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Assessment of the changes induced by a wave energy farm in the nearshore wave conditions

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A B S T R A C T

Starting from the observation that an important next stage in exploiting the ocean energy is to install large arrays of several identical devices in order to raise their overall electricity production, the present work has as objective to assess the local and coastal impact of a large wave farm that would operate in the Portuguese coastal environment. The target area is the Portuguese maritime pilot zone, São Pedro de Moel, which is located in the central part of the Portuguese continental nearshore. A generic wave farm was considered and various transmission situations were analyzed. The study started with the situation without wave farm (zero absorption) and subsequently different scenarios were considered by gradually increasing the conditions to the hypothetic case of the total absorption. For each case study, model simulations were performed covering the entire year 2009 using a wave prediction system based on Wave Watch 3, for the wave generation at the level of the entire North Atlantic Ocean, and on SWAN, for the coastal wave transformation. In this way, a comprehensive picture of the possible impact of the wave farm is provided. The results show that the presence of a wave farm operating offshore has a strong influence on the wave conditions immediately down wave. Although this influence is usually attenuated at the level of the coastline, it appears as obvious a general decrease in terms of significant wave height due to the wave farm, but also some other wave parameters are modified.

1. Introduction

Following the oil crises in the 1970s, the possibility of exploiting ocean waves for the production of electricity became more real. Since then, several methods are feasible and many areas of the world are shown to have the potential coastal wave energy that could be converted into useful electric power.

Ocean waves suitable for the energy extraction are a product of the surface winds. Hence the energy transferred depends on the wind speed, the wind duration and the distance over which the wind blows, known as fetch. In the coastal areas, several factors influence the wave power, such as: the type of the coastline, the nearshore bathymetry, the wave breaking type and the coastal refraction and diffraction. Deep offshore wave energy extractions are also being considered nowadays, although the accesses to the power grids and to the wave farms for maintenance are important challenges in these cases. Nevertheless, it becomes more and more obvious that waves represent a considerable renewable energy resource with great potential and relatively low environmental impact.

As regards the expected environmental impact, harvesting the wave power is less environmentally degrading than most of the other forms of power generation. Wave energy converters (WECs) produce no gaseous, liquid or solid emissions. However, their deployment, when it comes to a wave farm, may have some impact on the coastal zones (Brooke, 2003). A large WEC array has the power to alter the wave climate between the array and the coast. Large waves usually propagate from seaward and any effects of the WECs on the wave kinematics can be understood to be shoreward the devices. Most WECs extract energy from swell or low frequency wind waves, which generally corresponds to a much greater source of power than higher frequency local waves. Therefore, shoreward the WEC the energy, and implicitly the height, of the long waves will be reduced. Perhaps the most significant effect of the WECs will be on the sediment suspension and the sediment transport. This is because the longshore transport of material is dependent on the size and direction of the incoming waves (Shields et al., 2011).

In fact, even the presence of a wind farm in the coastal environment may induce some changes in the nearshore dynamics, as discussed in Ponce de Leon et al. (2011). From this perspective, the estimation of how much the wave climate will be changed and which will be the impact when an energy farm operates in the nearshore represents a problem of significant

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importance. Moreover, exactly due to their possible coastal impact, floating wave energy converters can play also an important role in the coastal protection, as analyzed by Zanuttigh and Angelelli (2013).

From this perspective, estimations of the effects on the wave conditions near the shoreline due to the installation of the wave farms have been studied by several researchers. The 30 MW-rated wave farm known as "Wave Hub" was the focus of two studies, done by Millar et al. (2007) and Smith et al. (2012), where the changes in the nearshore wave climate were analyzed. Both studies use the SWAN model (Simulating WAves Nearshore, Booij et al., 1999) to evaluate the impact of the wave farm. The first one implements an obstacle and varies the energy transmission percentages from 0% to 90%, representing different scenarios corresponding to different WEC arrays. The study of Smith et al. (2012) goes further and the SWAN code was modified in order to enable frequency-dependent wave energy transmission through a barrier rather than constant wave energy transmission. Three configurations for the barrier were considered: a line, a row with a series of small 100 m width barriers and two rows of 100 m barriers. The less complex study concluded that the wave height decreases linearly at the shore line with increasing wave energy transmission, the realistic scenario of 90% wave energy transmission produces an average change in terms of H_s of 1 cm or less over the 11 months modeled and the maximum change is of about 4 cm. The second study showed that the use of the spectral sea states rather than the integral wave parameters (height, period, etc.) is essential since it was observed that if the peak of the transfer function corresponds to the spectral region between tow peaks, minimal energy will be extracted. When compared with the previous studies, it is noticeable that previous assessments have over-estimated the shoreline impact.

In the northwest Iberian coastal environment, Carballo and Iglesias (2013) have also investigated the impact of a wave farm on the nearshore, but their study aimed more to quantify the interactions of the WECs with the waves using laboratory tests. The case study implemented illustrated a wave farm on the Death Coast (NW Spain). The wave energy transmitted was determined by means of a 3D physical model and based on those results the nearshore wave climate was evaluated using the SWAN model. The results indicated that the difference between a single-row and a double-row layout is negligible at a distance of 5000 m or greater down wave from the farm.

In the Portuguese continental nearshore, Palha et al. (2010) used the REFDIF model (Kirby and Dalrymple, 1994) to assess the energy extraction in one of the two Portuguese maritime pilot zones, São Pedro de Moel, which represents also the target area of the present work. Three different sinusoidal wave conditions were considered for five different wave farm configurations, varying the position and the number of the WECs as well as the width of the navigation channels at each wave farm. It was concluded that the energy extraction did not exceed 9.3%, 23% and 14% of the incident energy in the wave farms, respectively for January, July and October. In absolute terms, no major differences were found on the wave heights observed near the coast when considering each wave farm configuration and the case without wave farms. The maximum variation was of 29 cm for the month of July.

Rusu and Guedes Soares (2013a) also performed a study which was focused on the Portuguese coastal area of Peniche. The objective was to evaluate the local and coastal impact of a wave farm based on Pelamis convertors. This was done not only by estimating the influence of the wave farm on the down wave conditions with the SWAN model, but also by evaluating its effect on the nearshore circulation using the ISSM modeling system (the Interface for SWAN and Surf Models, Rusu et al., 2008, Rusu and Guedes Soares, 2010), which is an easily operable tool that has been designed to simulate waves and longshore currents. The ISSM system is composed of a MATLAB GUI in the foreground, which directs the integration of the SWAN wave model with a 1D surf model (Mettlach et al., 2002) in the background. Two wave farm configurations were considered, the first consisting in a line of five Pelamis convertors and the second in two lines. The wave directions assumed were 270° and 340° and for each direction average (H_s=2.8 m) and high (H_s=5.2 m) waves were considered, respectively. The results have shown that H_s decreases more than 10% for the first wave farm configuration and more than 20% for the second configuration, situation that also affected a sensible larger area. Then again, nearshore data demonstrate that the coastal impact is highly attenuated showing relative values of H_s not greater than 5%. In regard to the current velocities, the wave farm induced in general a decrease of about 5–8%, but also in some situations due to drastic changes in the wave directions the nearshore current velocities were also increased.

In this context, the objective of the present work is to evaluate the medium term coastal impact of a generic wave farm that would operate in the Portuguese maritime pilot zone at São Pedro de Moel, considering different scenarios by increasing gradually the conditions from zero absorption (situation without wave farm) to the hypothetic situation of the total energy absorption.

2. Modeling the wave climate in the Portuguese nearshore

A wave prediction system based on WAM (WAMDI group, 1988) for wave generation and SWAN for coastal transformation was considered for various evaluations of the wave patterns in the Portuguese continental coastal environment. These concerns especially the wave energy spatial distribution, as presented in Rusu and Guedes Soares (2008, 2009 and 2013b) and in Rusu et al. (2011). Considering the same approach the wave conditions and energy in the Portuguese archipelagoes Madeira and Azores, were analyzed in Rusu and Guedes Soares (2012a and 2012b).

Further wave predictions covering the entire western side of the European coast (including thus also the Portuguese continental nearshore) are based on medium term simulations with a different wave modeling system (Bento et al. 2011, Silva et al. 2012, Gonçalves et al. 2014a, 2014b) that uses Wave Watch 3 (WW3) (Tolman, 1991) for the wave generation at the scale of the entire North Atlantic Ocean forced using reanalysis wind data of NCEP/NCAR and SWAN for the coastal wave transformation forced with wind fields produced by the atmospheric model MM5 (Fifth-Generation NCAR/Penn State Mesoscale Model, Dudhia et al., 2000). More details related to the MM5 model implementation on the West Iberian coast are given in Guedes Soares et al. (2011). The computational domains defined for this modeling system, which was focused on the Portuguese maritime pilot zone (Pedro de Moel) are described in Table 1 and illustrated in Fig. 1.

The implementation of the SWAN model was made for 36 directions and 30 frequencies logarithmically spaced from 0.05 Hz to 0.6 Hz at intervals of $\Delta f/f$=0.1. The model was executed without the influence of currents. The computations were performed in the non-stationary mode with a 20 min time step. The number of

Table 1
Characteristics of the computational domains defined for the modeling system based on WW3 for wave generation and SWAN for coastal transformations (ΔX and ΔY represent the grid steps in the geographical space).

Computational domain	Geographical limits (lat/long)	$\Delta X \times \Delta Y$
North Atlantic (WWIII)	13°N–72°N/65°W–22°E	1.54° × 1.46°
Portugal continental (SWAN)	35°N–45°N/11°W–6°W	0.05° × 0.1°
São Pedro de Moel (SWAN)	39.5°N–40°N/9.5°W–8.8°W	0.5′ × 0.5′