. Among them, we selected Alghero and Mazara del Vallo as possible deployment sites for wave energy farms, because they are the most productive of the whole Mediterranean Sea and the most favourable in terms of inter-annual variability of the energy resource [5]. At these locations the prevalent sea states are characterized by relatively small and short waves with peak periods around 6 s and significant wave height below 1 m.

Preliminary work: Downscaling of existing wave energy converters

In order to study the feasibility of wave energy exploitation off the Italian coasts, we start by estimating the energy production of three of the most promising and documented wave energy converters (AquaBuOY, Pelamis and Wave Dragon) at Alghero and Mazara del Vallo [6, 7]. As the selected devices were designed to maximize their electric production for Atlantic wave conditions, the estimated energy production and the capacity factors at the two Italian sites are very low (the capacity factor is around 8% at Alghero and 4% at Mazara del Vallo). This result indicates that, as expected, the WECs are oversized with respect to the Italian wave climate and that a more efficient energy conversion could be possibly obtained by downscaling the devices. Figure 1 shows the capacity factors as a function of scale for the hypothetical wave farms of AquaBuOY, Pelamis and Wave Dragon at Alghero and Mazara del Vallo. The geometric scales of the devices maximizing the capacity factors at the study sites range between 0.3 and 0.4 and the corresponding capacity factors between 16% and 21%. The main characteristics and performance indices of these smaller rated devices are summarized in Table 2. The results of this analysis suggest that deploying classic wave energy converters in the Italian seas would not be

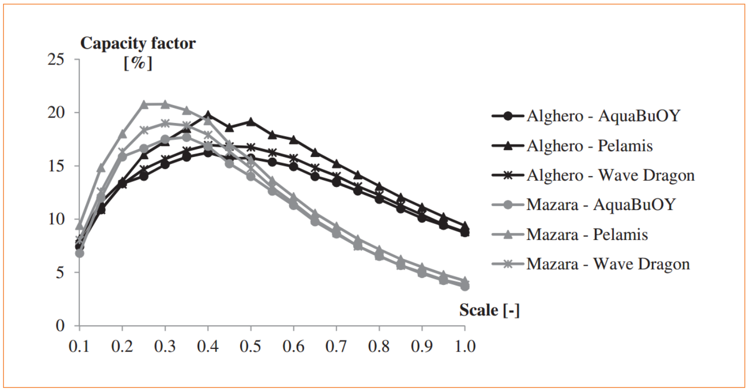

FIGURE 1 Capacity factors at Alghero and Mazara for different device dimensions
Source: [7]

cost effective, but if the devices could accommodate a proper downscaling their performance in energy conversion would become economically attractive also for some Italian locations.

Modelling and optimization of a point absorber for the Mediterranean Sea

The results of the previous study claim for a wave energy converter specifically tailored for the Italian wave climate. Due to its reduced size and heterogeneous geography, the Mediterranean wave climate is quite singular and unique in the world. With respect to the ocean wave climate, characterized by long-period swells, the Mediterranean Sea presents wind seas, where waves of different heights, periods and directions merge and produce random conditions. For this wave climate, the most suitable technology is probably a WEC of the point-absorber type, which can harness energy from all the incoming directions and can be located in deep waters, where energy availability is higher. Between the existing heaving point-absorber devices, we selected the Sea-based device [8] because of its simple power take-off mechanism and for the similarity between the Italian and Swedish wave climates, for which it was developed. This device consists in a floating buoy, connected by a rope to the piston of an electrical linear generator, placed on the seabed. The linear generator allows coupling directly the rotor to the vertical motion of the sea surface, eliminating the need of complex power take-off mechanism and gear-boxes.

Mathematical modeling

The behavior of the wave energy converter is simulated in regular waves of different heights and periods by a coupled hydrodynamic-electromagnetic model. The simulations are run in the time domain, due to the non-linearity of the

	Alghero			Mazara		
	AquaBuOY	Pelamis	Wave Dragon	AquaBuOY	Pelamis	Wave Dragon
Scale	0.4	0.4	0.4	0.35	0.3	0.3
Rated Power [kW]	10	30	283	6	11	104
Mean power output [kW]	1.6	6.0	48.1	1.1	2.3	19.9
Annual energy output [MWh]	14	53	421	10	20	175
Full load hours [h]	1423	1735	1486	1551	1837	1686
Capacity factor [%]	16	20	17	18	21	19
Coefficient of variation of monthly time series [%]	21	2	22	28	25	23
Correlation coefficient between energy input and output [-]	0.81	0.87	0.86	0.87	0.86	0.80

TABLE 1 Characteristics and performance of the downscaled devices at Alghero and Mazara del Vallo
Source: [7]

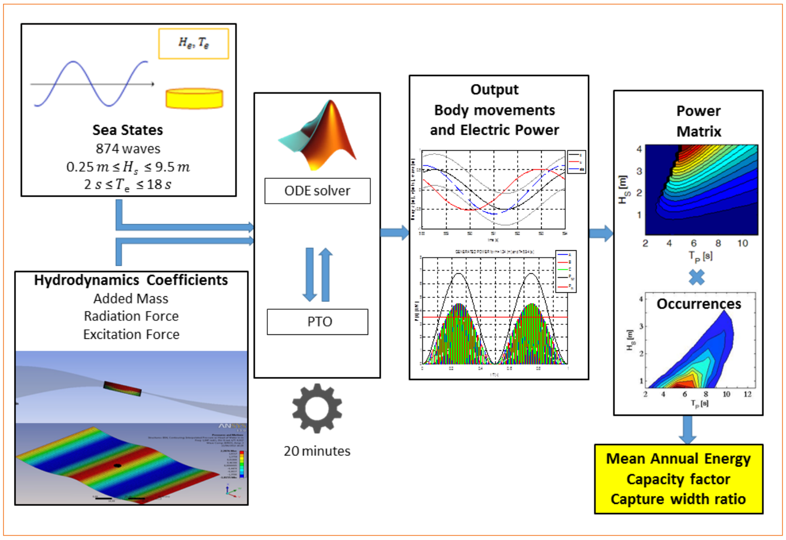

FIGURE 2 Sketch of the modelling procedure

PTO system. The power output of the device is calculated for each sea state to derive the so-called power matrix. This information is coupled with wave climate data to evaluate energy production and performance at each study site. The whole modelling procedure is summarized in Figure 2.

The floating body dynamics are determined by solving the following equation of motion, which combines the hydrodynamic forces $F_H(t)$ and the resistance forces $F_R(t)$ due to the PTO system:

$$m z(t) = F_H(t) + F_R(t) \qquad (1)$$

where m is the total mass of the system and $\ddot{z}(t)$ represents its vertical acceleration. The hydrodynamic forces on the heaving buoy are calculated by:

$$F_H(t) = -m_a z(t) - R_D z(t) - \frac{1}{2}\rho A C_D (z(t) - \eta(t))| \qquad (2)$$

$$|(z(t) - \eta(t))| - \rho g A z(t) + F_e \frac{H}{2}\cos(\omega t + \alpha)$$

where $z(t)$ is the vertical coordinate at time t, measuring deviation from the static equilibrium. The five terms on the right side of the equation represent the different forces acting on the buoy: (1) added inertial force, accounting for the fluid volume moving with the buoy, where m_a is the added mass; (2) radiation damping force, due to the waves created by buoy oscillations, where R_D is the radiation damping coefficient; (3) viscous damping force accounting for relative turbulent flow, where ρ is sea water density, A is the water-plane area, C_D is the viscous damping coefficient and $\dot{\eta}(t)$ is the vertical velocity of the free water surface; (4) hydrostatic restoring force, where g is gravity; and (5) vertical component of the excitation force, due to the incident waves on the assumedly fixed body, where F_e is force amplitude, H and ω are wave height and frequency, respectively, and ω is the phase angle between the wave and the wave-induced heaving force. The frequency-dependent coefficients of excitation and radiation force are estimated prior to model simulations by a boundary element code and given as inputs to the ODE solver (Fig. 2). More details on the numerical model can be found in Bozzi *et al.* [4]. The resistance force, $F_R(t)$, due to the PTO system, is modeled as:

$$F_R(t) = -F_M(t) - F_K(t) \qquad (3)$$

where $F_M(t)$ is the electromagnetic force, due to the electric linear generator, and $F_K(t)$ is the elastic force of the spring system attached to the translator, which is calculated by:

$$F_K(t) = K z(t) \qquad (4)$$

where K is the elastic constant of the spring. The electromagnetic force is obtained through Faraday's law and Maxwell equations that govern the magnetic induction in the stator-translator structure. The simplified analytical model presented by Thorburn and Leijon [9] is used to calculate the voltage generated in the stator with input parameters derived by finite element simulations of the electromagnetic field [10, 11]. Finally the electricity production is estimated by multiplying the expected power output of each sea state (defined by H, T_e pairs) by its occurrence (in hours) and then by summing over all sea states (Fig. 2).

Optimization of buoy and generator parameters

Several buoys of different shapes, radii, heights and drafts are simulated to investigate the effect of floating body geometry on power absorption and to find the optimal buoy for the study locations. Conical, cylindrical and hemispherical buoy shapes are evaluated, both with a cylindrical upper part [12]. The sensitivity analysis shows that (*i*) for a given diameter of the upper part, the cylindrical shape is the most efficient in wave power absorption; (*ii*) the height of the floating body influences the hydrodynamics response only if it is associated with a change in draft; (*iii*) the effect of buoy draft is related to buoy mass: as the draft decreases the hydrodynamic coefficients increase; and (*iv*) the buoy diameter plays a key role in the process of wave energy absorption since it is directly proportional to the wave front width captured by the device. As a result, by increasing the diameter, the loads on the structure increase. This effect is much more significant for long periods, as the body can better follow the wave movement. Moreover, the added mass is higher for larger buoy diameters because the volume of the fluid moving with the buoy increases with its size. The results of the sensitivity analysis lead to identifying the cylindrical buoy with 5 m diameter and 0.8 m draft as the one with the highest capture width ratio, for a linear generator with nominal power of 10 kW (Fig. 3).

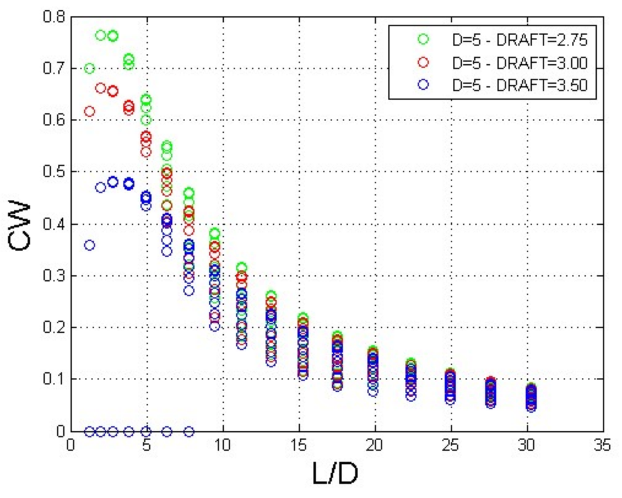

FIGURE 3 Capture width vs. L/D (L wave Length, D cylinder diameter) for the most efficient cylindrical buoy
Source: [12]

In order to better match the wave climate variability of the chosen locations, five linear generators of different nominal powers are designed (4, 6, 8, 10 and 12 kW, hereafter LG4, LG6, LG8, LG10 and LG12). Each electrical device is simulated with cylindrical buoys of different diameters to find the optimal buoy-generator configuration at each study site, using the maximum capacity factor criterion. Figure 4 shows that the capacity factor data plotted against the buoy diameter arranges in a concave curve, suggesting that for each generator there is a buoy diameter, which maximizes the energy production. If the buoy is too small, the excitation force is too low and the power absorption ability of the generator is limited by the available power. On the other hand, too large buoys have too much inertia to follow the sea motion and lower capture efficiency, due to larger diffraction effects. At the two study sites the maximum capacity factor (around 17%) is achieved by coupling a linear generator of 6 kW with a buoy of 5 m diameter. Although at Mazara del Vallo, the available wave power is almost half than Alghero's, the power output is almost the same, thanks to the lower intermittency in the wave climate. This fact makes it preferable than Alghero's, being a site with very energetic, albeit very rare sea storms.

Resonant body

A resonant point absorber system has significantly higher power absorption, due to its enhanced amplitude and speed. However, for small point absorber devices, such as the one studied here, the resonant frequency tends to be much higher than the typical sea state frequency, and so, the resonant state is practically impossible to be achieved. One

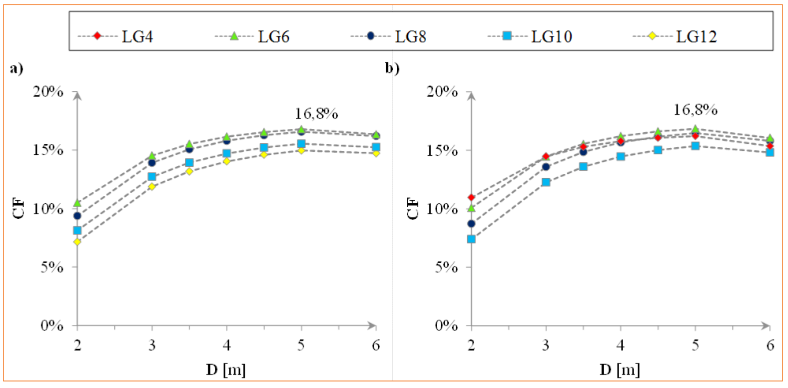

FIGURE 4 Capacity Factor (CF) as a function of buoy diameter (D) for different linear generators: (a) Alghero, (b) Mazara del Vallo

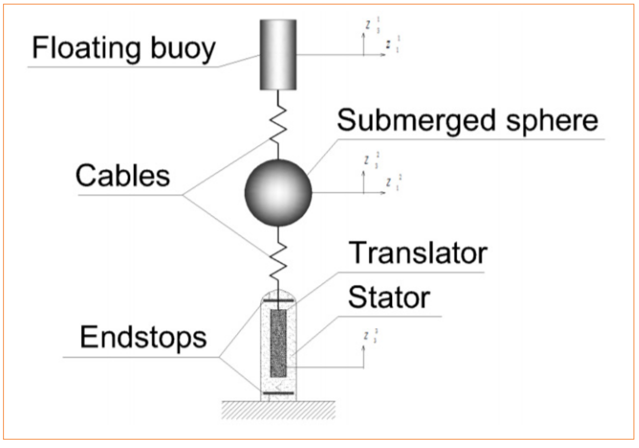

FIGURE 5 Sketch of the modelled device

way to increase the natural period of oscillation of a point absorber is by connecting to the floating buoy a deeply submerged object with neutral buoyancy [13, 14]. The additional inertia, due to the submerged body mass and added mass (Fig. 5), allows the decreasing of the natural frequency of the device, which is given by:

$$\omega = \sqrt{\frac{\rho g A + K}{m + m_a}} \qquad (5)$$

where m is the total mass of the WEC and m_a is the total added mass at the frequency of the incident wave. Depending on the submerged body mass, the system can be tuned to resonate with a different incident wave frequency. In this analysis, it is tuned to be in resonance with waves of peak periods of 5.5 s, which match quite well the wave climates of the study sites.

Figure 6 shows the hydrodynamic parameters of the 5 m-diameter buoy calculated by placing the submerged body at different depths, with respect to the ones of the single body system. It can be noticed that the distance

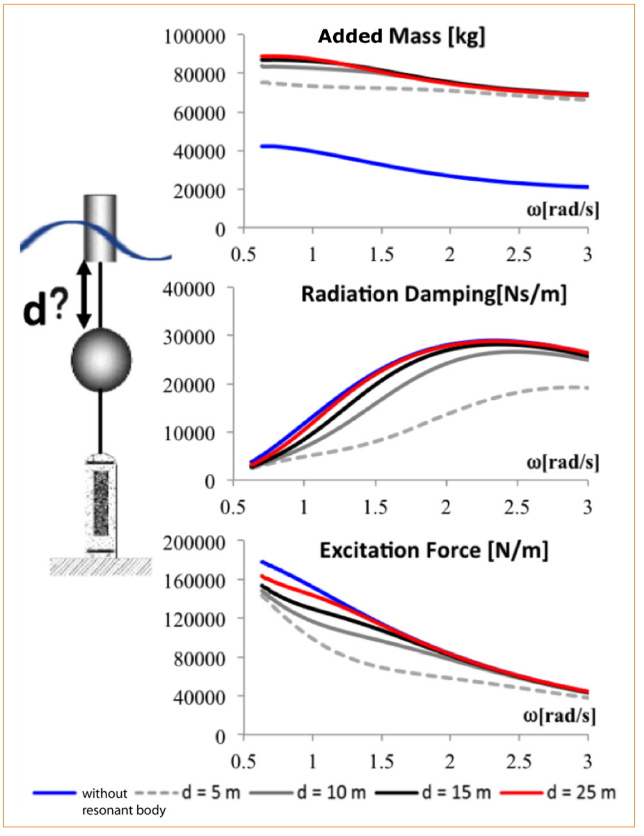

FIGURE 6 Hydrodynamic parameters of the buoy computed with the submerged body at different depths (d = 5, d = 10, d = 15 and d = 25) compared to the ones of the single-body device

between the floating and submerged body strongly affects the hydrodynamics of the buoy. In particular, if the sphere is placed too close to the free surface, it negatively affects the motion of the surface body, because it drives down excitation and radiation forces. On the other hand, when the submerged body is well below the motion of the waves, the radiation damping and excitation force coefficients of the single and two-body systems are practically coincident. In this case, the submerged body only contributes to add supplementary inertia to the system without destructively interfering with the floating body. As a result of this analysis the hydrodynamic parameters of the two body systems are calculated by placing the submerged body at a depth of 25 m (Fig. 6).

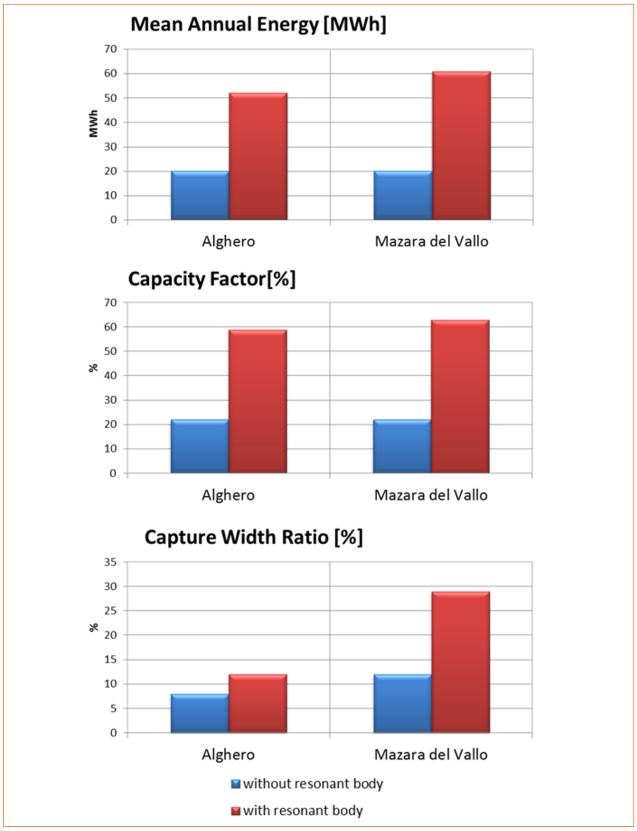

FIGURE 7 Mean annual energy, capacity factor and capture width ratio at Alghero and Mazara del Vallo without resonant body (Blue) and with resonant body (Red)

The simulation results show that the performance of the device substantially increases when the floating body is connected to a submerged sphere, thanks to the resonant behavior of the WEC. The capacity factor of the dual body device is higher than 40% at both locations and the capture width ratio doubles with respect to the single body system (Fig. 7).

Assessment of the surge effect

In this section, we investigate the effect of including more degrees of freedom (DoF) in the device model. In particular, the effect of the independence of the bodies and the contribution of the surge mode to wave energy absorption are assessed by implementing two more detailed modelling schemes. In the first scheme the two bodies are allowed to move independently but only along the vertical axis (3 DoF), while in the second one they can move independently both in heave and surge (5 DoF). The comparison with the results of the 1 DoF model shows that the energy production estimated by the simplified 1 DoF scheme is higher than the one predicted by the 3 DoF model. This is due to the fact that the 3 DoF model is less simplified and takes into account losses of energy which are neglected in the 1 DoF scheme [15]. On the contrary, passing from 3 DoF to 5 DoF does not imply significant changes in the energy production of the two sites. Regarding device efficiency, the capture width ratio decreases with the increase of the degrees of freedom: the reduction is about 20% from 1 DoF to 3 DoF and about 35% from 1 DoF to 5 DoF (Fig. 8). However, the value of wave height and energy period which maximizes the capture width is the same for the three models.
These results indicate that: (1) the modelling of the connections between the three bodies of the device (1 DoF versus 3 DoF) plays a considerable role in the prediction of energy production; (2) no relevant changes in power output are induced by adding the surge motion of the floater and of the submerged body; (3) the device efficiency is more sensitive to the modelling approach and accuracy than power output; and (4) surge motion can be significant for the estimation of capture width ratio.

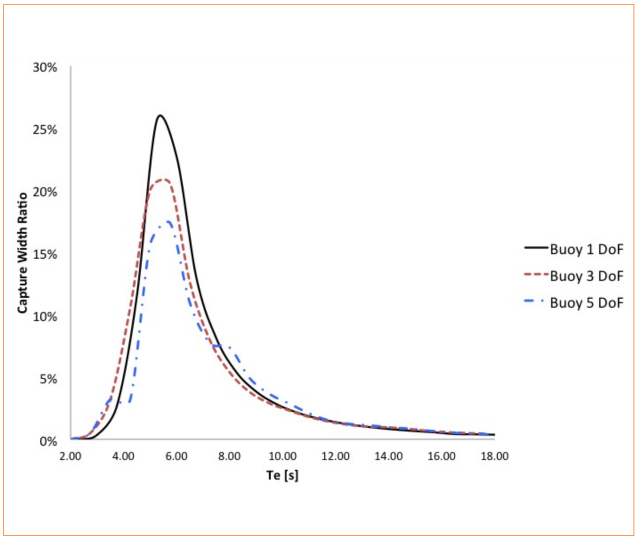

FIGURE 8 Capture Width Ratio of the modeled devices with 1, 3 and 5 DoFs vs. wave energy period

Array design

Point absorber WECs are designed to be deployed in large arrays, which allow increasing the power output and reducing the total cost. Within wave farms, each unit interacts with the others by absorbing, radiating and diffracting the incoming waves. The spatial distribution of the units plays a key role in their mutual interactions, which can be constructive, such as wave focusing or destructive, leading to the wave field attenuation. It is important to predict hydrodynamic interactions among wave energy converters in order to maximize the efficiency of the park.

In this section we present our recent research on this topic [16], aimed at providing advice for the design of small wave energy farms in the Italian offshore. A key strength of the work is the coupling between the hydrodynamic and electromagnetic model, which allows taking into account the effect of array interactions on the PTO system, instead of simply assuming a constant damping, as in many other works [17]. To evaluate the effect of WEC interactions on energy absorption and to identify the most important parameters affecting array production we simulated small arrays of two and four devices, considering different layouts (linear, square-based and triangle-based), WEC separation distances (5, 10, 20 and 30 diameters) and incident wave directions (every 45°).

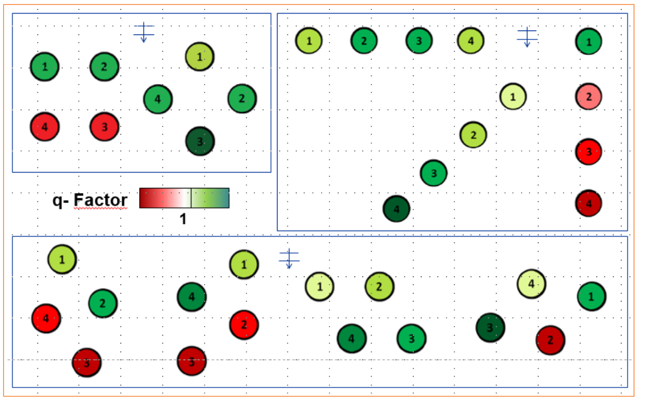

FIGURE 9 Interference factor of the park units for different array layouts, under unidirectional sea state

The results shows that: (*i*) assuming a unidirectional sea state and varying the distance between WECs, the energy production of the array varies up to 5%; (*ii*) the effect of the incident wave direction seems to be more important than the WEC separation distance, particularly for the linear and square based layout; (*iii*) depending on the wave attack angle, the absorbed energy varies up to 14%, 13% and 5% for the linear, square-based and triangle-based layout, respectively; (*iv*) when the wave climate has a dominant wave direction, the best array configuration should be parallel to the wave front for the linear layout, at 45° with respect to wave direction for the square-based layout and with the line connecting the two leeward devices parallel to the wave front, for the triangle-based layout (Fig. 9).

At both the study sites, the linear layout is found to be the most favorable (Fig. 10). However, given the small differences with the other layouts in terms of energy production, we suggest that the design of small wave energy parks focuses also on other issues, such as the occupied sea area and the quality of the electric signal.

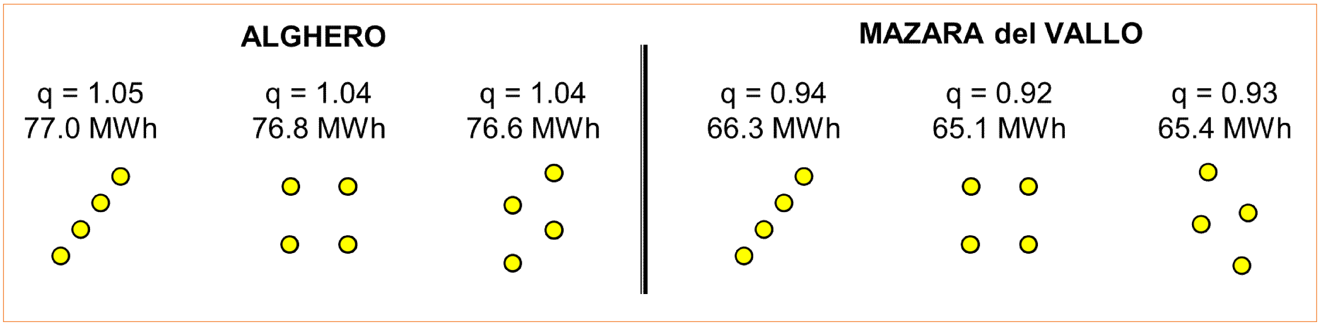

FIGURE 10 Optimal array configurations at the study sites

Discussion and conclusions

This paper presents a review of the recent research activities of the authors on the feasibility of wave energy conversion in the Italian seas. The work starts with the estimation of the energy production of two of the most promising wave energy converters, at two of the most energetic Italian sites: Alghero and Mazara del Vallo. The results of this study show that the considered WECs are oversized with respect to the local wave climate and suggest that they are resized according to the wave climate of the Mediterranean Sea. In this way, a more efficient energy conversion is obtained and promising results are found, in terms of energy production and degree of utilization of the available resource.
Following these conclusions, we investigated the feasibility of installing small-rated devices specifically designed for mild climates, such as the Seabased device. This simple point-absorber WEC consists in a floating body, capturing energy from incident waves, and a linear generator placed on the sea bottom and connected to the buoy via a rope. The device was simulated in the time domain by a hydrodynamic-electromagnetic model, coupled with a boundary element code for the estimation of the hydrodynamic parameters. To account for the different wave climates of the Italian coasts, five linear generators of different nominal powers were designed. Each of them was coupled with seven different buoys, which were designed after a sensitivity analysis of WEC hydrodynamics to buoy geometry (shape, radius, height and draft). The performance and the electricity production of each buoy-generator combination was calculated at Alghero and Mazara del Vallo, using 21 years of wave buoy records, covering the period from 1990 to 2011. The results showed that the best buoy-generator configuration at both sites is given by a device with nominal power between 6 and 10 kW and a buoy with diameter between 4 and 5 m. The selection criterion used in this work was based on the capacity factor, which enables to compare devices with different rated powers and to evaluate the economic feasibility of renewable energy technologies based on intermittent energy sources.
After the identification of the most suitable device configuration, we investigated the possibility of increasing the power output by adding a neutrally buoyant submerged sphere to the floating buoy, in order to bring the system into resonance with the typical wave frequency of the study sites. We showed that this solution allows to considerably increase the capacity factor of the device, from about 20% to more than 40%. Starting from this solution, we investigated the effect of including more degrees of freedom in the device model. In particular, we assessed the effect of the independence of the two bodies and the contribution of the surge mode to wave energy absorption. The results showed that the first contribution is important for energy production estimation, while including the surge mode in the hydrodynamic model does not provide significant improvements.
Finally, the work focused on the hydrodynamic interactions between the devices, deployed in small parks. Small arrays of two and four devices were

simulated considering different array layouts (linear, square based and triangle based), WEC separation distances (5, 10, 20 and 30 diameters) and incident wave directions (every 45°). The results showed that: (*i*) assuming a unidirectional sea state and varying the distance between WECs, the energy production of the array varies up to 5%; (*ii*) the effect of the incident wave direction seems to be more important than the WEC separation distance, particularly for the linear and square based layout; (*iii*) depending on the wave attack angle, the absorbed energy varies up to 14%, 13% and 5% for the linear, square-based and triangle-based layout, respectively; and (*iv*) at all the Italian study sites, the linear layout was found to be the most favourable.

The present work will be further improved, and other issues should be investigated before designing a wave energy farm off the Italian coasts. However, the work showed the feasibility of wave energy production in the Italian seas and provided advice on where and how to exploit the Italian wave energy potential.

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