Evaluation of wave power by integrating numerical models and measures at the Port of Civitavecchia

An assessment of the available wave power at regional and local scale was carried out. Two hot spots of higher wave power level were identified and characterized along the coastline of northern Latium Region, near the Torre Valdaliga power plant and in proximity of Civitavecchia's breakwater, where the presence of a harbour and an electric power plant allows wave energy exploitation. The evaluation process was implemented through measurements, and numerical model assessment and validation. The integration of wave gauges measurements with numerical simulations made it possible to estimate the wave power on the extended area nearshore. A downscaling process allowed to proceed from regional to local scale providing increased resolution thanks to highly detailed bathymetry.

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Introduction

The Mediterranean Sea is a semi-enclosed basin with a highly variable climate. Its central area, where Italy is located, is subject to a temperate climate with seasonal variation of weather conditions. In particular, at the Tyrrhenian Sea the most relevant wave conditions are from the third quadrant, due to the larger fetch length [1]. Wave propagation to the nearshore depends on several factors, such as coastal morphology and orientation related to wave direction, bathymetry and shape of the submerged beach. In particular, the northern Latium coast is characterized by the presence of Capo Linaro, which determines a change in both coastline orientation and morphology of the submerged beach. As for other renewable sources, a thorough resource assessment is a prerequisite for the successful exploitation of wave energy [2]. The object of this work is the assessment of wave energy potential from regional to local scale, detecting hot spot wave energy. The study was performed at Civitavecchia, taking advantage of the wave buoys that allow to evaluate wave power and wave propagation from deep to shallow water trough numerical model simulations. The proximity of a power plant, the presence of industrial activities and a large port infrastructure makes this area attractive for wave energy exploitation. Moreover, the deployment of coastal wave buoys allows to compare numerical results with data measured at the nearshore zone. The available wave energy is investigated in detail, characterising each sea stage that provides the energy resource in terms of intensity and direction. In order to assess the nearshore wave energy distribution, it is important to evaluate the propagation of waves, from deep to shallow waters, taking into account the modifications of their characteristics due to refraction, shoaling, diffraction (in some cases) and related physical processes [3]. To this concern, nearshore wave power patterns are investigated applying the CMS-Wave coastal wave

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model [4]. It is found that the irregular bathymetry of the northern Latium region leads to the concentration of wave energy in certain nearshore areas, while others are left with a relatively low resource. The knowledge of these patterns is a fundamental to selecting the optimum site for wave energy exploitation. This study drives the installation of a new experimental device for wave energy exploitation designed by RSE, in support of the port authority to achieve a more sustainable development.

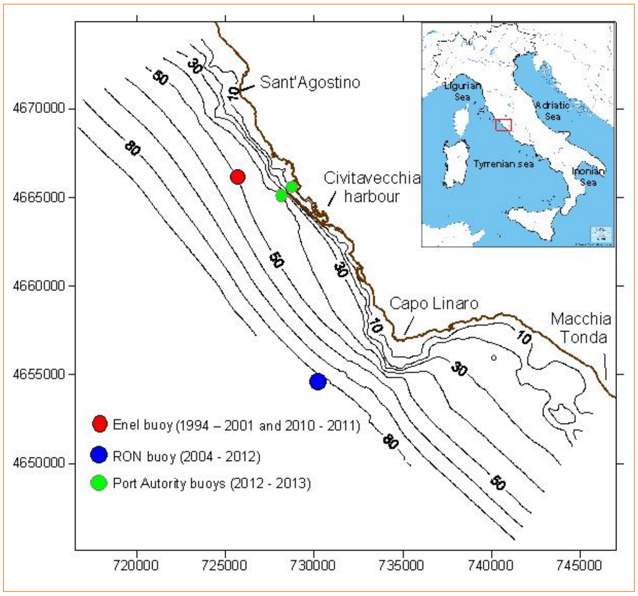

FIGURE 1 Study area (coordinates in UTM zone 32)

Methodology

The proposed methodology to assess the wave energy potential in the study area is composed of different main phases.

Wave data

The wave dataset is provided by different sources: National Wave Monitoring Network (RON) (www.idromare.it), National Authority for Electric Energy (ENEL) and Port Authority (Fig. 1). Significant wave height, peak period and direction are used in this work with a double purpose: assessing wave power and providing boundary conditions in the numerical simulations of wave propagation. The ENEL and RON time series (located at a depth of 50 and 100 m, respectively) do not correspond except for a short time window (2010-2011). However, considering the geographical proximity of the sites it may be very useful to merge datasets into a unique one, in order to enhance time data availability from 1994 to 2012. This was pursued through the application of the Geographical transposition method [5]. Therefore, the ENEL time series (1994-2001 / 2010-2011) were geographically transposed to the site of the RON time series (2004-2012) and the overlapping period was used to verify the method obtaining a determination coefficient (R2) of 0.80 and a residual mean square of 0.044. The two Port Authority's wave buoys (Fig. 1), located near Civitavecchia's harbour, were installed at a depth of 10 meters (onshore point) and 30 meters (nearshore point), respectively.

Bathymetry

In the simulations of wave trains through transitional waters, the resolution of the bathymetric map plays a fundamental role. As wave propagation dynamics

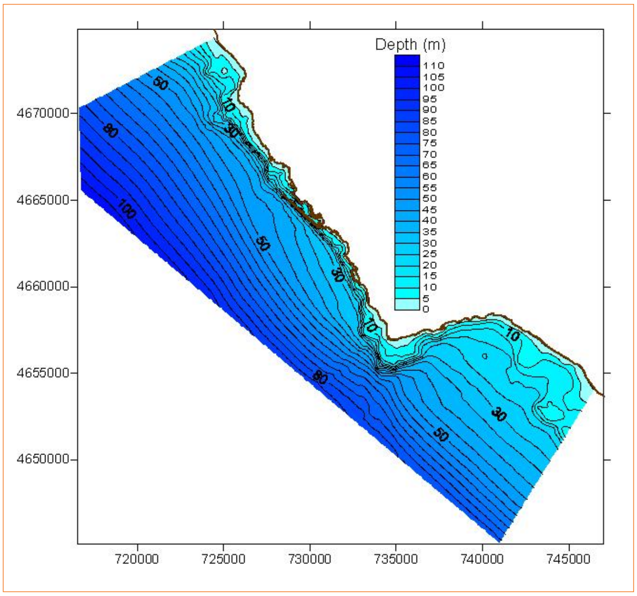

FIGURE 2 Bathymetric map of the regional domain

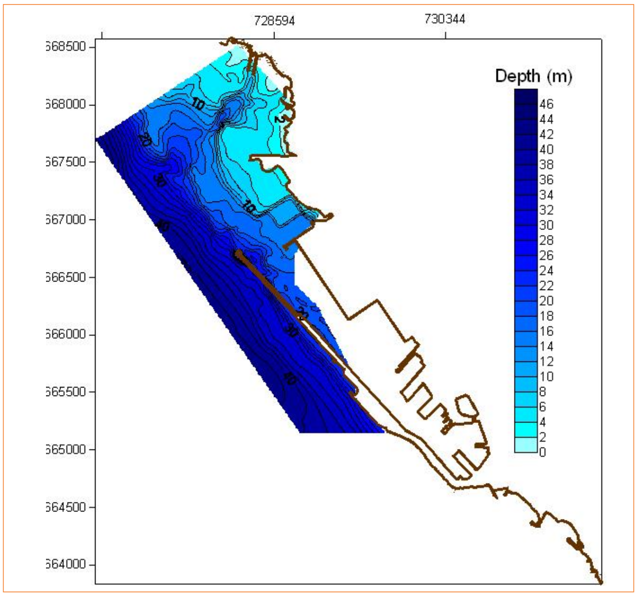

FIGURE 3 High resolution Bathymetric map of Civitavecchia harbour area

at regional and local scale are very much depending on the shape of the seabed, the accuracy of model results is deeply dependent on the accuracy of bathymetric information. Therefore, a bathymetric map with a resolution scale 1:30.000 is suitable for the regional study (Fig. 2). Instead, for the local scale analysis a finer resolution is needed. In the present study two surveys have been carried out, one with single bean till -30 m deep, another with multibeam in Civitavecchia's harbour area, as reported in Figure 3.
The Kriging gridding method [6] was used to build the 50 m resolution mesh for the regional study and the 10 m resolution mesh for the local analysis.

Wave power computation

In this work, wave power was computed in deep, transitional, and shallow waters.
For regular waves the sum of kinetics and potential energy density per unit area can be computed according to the linear wave theory.
According to Cornett [7] and Iglesias *et al*. [8] for irregular waves random in height, period and direction, the spectral parameters have to be used.

Significant wave height is based on the zero moment spectral function (m0) as:

$$Hs \equiv Hm0 = 4\sqrt{m_0} \qquad (1)$$

Where, m_n represents the spectral moment of order n,

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

In this expression $S(f,\theta)$ denotes the directional spectral density function, which specifies how energy is distributed over frequencies (f) and directions (θ). As for the energy period, it is defined as:

$$T_e = \frac{m_{-1}}{m_0} \qquad (3)$$

After appropriate simplification and substituting Hm0 and Te into equations of wave power of regular waves, under a wave crest the equation is given by:

$$\bar{P} = \frac{\rho g^2 Hm0^2 T_e}{64\pi}\left[1 + \frac{4\pi d/L}{\sinh 4\pi d/L}\right]\tanh\frac{2\pi d}{L} \qquad (4)$$

Every wave power value, corresponding to a certain sea condition, has been multiplied for the corresponding frequency of the events that, subsequently summed up, gives the annual wave power potential.

$$P_{rel} = \sum_{i=1}^{n} \bar{P}_i f_i \qquad (5)$$

Wave model

The wave model used in the present study is the CMS-Wave, a steady-state, finite difference, two-dimensional spectral wave model formulated from a parabolic approximation equation [9] with energy dissipation and diffraction terms. The wave model is based on the wave-action balance equation[10], which determines the evolution of the action density in space and time. The main boundary input is the wave spectra, that is a statistical representation of the wave field and is calculated from wave direction, significant height and peak period.

The JONSWAP wave spectra parameters, used as model boundary conditions, were derived considering the Tyrrhenian wave characteristics. The nesting process allows to produce wave power distribution maps in local scale at a very high resolution. Such a process is performed with a linear interpolation of wave spectra from the coarse to the fine grid domain, as proposed by Smith *et al.* [11]. A hundred and ten wave scenarios have been simulated to compute wave height (Hs), Peak period (Tp) and wave direction (Dir) at each grid point. Furthermore, wave power computation has been carried out applying equations (4) and (5).

Results

Measurements

The annual wave climate of Capo Linaro's buoy (Fig. 4) shows the predominant directions in the third quadrant. The seasonal analysis indicates that wave height is maximum in fall and winter, as well as the most frequent directions spread between 135 °N and 315 °N. In particular, during the fall the south direction occurs more often than other directions, while in winter season the highest frequency is between SSW and WSW. In summer and spring, the highest wave height comes from narrow direction spectra, ranging from 200 °N to 247 °N.

Figure 5 shows wave power spectra of Capo Linaro's buoy, where contour lines indicate the wave power for each sea state, whereas contour colours indicate the wave power values, for each wave condition, weighted with frequency. The spectra show two peaks of energy, The first one encloses the events with wave height of about 2 m and energy period of 6 sec, while the second one represents those with wave height of about 3 m and energy period of 8 sec. The yearly average wave power value computed for this area is 3.1 kW m^{-1} that represents the offshore value at the boundary of the model domain. Figure 6 shows the wave power spectra of Port Authority's wave buoy located at a depth of 50 m, where a different wave energy distribution is detected. The most energetic wave conditions occur for the events with wave height between 1.5 and 3 m and energy period between 5 and 6 sec. The yearly average wave power value computed is 3 kW m^{-1}.

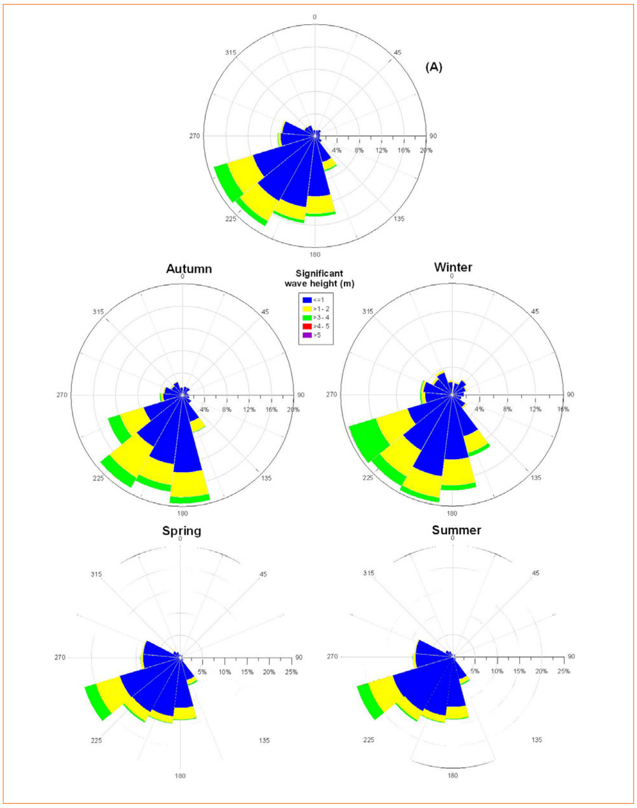

FIGURE 4 Seasonal and annual (A) wave rose based on data from Capo Linaro's buoy (RON) and transposed data from Torrevaldaliga's buoy (ENEL) between 1994-2012

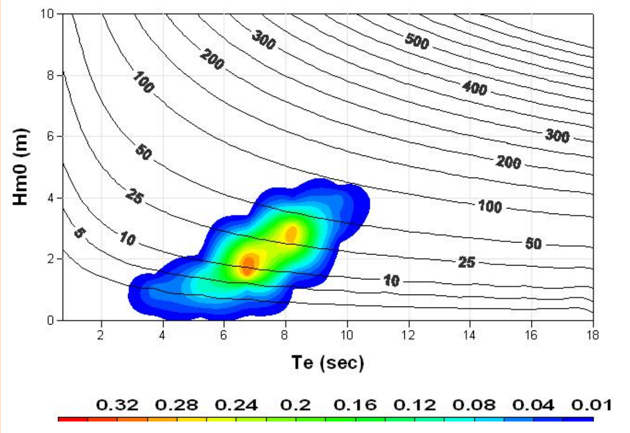

FIGURE 5 Combined map of relative wave power (kW/m) recorded at Capo Linaro. Contour lines indicate absolute wave power for each wave condition of Hs and Te

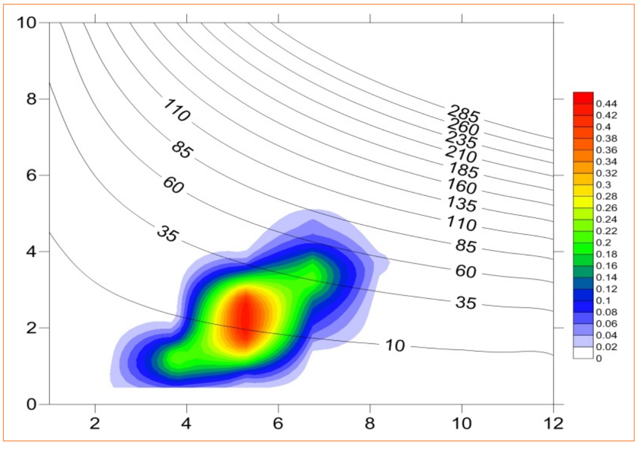

FIGURE 6 Combined map of relative wave power (kW m^{-1}) recorded at Port Authority's buoy. Contour lines indicate absolute wave power for each wave condition of Hs and Te

Regional model

At the regional scale, the nearshore energy distribution is influenced by two factors: morphology of the seabed and variation of coastal orientation. Figure 7 shows that the whole area is separated into two different energetic environments, north and south of Capo Linaro, respectively.

The northern area is more exposed to wave conditions and it shows higher values at short distance from the shoreline, in particular in proximity of the harbour breakwater where wave power reaches 2.6 kW m^{-1}. In the southern zone, high wave power is located far of the coast with two powerful spots, included between 2.6 and 2.8 kW m^{-1} in correspondence of Santa Severa and Ladispoli, respectively.

Local Model

In this chapter we discuss the results of wave energy propagation at local scale. In Figure 8, the yearly average wave power levels are presented in the highest resolution domain. The choice of the study domain corresponds to the area where the Port of Civitavecchia is placed, considering that a power device could be placed along the external breakwater with minimum costs and visual impact. As already stated above, for the local scale analysis, higher resolution bathymetry is fundamental. A 10-meter-detail bathymetric data from multi-beam survey is available for this area.

From Figure 8, it is possible to observe how wave power distribution strictly depends on the coastal morphological features and seabed shape.

The most suitable site is in front of the harbour breakwater, where wave power reaches 2.8 kW m^{-1}. Two additional high energetic hotspots are placed respectively at the north and south sides of the harbour, where wave power front gets closer to the coast.

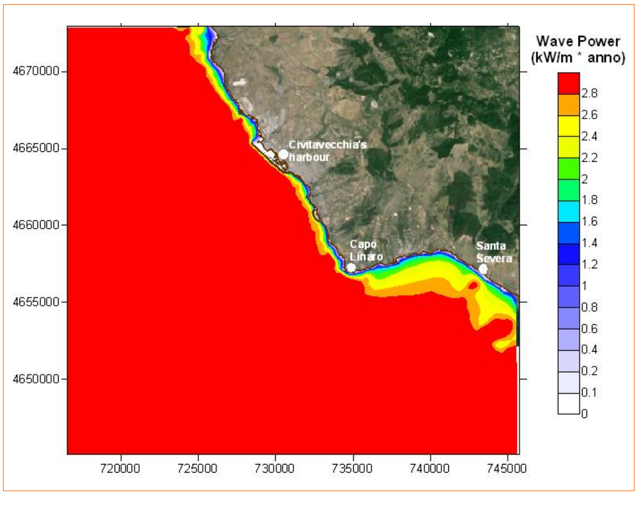

FIGURE 7 Numerically simulated wave power in the pilot area – Regional scale

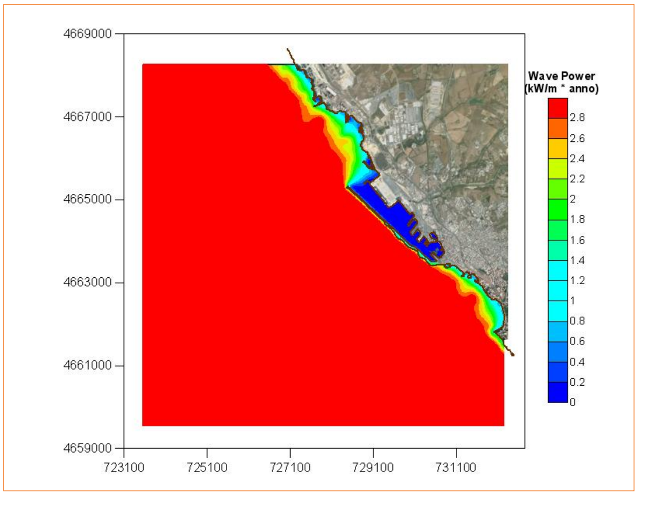

FIGURE 8 High resolution model result for wave power distribution in the pilot area

Nearshore point		Nearshore point	
Coefficient of determination (R^2)	Residual mean square	Coefficient of determination (R^2)	Residual mean square
0.912112	1.33674	0.879648	1.92103
Onshore point		**Onshore point**	
Coefficient of determination (R^2)	Residual mean square	Coefficient of determination (R^2)	Residual mean square
0.783192	0.0396924	0.831916	0.0850484

TABLE 1 Statistical results of computed wave power and measured wave power, for regional (left) and local (right) scale analysis

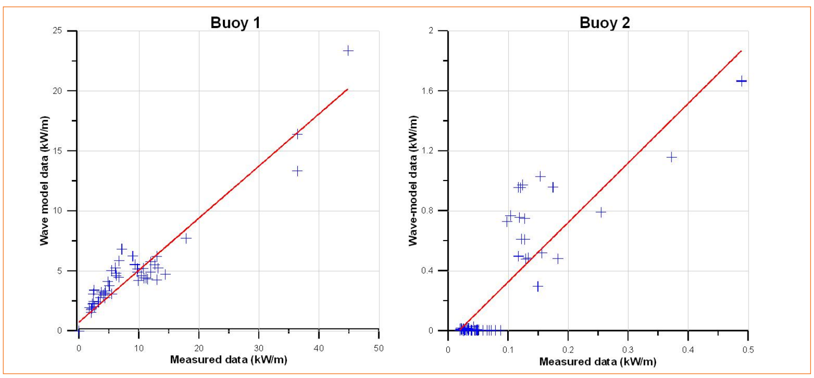

FIGURE 9 Regression analysis between wave buoy measure and regional model results nearshore (buoy 1) and onshore (buoy 2)

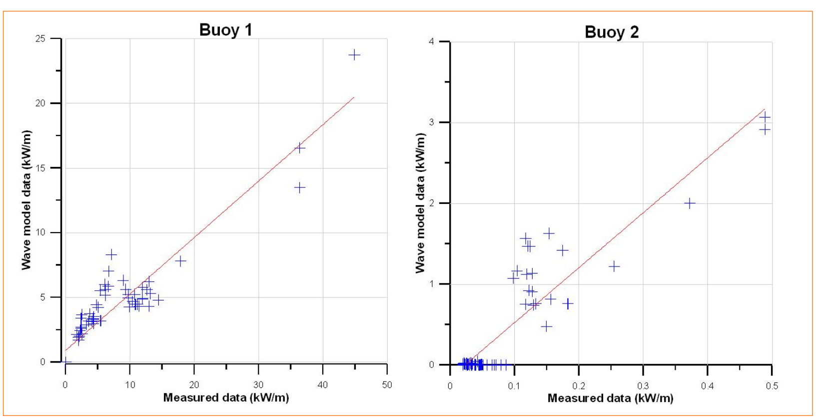

FIGURE 10 Regression analysis between wave buoy measure and local model results nearshore (buoy 1) and onshore (buoy 2)

Validation

We have evaluated the ability of CMS-Wave to simulate the propagation of the waves, as well as attenuation of wave energy in transitional and shallow waters.

The records of two wave Port Authority's buoys were used to compare *in situ* measurements with results from the numerical computation. Seventy wave events registered in both buoys have been chosen for the analysis, using the offshore wave data registered at Capo Linaro (RON).

Wave events with height from 0.8 to 3 m and direction range from 130° to 240°N were chosen.

Modelling validation has been carried out through wave power correlation, for both regional and local scale simulations. Linear regressions are shown in the Figure 9 and 10 and statistical values are summarized in the Table 1.

Present and future developments

The hotspot detection drives the implementation of measurements deploying the Mini-ADP Sontek 1.5MHz in order to verify the potential of the site. This device allows to measure the wave spectra through acoustic transducers and a strain gauge sensor. At present, the sensor was installed on 14/11/2014,in the hot spot in front of of Civitavecchia's harbour breakwater (Fig, 11).

Future development consists in the deployment of the experimental device WAVE SAX designed by RSE in the hot spot site. This modular system will be installed on the harbour breakwater, as reported in Figure 12, where the cross-section of breakwater and location can be observed.

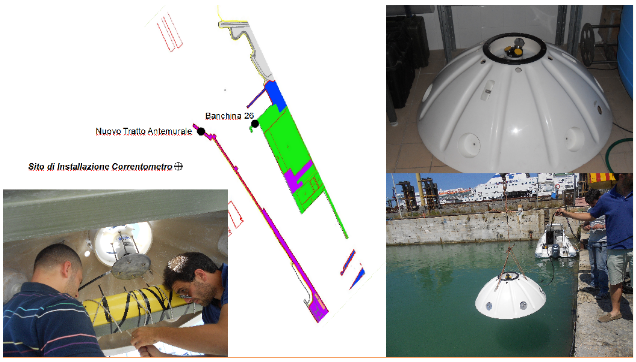

FIGURE 11 Map of location and operative phases of installation

divergence areas where wave energy is subject to concentration and dissipation. In the northern part of the regional domain the seabed is steeper, and higher values are present. In the southern part of the regional domain the seabed slope is smoother producing larger dissipation of energy. Two areas of shallower water are present that coincide with two hotspots of wave power, exactly at the Site of Community Importance (SCI) called Macchia Tonda. The nesting process with increased resolution allows a more accurate description of wave propagation in coastal areas and the wave power hotspots are clearly detected.

FIGURE 12 Location and cross-section of breakwater with experimental device

Conclusions

The methodology allows to assess the nearshore hotspots for wave energy exploitation and the downscaling process has proven to be very suitable to describe the dynamics at local scale.
At regional scale large variations in nearshore wave power distribution were identified. According to wave model results, wave propagation is strongly dependent on the effect of the morphology of the seabed, which generates convergence and At local scale resolution the model allowed to account for a more accurate description of wave propagation in coastal areas and the wave power hotspots are clearly detected. In particular, in front of the harbour breakwater higher depth occurs and it results in lower energy attenuation.
In addition, modelling results are confirmed by in situ wave measures and the downscaling process, which has proven to be a useful tool for the detection of wave distribution in transitional and shallow water areas. The methodology allows to

assess the nearshore hotspots where the presence of infrastructures (power plant, harbour, etc.) easily accessible ensures lower costs of installation, operation and maintenance for wave energy converters. Future developments, including the record of data at the hotspot, the installation of the experimental converter and the measure of energy production, will help to achieve more accurate methods and prediction of energy availability.

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