WAVE ENERGY RESOURCES ALONG CALABRIAN COASTS (ITALY)

Danilo Algieri Ferraro[1], Francesco Aristodemo[2], Paolo Veltri[3]

The assessment of wave energy is fundamental to well evaluate potential wave energy at different sea locations and time scales in conjunction with the related occurrence of hot spots for an optimal installation of Wave Energy Converters (WECs). The present study has been performed off the coasts of Calabria (Southern Italy), a Mediterranean region characterized by a mild wave climate and quite representative of mean sea states in the Mediterranean basin. The wave energy potential has been assessed in deep waters by means of ECMWF operational wave data validated against RON buoys and UKMO data. The wave power is calculated as a function of the energy wave period deduced from directional wave spectra and compared with widely adopted relationships based on the use of a standard JONSWAP spectrum. The mean yearly and seasonal wave energy is then assessed at selected hot spots for Tyrrhenian and Ionian Seas at a water deep of 100 m suitable for the installation of several offshore WECs.

Keywords: ECMWF data; energy wave period; wave energy; Calabria

INTRODUCTION

In the field of renewable energies, wind-generated waves represent a recent and interesting resource of energy option. The availability and persistency of wave data from different sources allows for an accurate assessment of their energy with respect to other renewable resources such as wind and sun whose production proves to be intermittent. With reference to the Europe, the greatest wave energy contribution refers to the countries located along the Atlantic coasts with respect to those referred to the Mediterranean Sea (e.g., Rusu and Onea, 2016). Nevertheless, the Mediterranean basin shows interesting energy potentialities for offshore and nearshore WEC installations (e.g., Liberti et al., 2013; Besio et al., 2016). For different areas in the Adriatic and Thyrrenian Sea off the italian coasts, several studies have been carried out to assess the wave energy potential for electricity production (Vannucchi and Cappietti, 2016). Highest wave energy contribution in Italy have been individuated in the North-West of Sardina (Vicinanza et al., 2013) and in the West coast of Sicily (Monteforte et al., 2015) with a yearly mean wave power of about 10 kW/m and 4.5 kW/m, respectively. Moreover, the development of different kind of devices for wave energy has led to recent field installations as in the case of nearshore WECs like REWEC3 (Boccotti, 2007), DIMEMO (Contestabile et al., 2016) and SYNCRES (Sammarco et al., 2013) respectively installed at the port of Civitavecchia near Rome, Naples and Piombino in Southern Tuscany. The above coastal structures are also configured in the family of perforated-wall caisson breakwaters (e.g., Aristodemo et al., 2015; Meringolo et al., 2015) which allow for a defense of port areas with an additional benefit in terms of harbor tranquillity. In the case of offshore WECs, a farm of ISWEC devices has been installed off Pantelleria Island close to Sicily (Bracco et al., 2015).

Owing to the lack of specific studies, the present analysis is performed off the coast of Calabria region (Southern Italy) which presents a relevant coastline length, i.e. about 700 km, and a variable wave climate also due to the different exposition of the coasts to Tyrrhenian and Ionian Seas. The assessment of wave energy along the Calabrian coasts is carried out using ECMWF operational wave data which have been validated against RON buoys and UKMO data by means of geographical transposition methods (e.g., Contini and De Girolamo, 1998) because of their different spatial position. The mean yearly and seasonal wave power is then assessed as a function of the energy wave period through the calibration of the spectral parameters deduced from observed directional wave spectra and compared with largely adopted relationships based on the use of the standard JONSWAP spectrum (e.g., Gonçalves et al., 2014). On the basis of the resulting spatial distribution of the wave power evaluated at a water depth of 100 m where a large amount of WECs can be installed (e.g., Babarit et al., 2012), the mean yearly and seasonal wave energy is then evaluated at selected hot spots for Tyrrhenian and Ionian Seas of the involved Italian region.

The present work is organized as follows. Firstly, ECMWF wave data are processed and then subjected to a validation using other wave sources. Afterwards, the wave power formula has been assessed paying attention to the estimation of the energy period. The evaluation of mean yearly and seasonal wave power allowing for successive analysis of wave energy in selected hot spots is finally performed.

[1]Department of Civil Engineering, University of Calabria, Via P. Bucci, Cubo 42B, 87036 Arcavacata di Rende (CS), Italy
[2]Department of Civil Engineering, University of Calabria, Via P. Bucci, Cubo 42B, 87036 Arcavacata di Rende (CS), Italy
[3]Department of Civil Engineering, University of Calabria, Via P. Bucci, Cubo 42B, 87036 Arcavacata di Rende (CS), Italy

WAVE INPUT

Wave data

Input wave data have been obtained through the European Center for Medium-Range Weather Forecasts (ECMWF) atmospheric operational model from 1992 to 2015. The considered synthetic parameters of sea states refer to significant wave height, H_s, mean wave period, T_m, peak period, T_p, mean wave period from 2^{nd} moment, T_{m2}, and mean wave direction, θ. Even if the global atmospheric reanalysis ERA-INTERIM by ECMWF covers a larger time window (1979-2015) and the data were well validated, the operational model has been here preferred for the higher spatial resolution of the nodes (0.125° x 0.125°) since it operates at the Mediterranean scale. Wave measurements furnished by directional buoys at Cetraro (1999-2008) and Crotone (1989-2007) of the Italian Wave measuring Network (RON) and some nodes of UK Met Office (UKMO) dataset (1986-2006) have been also taken into account for the validation of ECMWF data. A plan view along the considered Calabrian coasts of the adopted ECMWF, RON and UKMO wave dataset is shown in Fig. 1. All wave data refer to the deep wave condition $d/L_m > 0.5$, where d is the depth and L_m is the mean wavelength. In particular, the considered ECMWF nodes are located in a depth ranging from 80 m to 700 m.

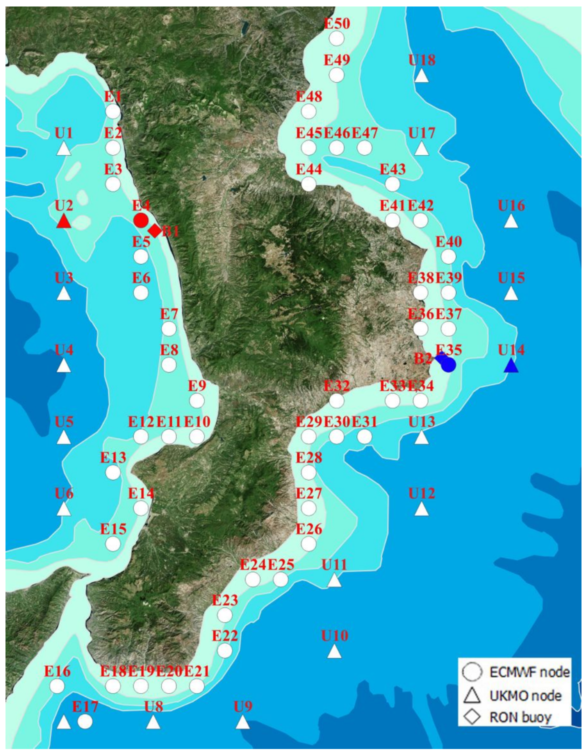

Figure 1: Map of adopted wave data along Calabrian coasts (circles = ECMWF nodes, triangles = UKMO nodes, diamonds = RON buoys).

It is worth noting that the wave parameters using ECMWF were measured every 6 h as well as UKMO, while RON buoys sampled with a time window of 3 h and of 30 minutes when sea storms occur. As a result, a general underestimation of wave peaks of ECMWF data with respect RON buoys was observed (e.g., Vicinanza et al., 2013) and this effect tends to influence the analysis of extreme events. However, ECMWF data can provide a good and conservative assessment of mean seasonal and yearly quantities for the wave energy analysis, as adopted in several seas of the world (e.g., Reikard et al., 2011). Moreover, their better spatial resolution of ECMWF nodes with respect to the other considered wave data (RON and UKMO) along the involved italian region allows therefore for a more accurate evaluation of the wave energy potential.

Input wave data deduced from ECMWF, RON and UKMO datasets have been subjected to a processing in order to check their quality for successive analyses of wave energy. The following criterion has been adopted to eliminate inconsistent i-th wave parameters:

- presence of NaN, zero and repeated values;
- outlier events not compatible with their spatial position;
- ($H_{s,i+1}$ - $H_{s,i}$) > 1.5 m;
- ($T_{p,i+1}$ - $T_{p,i}$) > 5 s;
- (θ_{i+1} - θ_i) > 30°;
- $T_{p,i}/T_{m,i} > 2$;
- wave steepness in deep waters up to its breaking limit.

As a consequence, the mean efficiency, given by the ratio between filtered data and raw ones, is 89.5 % for ECMWF data, while for RON and UKMO data is respectively equal to 82.1 % and 94.7 %.

Calibration

The reliability of adopted ECMWF wave data have been assessed against RON buoys and UKMO nodes. By using the ECMWF nodes no. E4 and no. E35 for the Thyrrenian and Ionian Sea, the comparisons have been carried out considering the closest UKMO and buoy locations to them (see red and blue symbols in Fig. 1). As successively performed, the choice of the selected two ECWMF nodes is due to the highest wave power appearing along the Thyrrenian and Ionian Seas of Calabria region. Owing to the different spatial position, UKMO and RON have been subjected to geographical transposition methods, largely adopted for applications studies along the italian coasts, at the location of two selected ECWMF nodes. The empirical approach of Contini and De Girolamo (1998) allows to virtually transfer the values of H_s and T_p by means of the effective fetches, F_e. Under the hypothesis that the wind velocities are the same in the original and final locations, this geographical transposition method is derived by the wave forecasting given by the classical SPM approach for fetch limited conditions. The new quantities H_{si} and T_{pi} at the final points have been then calculated as:

$$H_{si} = H_{so} \left(\frac{F_{ei}}{F_{eo}}\right)^{1/2} \qquad T_{pi} = T_{po} \left(\frac{F_{ei}}{F_{eo}}\right)^{1/3} \tag{1}$$

where the subscripts i and o indicate the final and initial points. The evaluation of other wave periods T_{mi} and T_{m2i} has been performed as a function of T_{pi} and the statistical relationships between the wave periods at the original node as follows:

$$T_{mi} = T_{mo} \left(\frac{F_{ei}}{F_{eo}}\right)^{1/3} \frac{T_{mo}}{T_{po}} \qquad T_{m2i} = T_{m2o} \left(\frac{F_{ei}}{F_{eo}}\right)^{1/3} \frac{T_{m2o}}{T_{po}} \tag{2}$$

Under the above hypothesis on wind velocities, the wave directions at the new sea points have been evaluated by calculating the angle, β, between the mean wind direction and the modeled mean wave one through a geographical approach (e.g., Lo Re et al., 2016):

$$\beta = arctan\left[\frac{\sum_i F_i sin(\phi_i - \phi_w) cos^n(\phi_i - \phi_w)}{\sum_i F_i cos(\phi_i - \phi_w) cos^n(\phi_i - \phi_w)}\right] \tag{3}$$

where F_i is the geographical fetch, N is the number of directions taken every 5° and ϕ_i is the wind direction, while the neighbouring directions, ϕ_w, range from ϕ_i-θ and ϕ_i+θ.

On the basis of the exposition of the coasts of Calabria to the open sea, the highest agreement between the wave data (ECMWF vs. RON and UKMO) in the considered sea locations has been obtained through the evaluation of effective fetches using the canonical Saville's formula by setting the angular sector across the mean wave direction, θ = 45°, and the directional spreading parameter, n = 2 in Eqs. 1, 2 and 3.

As applied by Liberti et al. (2013), several performance indices have been determined at the selected ECMWF points to check the suitability of ECMWF wave data. Specifically, the *bias*, the root mean square error, *rmse*, the *slope* of the regression line through the origin, the scatter index, *si*, and the Wilmott index of agreement, *d*. With reference to H_s (i.e. the most weighting wave parameter in evaluating the wave power), Figs. 2 and 3 illustrate the performance indices of ECMWF data compared with RON and UKMO ones at the selected ECMWF nodes of Tyrrhenian and Ionian Sea, respectively. The indices in Figs. 2 and 3 show an overall agreement between ECMWF and satellite H_s. The values of *bias* and *rmse* are enough small as well as d is greater than 0.9 for all cases. The *slope* is less than 1, indicating an underestimation of ECMWF dataset in modeling highest sea states as previously observed about the time sampling of wave data. It can be noticed an higher agreement between ECMWF and RON data manly due the closest spatial position of these points with respect to ECMWF and UKMO ones (see Fig. 1).

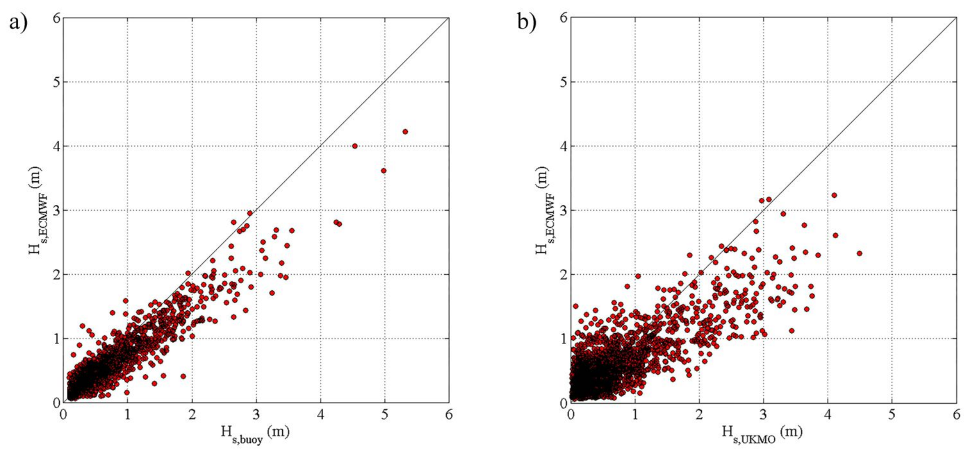

Figure 2: Performance indices of ECMWF data compared with RON and UKMO (node no. E4 of Tyrrhenian Sea): (a) ECMWF-RON; (b) ECMWF-UKMO.

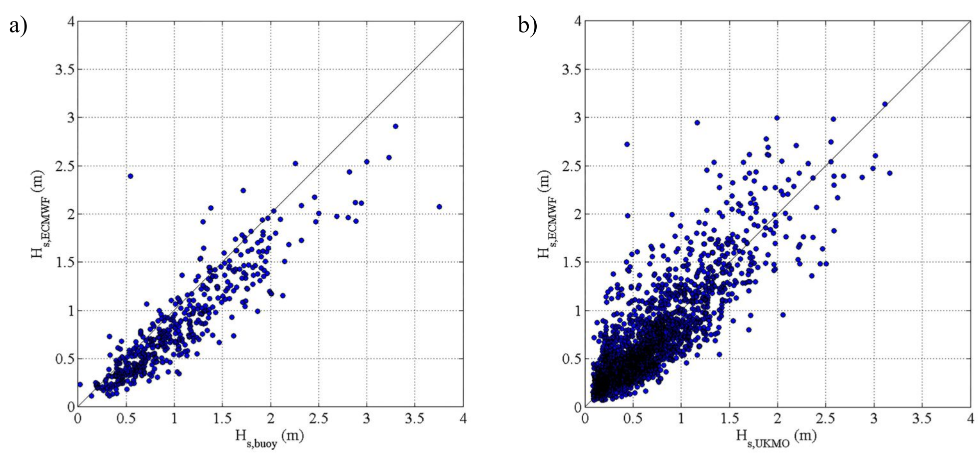

Figure 3: Performance indices of ECMWF data compared with RON and UKMO ones (node no. E35 of Ionian Sea): (a) ECMWF-RON; (b) ECMWF-UKMO.

CHARACTERIZATION OF WAVE POWER

Since the involved ECMWF nodes are located in deep water conditions, the largely used expression in literature to estimate the wave power per unit of wave front length, P, is adopted:

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_e \quad (4)$$

where ρ is the water density and g is the gravity acceleration. The energy wave period, T_e, representing the variance-weighted mean period of the one-dimensional period density spectrum. It is evaluated as the ratio m_{-1}/m_0, in which m_n is the n-th spectral moment that is defined as:

$$m_n = \sum_{ij} f_i^n S_{ij} \Delta f_i \Delta\theta_j \quad (5)$$

where f_i is the i-th frequency, S_{ij} is the density over the i-th frequency and the i-th direction, Δf_i is the i-th frequency width of the density and $\Delta\theta_j$ is the angular width of the density.

A widespread approach adopted in literature (e.g., Gonçalves et al., 2014; Monteforte et al., 2015) is to assess the value of T_e in Eq. 4 by considering relationships deduced from the use of a mean JONSWAP unimodal spectrum with peak-enhancement factor $\gamma = 3.3$, energy scale parameter, $\alpha = 8.1*10^{-3}$, and spectral width parameters $\sigma_a = 0.07$ (for $f < f_p$), and $\sigma_b = 0.09$ (for $f > f_p$), where f_p is the peak frequency. The expression of JONSWAP density spectrum reads as:

$$S_J(f) = S_{PM}(f)\gamma e^{\left[-\frac{1}{2}\left(\frac{f/f_p-1}{\sigma}\right)^2\right]} \quad (6)$$

where S_{PM} represents the Pierson-Moskowitz (PM) spectral density given by:

$$S_{PM}(f) = \frac{\alpha g^2}{(2\pi)^4 f^5} e^{\left[-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right]} \quad (7)$$

The related statistical relationships for the practical calculation of the wave energy period as a function of a JONSWAP spectrum with canonical shape parameters lead to: $T_e = 0.904 T_p$ or $T_e = 1.143 T_{m2}$, where $T_{m2} = (m_0/m_2)^{0.5}$.

For two ECMWF nodes off Thyrrenian and Ionian coasts where successive energy analyses will be performed, Figs. 4 and 5 show the relative differences in evaluating the mean monthly and yearly wave power, P_m, as a function of $T_e = m_{-1}/m_0$ against those referred to the use of T_e as a function of T_p and T_{m2} when a standard JONSWAP spectrum is adopted. A substantial underestimation of about 10 % can be observed when T_{m2} is adopted, while a general overestimation of about 5 % can be highlighted when T_p is used. A quite constant seasonality variation is noticed, except for a slight different trend during the summer when these differences increase due to a lowest wave climate in the year.

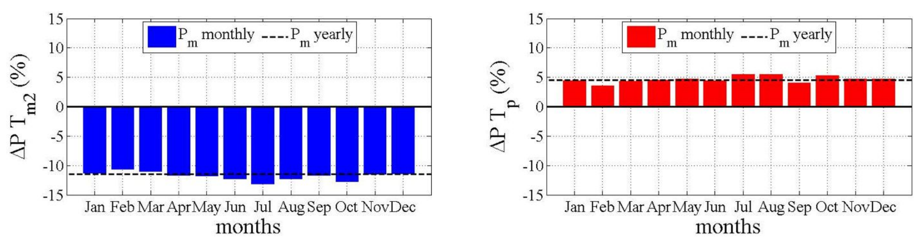

Figure 4: Relative differences in assessing the mean yearly and monthly wave power, P_m, as a function of T_e, T_p and T_{m2} at the ECMWF node no. E4 off Tyrrhenian coast.

The above differences in evaluating P_m are consistent with the milder wave climate of the involved Mediterranean location with respect to the severe sea states appearing in the Northern Sea where the JONSWAP spectrum was calibrated. As a consequence, the use of approximate relationships can lead to a certain difference when real sea states are taken into account. In order to deduce more correct statistical relationships between the involved wave parameters, directional wave spectra discretized by 24 Δf and 30 $\Delta\theta$ from an available ECMWF dataset (2001-2015) has been considered. The analysis has been limited for wind-driven seas by modeling the shape parameters of the JONSWAP spectral form. The procedure to

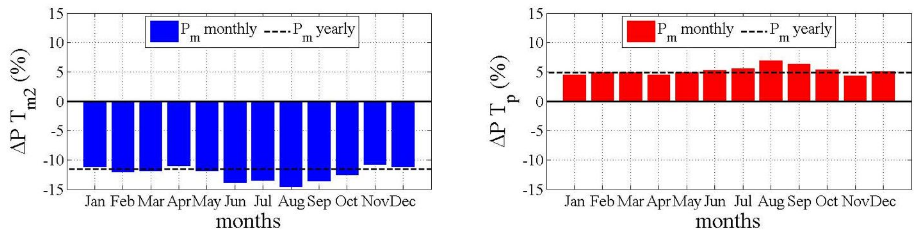

Figure 5: Relative differences in assessing the mean yearly and monthly wave power, P_m, as a function of T_e, T_p and T_{m2} at the ECMWF node no. E35 off Ionian coast.

fit the shape parameters of JONSWAP spectrum has consisted in the initial evaluation of the energy scale parameter, α. On basis of the spline interpolation to better discretize the measured frequency spectrum, α has been calibrated by means of a non-linear least square fitting method in order to minimizing the difference between measured and simulated wave spectrum in the range $f_p < f < 4f_p$. Afterwards, the peak enhancement factor γ has been determined as the ratio $S(f)/S_{PM}(f)$ for $f = f_p$. The peak width factors σ_a and σ_b have been respectively evaluated in the frequency band $0.9f_p < f < 1.1f_p$, as performed by Piscopia et al. (2002). The monthly and yearly changes of JONSWAP shape parameters, γ, σ_a and σ_b, as well as the period ratios, $\alpha_1 = T_e/T_p$ and $\alpha_2 = T_e/T_{m2}$, are respectively illustrated in Figs. 6 and 7 for the hot spots at the Thyrrenian and Ionian Sea.

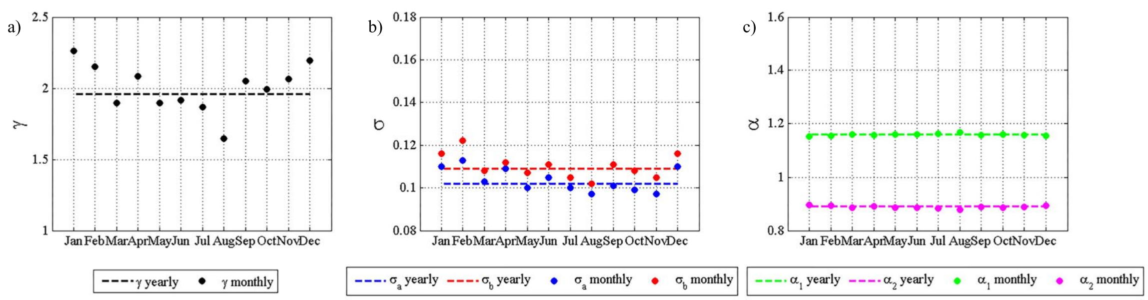

Figure 6: Mean yearly and monthly variation of JONSWAP shape parameters and period ratios at the ECMWF node no. E4 off Tyrrhenian coast. (a) γ, (b) σ_a and σ_b, (c) α_a and α_b.

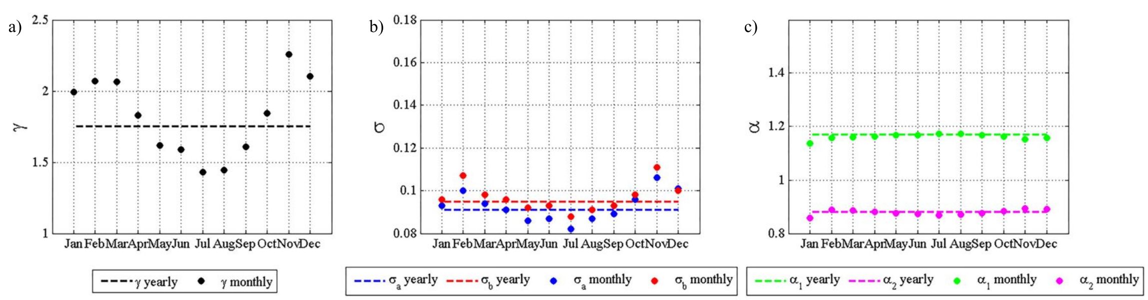

Figure 7: Mean yearly and monthly variation of JONSWAP shape parameters and period ratios at the ECMWF node no. E35 off Ionian coast. (a) γ, (b) σ_a and σ_b, (c) α_a and α_b.

As expected, the mean yearly shape parameters at the considered two nodes are lower that those set in the canonical JONSWAP spectrum. Higher values of γ, σ_a and σ_b occur at the ECMWF node for Tyrrhenian coast as well as during the winter months. The mean spectral parameters are quite close to those determined by Piscopia et al. (2002) by analyzing the wave spectra recorded by RON buoys (1989-2001) of Crotone and Ponza, whose wave climate is quite similar to the Thyrrenian coast of Calabria. For what concerns the period ratios, improved relationships between T_e against T_p and T_{m2} have been found: α_1 = 0.88 and α_2 = 1.17 for the node of the Thyrrenian Sea, and α_1 = 0.89 and α_2 = 1.16 for that related to the Thyrrenian Sea. By inspecting the recorded directional wave spectra by ECMWF, it has been moreover observed a certain percentage of bimodal sea states with low wave energy (up to 30 %) due to the occurrence of swell components which are usually linked to sea states produced by wind rotation along the generating area.

ANALYSIS OF WAVE POWER AND WAVE ENERGY

Starting from the ECMWF nodes, the geographical transposition methods expressed by Eqs. 1, 2 and 3 have been applied to transpose the initial values of H_s, T_m, T_p, T_{m2} and θ to a water depth of 100 m. Each point has been transposed to the closest reference depth for a distance of order of few km. The selected water depth has been chosen as a suitable location to further studies on the performances of WECs like point absorbers, linear absorbers and terminators. For more details for more of them, the reader can refer to the comprehensive review of Babarit et al. (2012). The wave power has been then assessed at a mean yearly and seasonal scale by applying Eq. 4. Adopting Cartesian coordinates, Fig. 8 describes the spatial distribution along Calabrian coasts of the linearly interpolated values of mean yearly and seasonal wave power, P_m, at a water depth of 100 m. The seasonal distribution has been organized intro groups of months as follows: Winter (December, January and February), Spring (March, April and May), Summer (June, July and August) and Autumn (September, October and November). The most relevant wave power potential appears generally along the Northern and Central part off Thyrrenian coast of Calabria. In this area, the related mean annual values of P_m range between 2.2 kW/m and 2.7 kW/m, while they oscillate between 0.4 kW/m and 2.5 kW/m for the Ionian coast. Lowest P_m are noticeable near the Strait of Messina and along the Northern part of Ionian coast with a mean annual P_m less than 1 kW/m. By a seasonal point of view, remarkable temporal variability of wave power can be observed in the considered four time windows. For winter, spring, summer and autumn, the maximum values of P_m are respectively 4.7 kW/m, 2.5 kW/m, 0.8 kW/m and 2.3 kW/m. This inter-annual fluctuation was also highlighted by Liberti et al. (2013) about the analysis of Coefficient of Variation in the Italian Seas, showing a relevant variation in the southern zone of Tyrrhenian Sea. A hot spot area for Tyrrhenian coast has been individuated along a coastline length of about 50 km between the towns of Amantea and Cetraro, as highlighted in Fig. 8. The highest mean yearly wave power is 2.69 kW/m and it occur in front of the town of Fiumefreddo Bruzio. A more restricted zone (about 5 km) has been observed for the hot spot for Ionian coast, reaching a peak in the yearly wave power equal to 2.51 kW/m. The hot spot is located in front of the town of Isola Capo Rizzuto near Crotone. The obtained yearly and seasonal values of P_m are quite in agreement with the spatial variations calculated at a Mediterranean scale by adopting different wave datasets (Liberti et al., 2013; Besio et al., 2016).

Paying attention to the hot spot locations of Fiumefreddo Bruzio for the Thyrrenian Sea and Isola Capo Rizzuto for the Ionian Sea, Figs. 9 and 10 show respectively the polar diagrams of mean yearly and seasonal wave power climate, P_m, as a function of selected classes of H_s and θ. It is evident a different directional distribution of P_m for the above two selected sites. For the Thyrrenian site, the main contribution of directional wave power is substantially restricted to the angular sector 250°-290° related to the Western direction. In case of Ionian site, significant values of P_m are related to two different directional sectors associated to the longest fetches: 10°-40° and 170°-200°. The seasonal polar diagrams of P_m reveal similar features at the Thyrrenian hot spot, except during the summer when a high percentage of sea states come from North-West. For the Ionian hot spot, highest seasonal values of P_m are substantially associated to the above two main directional sector observed for the yearly assessment It can be generally observed that the large spreading of mean wave direction of sea states at the Ionian hot spot could lead to uncertainties in order to assess the best planimetric disposition of WEC fronts in terms of real electricity production.

For the selected two hot spots, the assessment of mean yearly and seasonal wave energy, E, has been represented in the scatter diagrams given by Figs. 11 and 12 as a function of classes of H_s every 0.5 m and T_e every 0.5 s. In particular, the upper colour bar defines the level of energy per meter of wave front (in kWh/m), the numbers within the graph refer the occurrence of classes of sea states in terms of number of mean hours per mean year, and the isolines illustrate the wave power, P, expressed in kW/m. The values of E are determined by multiplying the classes of wave power to the corresponding time windows (6 h) occurring between successive sea states. Within a mean year, the highest E are associated to the bins with H_s = 1.25 - 1.75 m and T_e = 6.25 - 7.25 s at the Thyrrenian hot spot and to the bins with H_s = 1.75 m

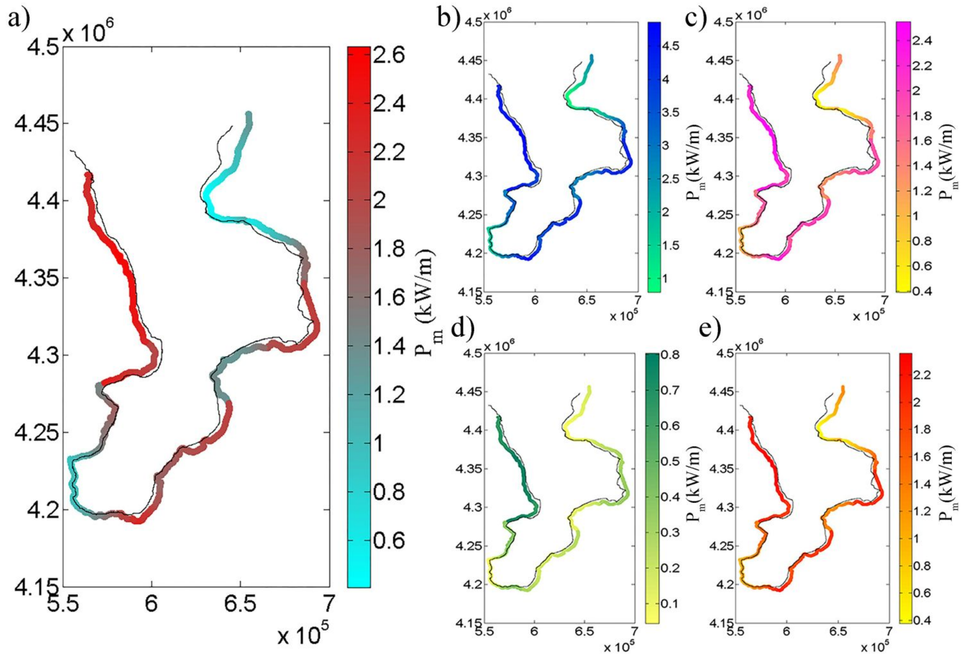

Figure 8: Spatial distribution of interpolated values of mean yearly and seasonal wave power, P_m, at a depth of 100 m off Calabrian coasts. (a) year, (b) winter, (c) spring, (d) summer (e) autumn.

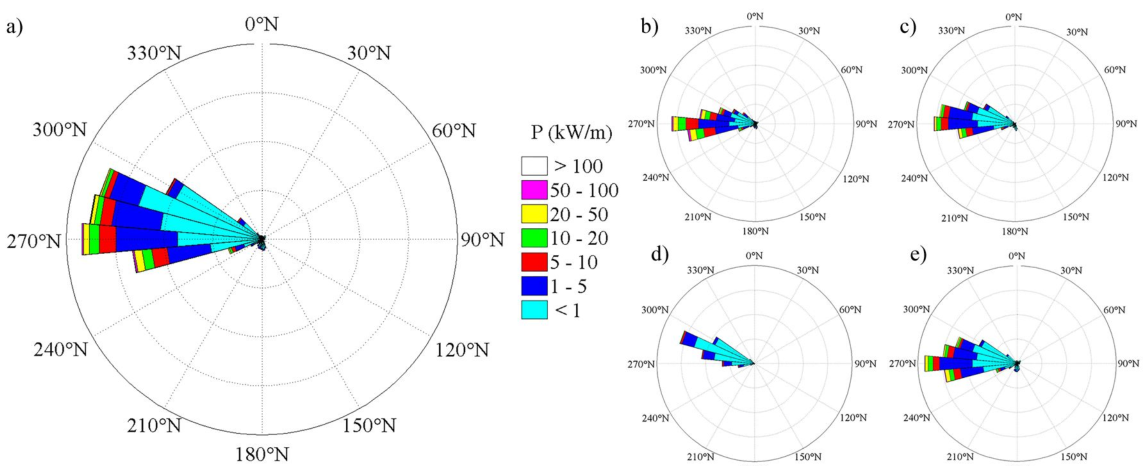

Figure 9: Polar plot of mean yearly and seasonal wave power climate, P_m, at the hot spot of Tyrrhenian Sea. (a) year, (b) winter, (c) spring, (d) summer, (e) autumn.

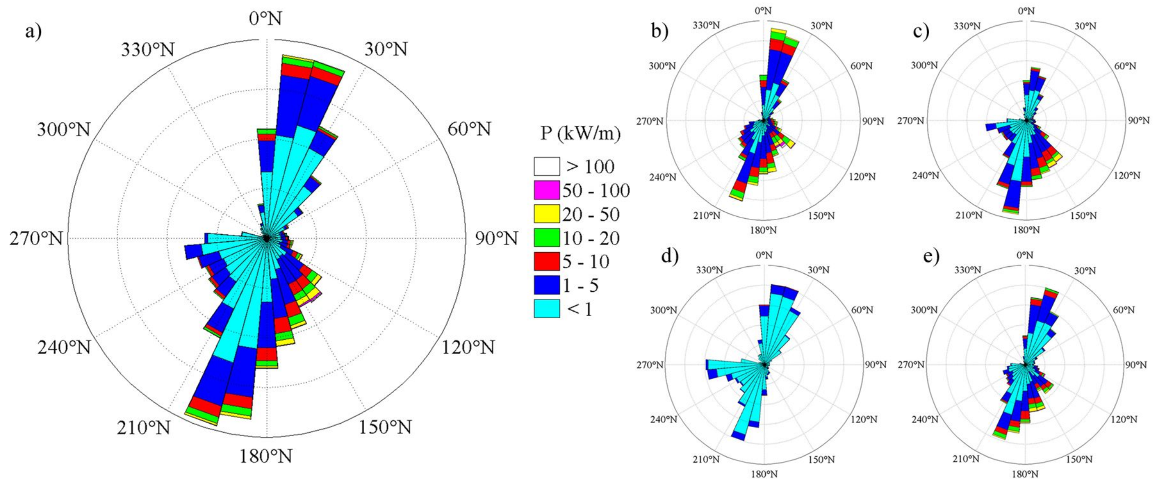

Figure 10: Polar plot of mean yearly and seasonal wave power climate, P_m, at the hot spot of Ionian Sea. (a) year, (b) winter, (c) spring, (d) summer, (e) autumn.

- 2.25 m and T_e = 5.75 - 6.25 s at the Ionian hot spot. The mean yearly wave energy at the hot spot of Tyrrhenian Sea is about 2900 kWh/m and of Ionian Sea is about 2750 kWh/m. As expected, a consistent seasonal variation of mean wave energy is noticed. Highest values during the winter for the two locations show values of E equal to about 1500 kWh/m and 1450 kWh/m, respectively. The maximum values of E in winter occur in the ranges H_s = 3.25 - 3.75 m and T_e = 7.75 - 8.25 s at the Thyrrenian site and in the same yearly classes at the Ionian site. During spring, highest values of E refer to the ranges H_s = 1.25 - 1.75 m and T_e = 6.25 - 6.75 s for Thyrrenian, and H_s = 0.75 - 1.25 m and T_e = 3.75 - 4.25 s for Ionian. During summer, maximum values of E is related to the bins with H_s = 0.75 - 1.25 m and T_e = 5.25 - 5.75 s for Thyrrenian Sea and the bins with H_s = 0.25 - 0.75 m and T_e = 2.75 - 3.25 s for Ionian Sea. Finally, in the same classes of summer for Thyrrenian Sea and in the classes with H_s = 0.75 - 1.75 m and T_e = 3.75 - 4.25 s for Ionian Sea appear the maximum values of E in autumn.

CONCLUSIONS

A wave energy assessment has been performed off the coasts of Calabria region (Southern Italy). ECMWF wave data, processed and calibrated with other sources (RON buoys and UKMO nodes), have been adopted to estimate the wave power. Particular attention has been paid to the differences in assessing correctly the energy wave period as a function of the real directional wave spectra against relationships based on the use of a standard JONSWAP spectrum. Owing to the different water depth of ECMWF nodes, the geographical transposition has been adopted to evaluate the wave power off Calabrian coasts at -100 m. For the Thyrrenian Sea, a hot spot has been individuated in front of the town of Fiumefreddo Bruzio located with a yearly wave energy of 2900 kW/m. Across this location, a quite constant wave energy has been observed in this central part of Calabria for an extension of about 50 km between the town of Amantea and Cetraro and suitable for potential WEC installations. For the Ionian Sea, the highest yearly wave energy is just restricted in few km off the town of Isola Capo Rizzuto with a resulting value of 2750 kW/m. By crossing the present wave energy with the power matrices of offshore WECs, further developments of the study will be addressed to evaluate the performance of the devices in terms of electricity production for domestic and public supplies for coastal towns located near the selected hot spot areas.

ACKNOWLEDGEMENTS

The ECMWF data were provided by the MARS archive under the authorization of the Italian Air Force. The authors thanks F. Reale (CUGRI, University of Salerno) for the suggestions on the access of ECMWF dataset.

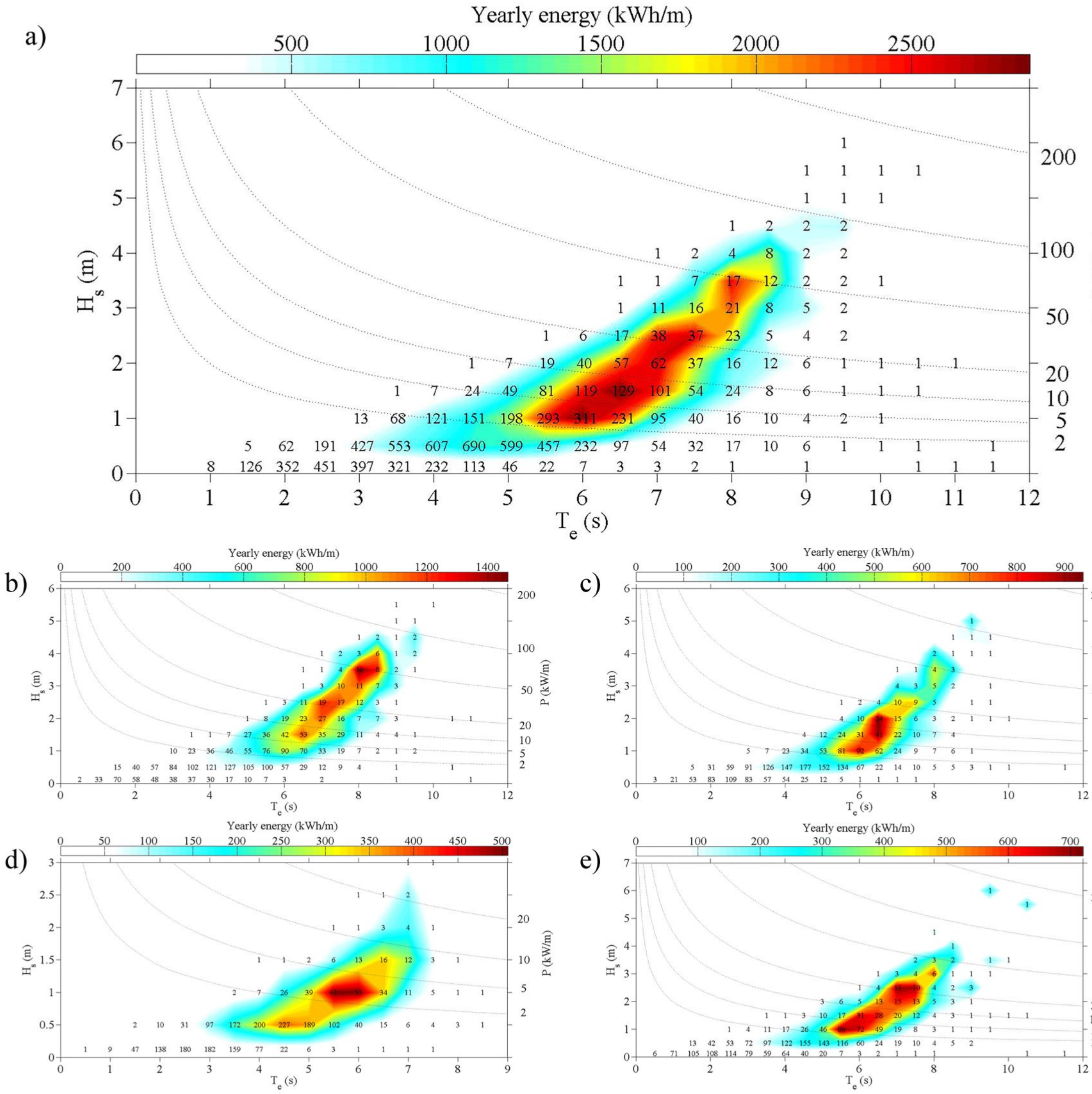

Figure 11: Scatter diagrams of mean yearly and seasonal wave energy at the hot spot of Tyrrhenian Sea. (a) year, (b) winter, (c) spring, (d) summer, (e) autumn.

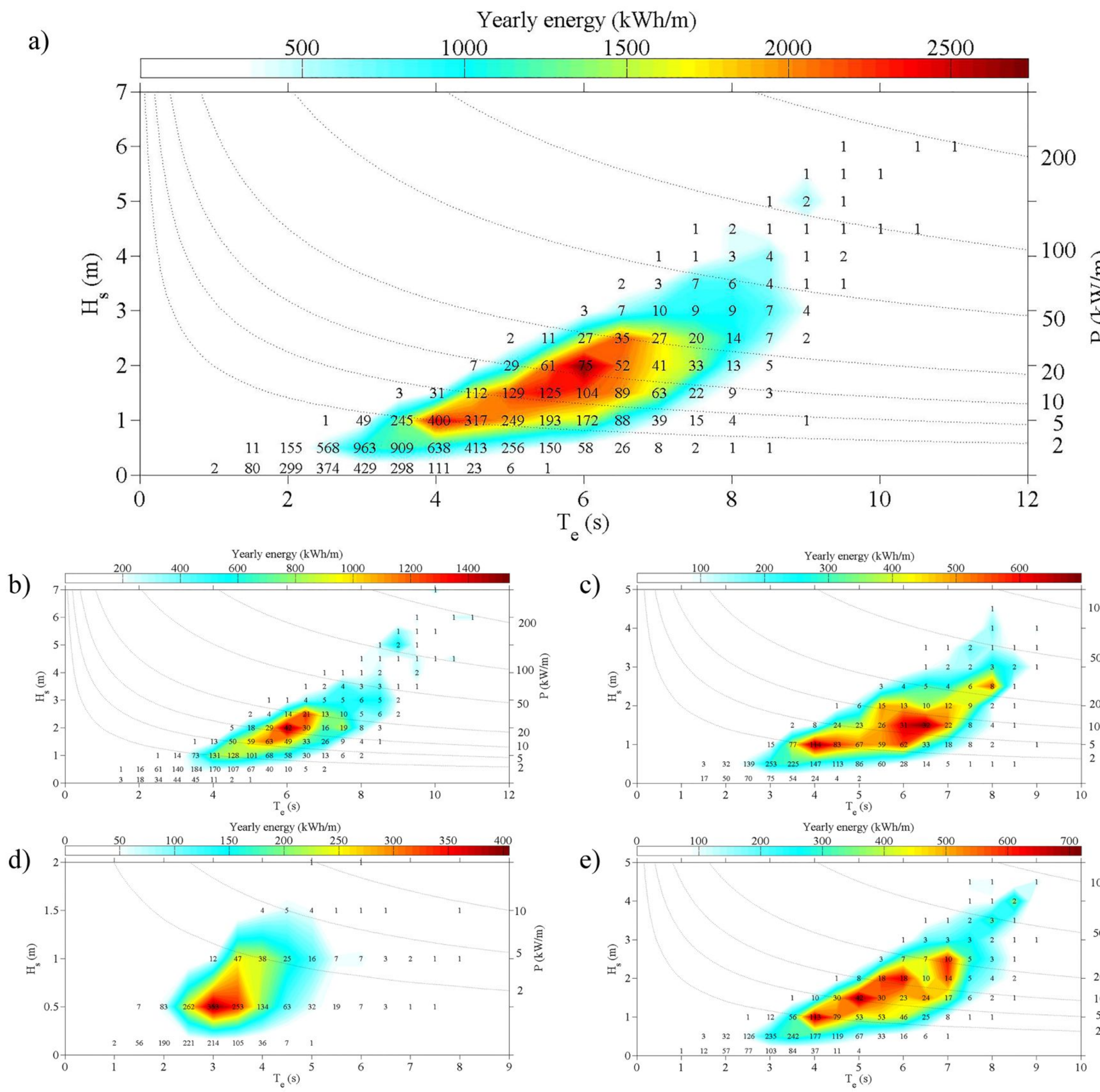

Figure 12: Scatter diagrams of mean yearly and seasonal wave energy at the hot spot of Ionian Sea. (a) year, (b) winter, (c) spring, (d) summer, (e) autumn.

References

Aristodemo, F., Meringolo, D.D., Groenenboom, P., Lo Schiavo, A., Veltri, P., Veltri, M., 2015. Assessment of dynamic pressures at vertical and perforated breakwaters through diffusive SPH schemes. *Mathematical Problems in Engineering*, ID 305028, 1-10.

Babarit, A., Hals, J., Muliawan, M.J., Kurniawan, A., Moan, T., Krokstad, J., 2012. Numerical benchmarking study of a selection of wave energy converters. *Renewable Energy*, 41, 44-63.

Besio, G., Mentaschi, L., Mazzino, A., 2016. Wave energy resource assessment in the Mediterranean Sea on the basis of a 35-year hindcast. *Energy*, 94, 50-63.

Boccotti, P., 2007. Comparison between a U-OWC and a conventional OWC. *Ocean Engineering*, 34(5-6), 799-805.

Bracco, G., Carillo, A., Giorcelli, E., Liberti, L., Mattiazzo, G., Prudentino, E., Sannino, G., Vissio, G., 2015. Use of wave forecast for the regulation of ISWEC. *Proc. of 11th EWTEC*, Nantes, 1-6.

Contestabile, P., Ferrante, V., Di Lauro, E., Vicinanza, D., 2016. Prototype Overtopping Breakwater for Wave Energy Conversion at Port of Naples. *Proc. of 26th ISOPE Conference*, Rhodes, 616-621.

Contini, P., De Girolamo, P., 1998. Impatto morfologico di opere a mare: casi di studio, *Atti VIII Convegno AIOM*, Lerici (in Italian).

Gonçalves, M., Martinho, P., Guedes Soares, C., 2014. Assessment of wave energy in the Canary Island. *Renewable Energy*, 68, 774-784.

Liberti, L., Sannino, G., Carillo, A., 2013. Wave energy resource assessment in the Mediterranean, the Italian perspective. *Renewable Energy*, 50, 938-949.

Lo Re, C., Cannarozzo, M., Ferreri, G.B., 2016. Present-day use of an empirical wave prediction method. *Proceedings of the Institution of Civil Engineers, Maritime Engineering*, 169(MA1), 3-14.

Meringolo, D.D., Aristodemo, F., Veltri, P., 2015. SPH numerical modeling of wave-perforated breakwater interaction. *Coastal Engineering*, 101, 48-68.

Monteforte, M., Lo Re, C., Ferreri, G.B., 2015. Wave energy assessment in Sicily (Italy). *Renewable Energy*, 78, 276-287.

Piscopia, R., Inghilesi, R., Panizzo, A., Corsini, S., Franco, L., 2002. Analysis of 12-year wave measurements by the Italian Wave Network. *Proc. of 28th International Conference on Coastal Engineering*, Cardiff, pp. 121-133.

Reikard, G., Pinson, P., Bidlot, J.-R., 2011. Forecasting ocean wave energy: The ECMWF wave model and time series methods. *Ocean Engineering*, 38, 1089-1099.

Rusu, E., Onea, F., 2016. Estimation of the wave energy conversion efficiency in the Atlantic Ocean close to the European islands. *Renewable Energy*, 85, 687-703.

Sammarco, P., Michele, S., D'Errico, M., 2013. Flap gate farm: from Venice lagoon defense to resonating wave energy production. Part 1: Natural modes. *Applied Ocean Research*, 2013, 43, 206-213.

Vannucchi, V., Cappietti, L., 2016. Wave energy assessment and performance estimation of state of the art Wave Energy Converters in Italian hotspots. *Sustainability*, 8, 1300, 1-21.

Vicinanza, D., Contestabile, P., Ferrante, V., 2013. Wave energy potential in the north-west of Sardinia. *Renewable Energy*, 50, 506-521.