13th ewtec 2019 Proceedings of the 13th European Wave and Tidal Energy Conference 1-6 Sept 2019, Naples, Italy

Efficiency of Wave Energy Converters off the Sicilian Channel

Carlo Lo Re, Giorgio Manno, Giovanni Besio, and Giuseppe Ciraolo

***Abstract*—This paper presents a preliminary analysis on efficiency of wave energy converters off the Sicilian Channel (Italy) carried out using the SNL-SWAN spectral model ("Sandia National Laboratories – Simulating WAves Nearshore"). This open source numerical code makes possible to calculate the power extracted from wave energy converter (WEC) devices, arranged in arrays. The WEC arrays were located parallel to the coastline, near the 20 m bathymetric isoline. Three devices were tested: Pelamis, Wave Dragon and Oyster 2; one of the input data of the numerical model is the WEC power matrix, expressed as a function of the wave height and period. This matrix was determined experimentally by the prototype manufacturers and it allows to compute the energy flux that can be extracted, depending on the significant wave height and on the peak period. Wave climate has been obtained from the Mazara del Vallo wave buoy dataset, covering the years from 1995 to 2005. The numerical model analysis results include the comparison between the energy flux distribution both in the case of presence of WECs and in their absence. The results obtained through the nearshore analysis allowed to assess the devices efficiency. Among the simulated devices only the Oyster 2 had a high value efficiency whereas for the other two devices lower power values were obtained. This results because the prototypes were designed considering the ocean wave conditions, which are of an order of magnitude higher than the conditions that occur in a closed sea basin, as is the Mediterranean Sea.**

***Index Terms*—wave energy, power matrix, WEC devices, coastal defence, Sicilian Channel**

I. Introduction

NOWADAYS, in the international framework of renewable energies, we are observing an increasing interest in the production of energy from the sea waves. Indeed this is a huge source of clean energy able to provide electricity to the whole world population, in principle. Actually, in recent years we are witnessing a race to develop a great number of Wave Energy Converters (WEC) [1] (e.g., AcquaBuOY, Pelamis, Wave Dragon, etc.) but, obviously, these devices must be designed and sized for the various installation sites and, therefore, they cannot disregard from the energy resource availability of the sites themselves [2]. Numerous studies on the wave energy assessment have been carried out for many world's areas and different ones have been dedicated to the Mediterranean Sea. Although most of the wave flux is available in the oceans, Ref. [3] assessed the gross wave power resource to be 3 GW in the Mediterranean Sea. Ref. [4] and [5] carried out an assessment of the wave energy resources in the Mediterranean Sea using a third generation wave model, showing the area between Sardinia and Balearic Islands as the most convenient of the entire Mediterranean Sea. Furthermore, their result affirmed that the western Sardinia and the southern and western Sicily as the most promising Italian areas for the wave energy production. Particularly, as the most productive area of Sicily, it was identified the coastal stretch north of Mazara del Vallo with average power equal to about 6 kW/m, reaching values around 7 kW/m near Favignana Island. Ref. [6] confirmed the results of Ref. [4] and detected the western coast of Sicily, in front of the Aegadian Islands, as the most energetically promising, with average wave power reaching about 5 kW/m. Ref. [7] and [8] presented studies about the wave energy assessment off the Sicilian coast. In particular, the authors focused both on the localization of high energetic Sicilian coastal areas and on the performance and efficiency of different types of wave energy converters (WEC). These studies confirm the west coast of Sicily (nearby Trapani) and the Sicilian strait as the most energetic areas of the main island. Ref. [8] estimated that the marine area near Trapani has an energy flux between 5.33 and 7.52 kW/m, moreover the authors showed that the capacity factor of all the tested WEC (in their original configuration) has a value in the range of 2.19% - 5.12%. These low values are explained by the fact that the original WECs were designed and optimized for a different type of wave climate having as a target the high energetic ocean (mainly Atlantic and Pacific) waves. Ref. [9] analyzed the efficiency of several nearshore WEC devices localized off the West coast of Sicily near Favignana. In particular, the authors tested four WEC devices: Wave Star, Oyster, Wave Dragon and Archimedes Wave Swing. The Wave Dragon (500 kW) among those investigated was the most efficient. Similar studies were carried out by [10] in the proximity of Pantelleria island, testing and validating a specific type of WEC designed by the authors themselves. Furthermore, Ref. [11] discusses the use of renewable energy for desalination plants in Sicily. These authors studied the possibility of conversion of wave power into electrical energy to supply water treatment. Ref. [12] presented

Paper ID 1713 Conference Track WRC

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a performance evaluation of Wave Energy Converters (WECs) in terms of electricity production for domestic and public supplies of the coastal towns located off the Calabria (Southern Italy) coasts. Moreover shallow water WECs array can also protect coasts from erosion [13]–[17], attenuating significant wave heights and inducing also variations in near-shore currents [18], [19]. The greatest limitation for wave energy production in the Mediterranean sites is the available energy, rather low if compared with that estimated for oceanic coasts [20]. As demonstrated by [21], [22] and [2] however, the above-mentioned limitation does not preclude the WEC installation, because these devices can be scaled and fixed to the relatively low energetic availability of the Mediterranean Sea. The main objective of this paper is to assess the amount of convertible energy, in the area identified by previous studies [6], [23], and to evaluate the effects of WEC devices on coastal erosion protection. The wave propagation from offshore to nearshore was performed using the SNL-SWAN spectral model ("Sandia National Laboratories – Simulating WAves Nearshore").

II. Study area and data set

The data used in this paper were collected from the buoy of Mazara del Vallo off the Trapani coast, (37.52 N; 12.53 E) and the availability period, was from July 1995 to June 2005. RON (*Rete Ondametrica Nazionale* - Italian Data Buoy Network) data consist of significant wave height (H_s), peak wave period (T_p), and mean wave direction (θ). RON collected data for 30 min within each 3-h interval, but collection was continuous when H_s exceeded 4.5 m.

The study area is inside the continental shelf, with water depths between 450 and 5 m. A 2D unstructured grid was implemented in the computational domain (Fig. 1 A,B). The implementation of the spectral wave model by using unstructured meshes allows resolution to vary over several orders of magnitude with respect to a single mesh. Moreover, the unstructured meshes allow high levels of resolution along a specific stretch of coastline but relatively low levels of resolution between distant coasts or islands. The implemented mesh of the present model was constituted by 5573 triangles covering an area of about 82.287 x 65.473 km^2. A density function was used to build the unstructured mesh in which the size of triangles depended on local water depth and wave length (calculated by means of the peak period). The depths at the mesh nodes were calculated by a linear interpolation of bathymetric data taken from nautical charts of the *Istituto Idrografico della Marina Militare* (the Italian Hydrographic Institute). Wave parameters obtained from the Mazara del Vallo buoy were assigned as input along the deep water side of the domain. Along the remaining side a no-wave condition was used (Fig. 1 A,B). The *Egadi* Islands, in particular *Favignana* Island, shield the coast in the 320° N direction. The geographical fetch is limited from the west by the Spanish coast, from the south by the African coast and from the north-west by the Sardinian coast.

III. Method

The nearshore wave energy potential along the coastal stretch between Marsala and Mazara del Vallo was characterized by performing wave propagation using a spectral numerical model. The SNL-SWAN Sandia National laboratories - Simulating WAves Nearshore [24], [25]. The code is a modification of the open source code, SWAN (Simulating WAves Nearshore) developed by TU Delft that is a third generation phase-averaged wave model [26], [27]. The SNL-SWAN numerical code includes a WEC module which improves how SWAN accounts for power performance of WECs and the effects on the wave field. This makes possible to calculate the energy flux extracted from WEC devices, arranged in arrays. The numerical code solves the spectral wave action balance equation:

$$\frac{\partial N}{\partial t}+\frac{\partial(c_{gx}+U_x)\cdot N}{\partial x}+\frac{\partial(c_{gy}+U_y)\cdot N}{\partial y}+\frac{\partial(c_\theta)\cdot N}{\partial \theta}+ \\ +\frac{\partial(c_\sigma)\cdot N}{\partial \sigma}=\frac{1}{\sigma}\cdot(S_{nl4}+S_{brk}+S^{+}_{i,j}) \quad (1)$$

where $N(t,x,y,\sigma,\theta)=E/\sigma$ is the wave action, E the wave energy density, t the time, x and y the planimetric coordinates, θ the direction of the wave propagation, and σ the radian frequency. U_x and U_y are the components of the depth- and time-averaged current velocity vector; c_{gx}, c_{gy}, and c_θ are the velocities of energy propagation in the geographic plane, and c_σ is the velocity in the spectral plane. The terms on the right-hand side of equation (1) represent energy losses and sources: S_{nl4} the nonlinear transfer of wave energy through four-wave interactions, and S_{brk} the wave dissipation due to depth-induced breaking. Wind input and bottom friction have little effect on numerically modeled bulk wave parameters and for this reason were neglected. The term S_{brk} was modelled by the approach described by [28]; the default breaking (Γ = 0.73) and intensity (α = 1) coefficients were adopted in the model. To model WECs in SNL-SWAN, the obstacle feature is used. The SWAN obstacle is defined by a line crossing between two grid points that is used as an energy sink term ($S^{+}_{i,j}$) in the governing equation. The sink term of eq. (1) is shown in the following:

$$\left(\frac{1}{\Delta t}+(D_{x,1}+D_{x,2})c^{+}_{x,i,j}+(D_{y,1}+D_{y,2})c^{+}_{y,i,j}\right)N^{+}_{i,j} \\ -\frac{N^{-}_{i,j}}{\Delta t}-D_{x,1}(c_xK^2_{t,1}N)^{+}_{i-1,j} \\ -D_{y,1}(c_yK^2_{t,1}N)^{+}_{i-1,j}-D_{x,2}(c_xK^2_{t,2}N)^{+}_{i-1,j} \\ -D_{y,1}(c_yK^2_{t,2}N)^{+}_{i-1,j}=S^{+}_{i,j} \quad (2)$$

where D is the diffusion coefficients, i,j the grid point indexes.

Using the SLN-SWAN numerical code, it is possible to calculate the transmission coefficient $K^2_t=P_t/P_i$. One of the input data of the before-mentioned model are the WEC power matrices, expressed as a function of the wave height and period. These matrices were determined experimentally by the prototype manufacturers and allowed to compute the extractable power,

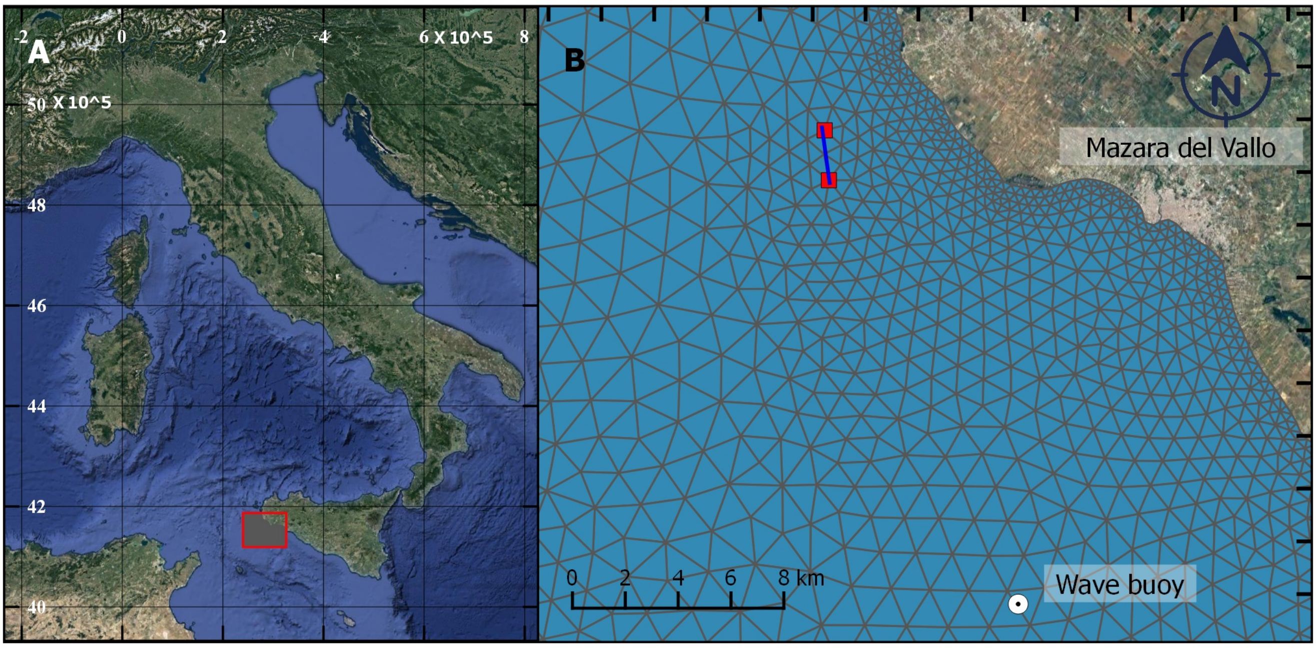

Fig. 1. A) Map overview of the studied area. The red rectagle shows the computational domain. The coordinate system is ED50 - UTM 33 N. B) Zoom of the numerical domain showing the triangular mesh and the WEC arrays (blue line).

depending on the significant wave height and on the peak period. The parameter K_t^2 was calculated as the ratio of the transmitted energy flux P_t and the incident energy flux P_i. In the used numerical model the WEC arrays were located parallel to the coastline, near the 20 m bathymetric isoline; the devices considered are Pelamis, Wave Dragon and Oyster 2. In Figures 2, 3 and 4 power matrix are shown, in particular the length of each devise are 150 m (Pelamis), 30 m (Wave Dragon)and 26 m (Oyster 2).

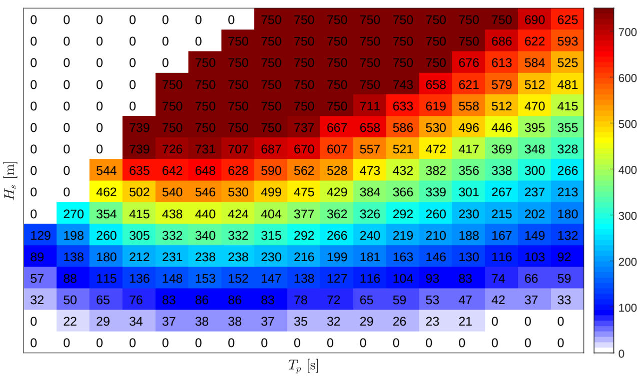

Fig. 2. Power matrix of the Pelamis device. The color bar shows the Energy flux [kW].

The WEC array start from point having coordinate 4,173,578 N 274,460 E and ends to point with coordinate 4,171,686 N 274,618 E (reference system: ED50 UTM 33 N). The array was implemented in the computational mesh, Figure 1, using the *obstacle* feature of SNL-SWAN. The array consist of a line (2,000 m long) in which can fall n devices. The number of devices depends on the length of each of them: a) 13 Pelamis devices, b) 77 Oyster devices and c) 7 Wave dragon.

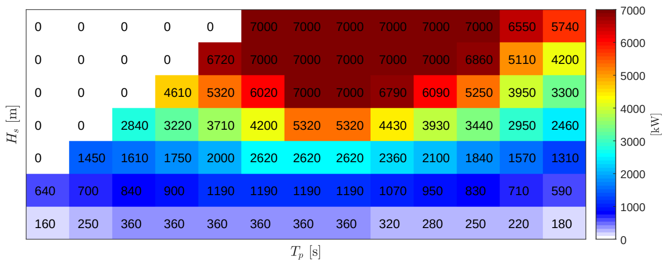

Fig. 3. Power matrix of the Wave Dragon device. The color bar shows the Energy flux [kW].

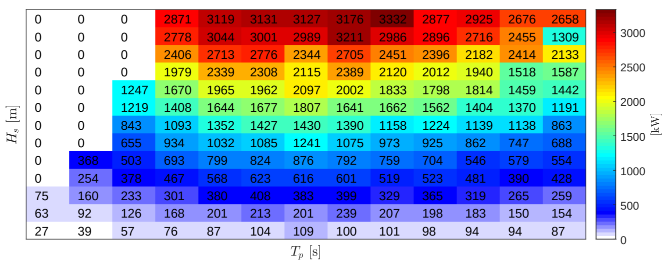

Fig. 4. Power matrix of the Oyster device. The color bar shows the energy flux [kW].

IV. Results and Discussion

In order to perform a preliminary analysis of the wave climate in the study area, a non-stationary simulation was performed from 1995 to 2005. The time series was sampled at three hour intervals. The energy analysis was performed for the area in which Ref. [6] identified an hotspot. This area is a potential energy farm deployment zone. The maximum energy, of about 5,000 kWhm^{-1}, is produced by waves having H_s = 1.5-2.0 m and T_e = 6-7 s, as showed in figure 6.

In the Table I are shown the energy flux calculated from first analysis performed with the present model.

TABLE I
EXTRACTED ENERGY FLUX

	P_i	P_t	E_i	E_t	η_p [a]
Pelamis	95.1	93.8	13.3	13.2	1%
Wave Dragon	95.1	82.7	13.3	11.9	13%
Oyster 2	95.1	38.8	13.3	6.1	59%

[a] The energy fluxes P_i and P_t are in kW/m, the total energy E_i and E_t are in kJ/m^2 the efficiency in %. The i and t subscripts states respectively incident and transmitted energy.

The analysis of results of the numerical model include the comparison between the significant height distribution both in the case of presence of WECs and in their absence.

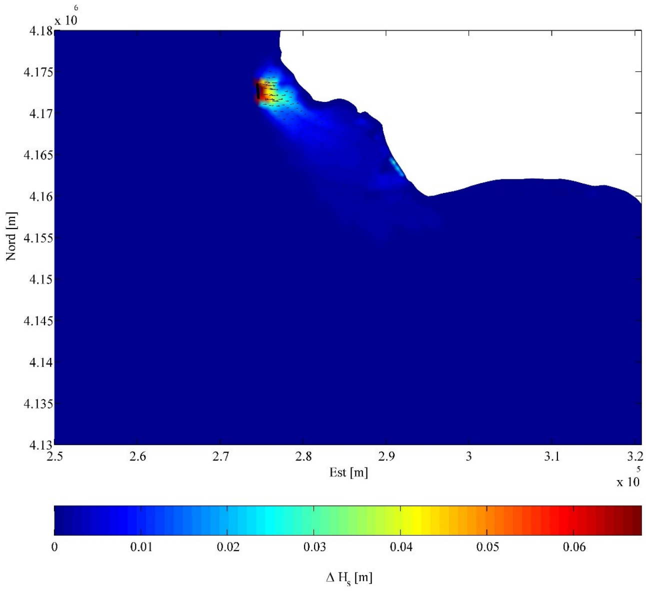

Fig. 5. The difference between the spectral significant wave heights in the presence of the device and in the absence of WEC (energetic wave event, $H_s = 4.76$ m; $T_p = 10$ s; $\theta = 272°$).

Among the simulated devices only the Oyster 2 has an high efficiency value of about 59%, whereas for the other two devices lower energy flux values were obtained, respectively 1% and 13%. The presence of a WEC array, on the one hand, allows absorbing the incident wave motion, on the other, decreases the energy flux of the wave itself during onshore propagation. In the figure 7 is showed the energy flux distribution in the case of presence a Oyster 2 device. The energy values in the figure 8 were obtained by subtracting the energy value, at each grid point, without device with the energy values with the presence of Oyster 2 device. In the inner part of Pelamis device a very slight reduction of the energy flux was found, less than 2.5 kW/m. This value is almost negligible compared to the energy flux available without devices, equal to 120 kW/m, corresponding to a reduction of 2%. On the basis of this result, it can be assumed that the energy flux convertible into electric energy is even lower since

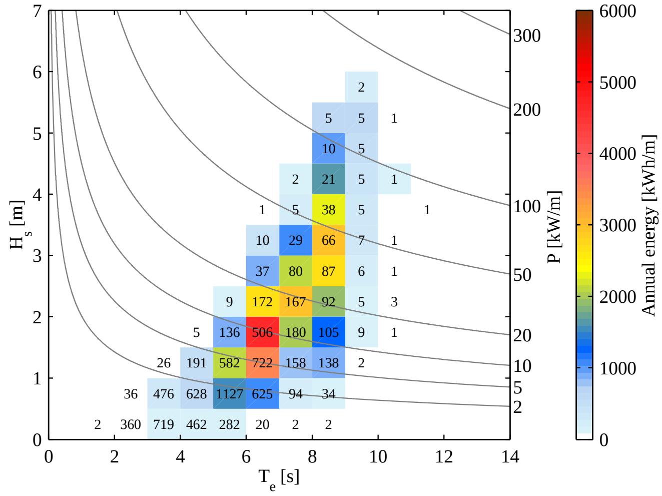

Fig. 6. Characterisation of mean yearly wave energy and wave energy flux climate. The scatter plot of H_s e T_e, the colour scale indicates annual energy per meter of wave front (kWh/m), the numbers within the bins indicate the occurrence of sea states (hours/year) and the isolines specify the wave energy flux

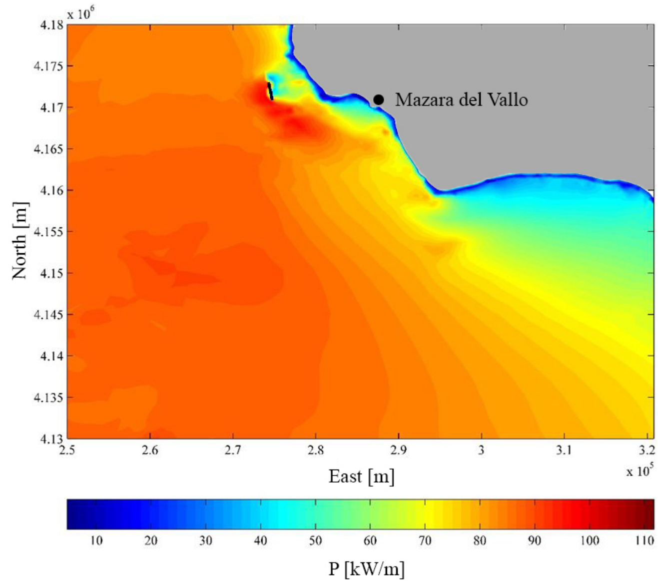

Fig. 7. Energy flux distribution, during an energetic wave event ($H_s = 4.76$ m; $T_p = 10$ s; $\theta = 272°$) , in the presence of the Oyster 2 device. The black line represents the arrangement of the WEC arrays.

part of the energy is dissipated. As a result, the Pelamis system is not suitable for installation in the area off Marsala and Mazara del Vallo.

The Wave Dragon system produces a moderate, but not negligible reduction of the wave energy flux, even if located within a limited area beyond the array. The energy flux is reduced to a maximum of 14 kW/m, corresponding to 12% of the outer energy flux. This result is encouraging for energy exploitation, but can be further improved by optimizing the system geometry for the specific area of installation. The last system studied, the Oyster 2, was the one that more than others reduced the wave energy flux: the maximum decrease is about 60 kW/m and corresponds to 50% of the incident energy flux (sea Figure 8). In Table I was shown the efficiency $\eta_p = (P_i - P_t)/P_1 \cdot 100$ of the

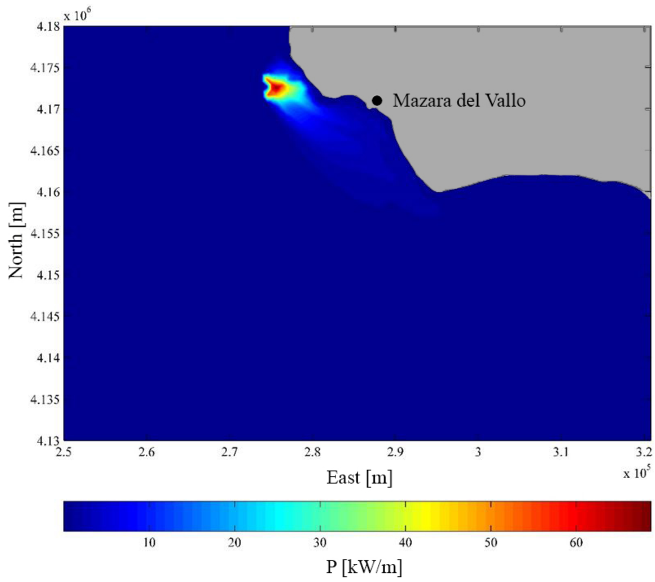

Fig. 8. The difference between the energy flux distribution in the presence of the device and in the absence of WEC device (energetic wave event, $H_s = 4.76$ m; $T_p = 10$ s; $\theta = 272°$).

three selected devices. The most relevant points are: i) Pelamis is not suitable for the studied site since the hydraulic efficiency is of the order of 1%; ii) the Wave Dragon has a performance of an order of magnitude higher than the previous one and is therefore interesting for the purposes of the application in the studied site, a further improvement of its efficiency can be performed by means of the geometric modification of the device; iii) Oyster 2 has a remarkable performance, in line with the possibility of energy exploitation in the studied area. This result can be justified because the prototypes were designed considering the ocean wave conditions, which are of an order of magnitude higher than the conditions that occur in a closed sea basin, as is the Mediterranean Sea. In order to improve the efficiency of the Wave Dragon for the typical Mediterranean wave conditions a further study will be performed considering the device scaled according to the Froude similarity.

Such a scaling approach will allows Oyster 2 to work with a lower available power, that is more compatible with the wave conditions present in the Sicilian Channel.

V. Conclusion

The analysis carried out on the numerical model results included the comparison between the spectral significant height distribution with and without WECs devices. It is important to point out that on the back of the obstacle there is a significant decrease in wave height compared to the case in which the conversion system is not present. As regards to the comparison among the energy fluxes, only the Oyster 2 device has high efficiency. For the other two devices, lower power values were obtained. These results because the prototypes were designed considering the wave conditions of the ocean, which are of an order of magnitude higher than the conditions that there are in a closed sea basin, as is the Mediterranean Sea.

In order to improve the efficiency of the Wave Dragon for the wave conditions typical of the Sicilian channel, a further study should be performed considering the device scaled according to the similarity of Froude, which will make it work with lower available power. The most performing studied device, Oyster 2, would cover the energy requirements of 5,100 inhabitants. This result, although preliminary, is encouraging and draws a first step towards the energy independence of an island like Sicily, with more than 1,000 km of coastline.

TABLE II
Acronyms and Symbols

RON	Rete Ondametrica Nazionale (Italian wave buoy network)
SNL-SWAN	Sandia National Laboratories Simulating WAves Nearshore
WEC	Wave Energy Converters
α	Breaking intensity parameter
c_{gx}	x component of group celerity
c_{gy}	y component of group celerity
c_θ	θ component of group celerity
c_σ	Group celerity in the spectral plane
D	Diffusion coefficient
E	Wave energy density
E_i	Incident energy
E_t	Transmitted energy
Γ	Breaking parameter
H_s	Spectral significant wave height
i	Grid point index
η_p	WEC device efficiency
j	Grid point index
k_t^2	Transmission coefficient
N	Wave action
P	Wave energy flux
P_i	Incident energy flux
P_t	Transmitted energy flux
S_{nl4}	Nonlinear transfer of wave energy through four wave interactions
S_{brk}	Wave dissipation due to depth-induced breaking
σ	Angular frequency
T_e	Energy period
T_p	Peak period
t	Time
θ	Mean wave direction
U_x	x Component of current velocity vector
U_y	y Component of current velocity vector
x	Planimetric coordinate
y	Planimetric coordinate

Acknowledgement

We want to thank Natalia Viviano for her valuable work done during the MSc degree thesis.

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