CO-LOCATED WAVE AND OFFSHORE WIND FARMS: A PRELIMINARY CASE STUDY OF AN HYBRID ARRAY

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In recent years, with the consolidation of offshore wind technology and the progress carried out for wave energy technology, the option of co-locate both technologies at the same marine area has arisen. Co-located projects are a combined solution to tackle the shared challenge of reducing technology costs or a more sustainable use of the natural resources. In particular, this paper deals with the co-location of Wave Energy Conversion (WEC) technologies into a conventional offshore wind farm. More specifically, an overtopping type of WEC technology was considered in this work to study the effects of its co-location with a conventional offshore wind park.

Keywords: wave energy; wind energy; synergies; co-located wind-wave farm; shadow effect; wave height

INTRODUCTION

Wave and offshore wind energy are both part of the Offshore Renewable Energy (ORE) family which has a strong potential for development (Bahaj, 2011; Iglesias and Carballo, 2009) and is called to play key role in the EU energy policy, as identified by, e.g. the European Strategic Energy Technology Plan (SET-Plan). The industry has established, as a target for 2050, an installed capacity of 188 GW and 460 GW for ocean energy (wave and tidal) and offshore wind, respectively (EU-OEA, 2010; Moccia et al., 2011). Given that the target for 2020 is 3.6 GW and 40 GW respectively, it is clear that a substantial increase must be achieved of the 2050 target is to be realized, in particular in the case of wave and tidal energy.

Offshore wind energy is defined as the energy generated from the wind at sea, and wave energy as the energy present in oceans and other water bodies in form of waves. Sharing the same hostile marine environment, wave and offshore wind energies face similar challenges. However, their level of technological development is not the same. Whereas offshore wind is a proven technology, with 3.8GW of installed capacity in Europe and employing 35,000 people directly and indirectly at the end of 2011 (EWEA, 2012), wave energy – as well as floating offshore wind energy – is still at an early stage of development.

A sustainable development of wave and offshore wind industries requires an efficient planning and use of the natural resources, i.e. one that optimises their exploitation safeguarding the natural environment. It is in relation to this and share challenge to both industries to reduce costs that the possibility of integrate them arises. This paper is focused on a specific type of combined alternative, the co-location, where a wave energy farm and a conventional offshore wind farm are “co-located” at the same maritime space sharing common installations and facilities.

The aim of the present paper is to introduce the singularities of integrating wave energy into a conventional offshore wind farm, and in particular proses a case study where a hybrid array is considered in order to understand the effects of this co-location for both energies. It is structured as follows: First, the positive synergies between both energies are outlined and also in particular the specific development issues of co-located wave-wind farms. Secondly, the different combined wave-wind systems are classified. Thirdly, the methodology followed to study the case study is defined. Fourthly, the results of the case study are presented and discussed. Finally, the conclusions and future works are drawn.

SYNERGIES AND DEVELOPMENT ISSUES

Apart from the two main reasons to consider the combination of wave and offshore energy systems already drafted in the introduction - i.e. an increased sustainability of the energy resources and the cost reduction of both energy sources - there are a number of other synergies which arises when this combination is considered. Furthermore, there are also a number of technology development issues which also arises from this possibility. Both, synergies and development issues are presented next.

Synergies

At a project or technology level the combination of marine energies gains momentum as a real alternative. This is supported by a number of synergies ranging from an increase in the energy yield to a reduction in the operation and maintenance cost. Based on the work by (Casale et al., 2012; Perez-

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Collazo et al., in press; Perez-Collazo et al., 2013) the project or technology synergies can be defined as follows:

- *Enhanced energy yield***.** The combination of marine energies will increase the global energy yield per unit area of marine space, contributing to a better use of the natural resources.
- *Better predictability.* The wave resource is more predictable and less variable than the wind resource (Veigas et al., 2014a), and the combination of both will reduce the system balancing costs, as seen in (Fernandez Chozas et al., 2012).
- *Smoothed power output.* For the same weather system the wave climate peaks trail the wind peaks (Fernandez Chozas et al., 2013). In consequence, a combined exploitation will result in a reduction of sudden disconnections from the electric grid, an increase in availability (thus reducing the number of hours of non-activity) and a more accurate output forecast.
- *Common grid infrastructure.* The electric grid infrastructure represents one of the most important costs for an offshore project – up to one third of the entire project (Musial and Ram, 2010). Therefore, the combined production of electricity using a shared grid infrastructure would become an important factor in reducing energy costs.
- *Shared logistics.* The dimensions and special characteristics of offshore renewable energy projects require the use of expensive specialist marine equipment and facilities, such as port space or installation vessels. A combined project where these are shared would also contribute to reducing the costs.
- *Common substructure or foundation systems.* Where possible, the combination of wave and offshore wind technologies on the same structure, on hybrid platforms or systems, would signify an important reduction in the cost of the substructures compared with separate projects.
- *Shared Operation and Maintenance (O&M).* The situation and accessibility conditions of the ORE projects makes it necessary to use dedicated installations by specialised technicians to ensure an effective O&M and to minimise the non-working times of the equipment. The combination of both energies would lead to an important cost reduction as result of the shared use of these installations and technicians.
- *Shadow effect.* It is clear that the energy extraction of an array of WECs creates a wake that modifies the local wave climate by reducing the mean wave height - shadow effect (Carballo and Iglesias, 2013). Combining WECs and offshore wind parks at the same location, in a way in which this shadow effect can be used to obtain a milder wave climate inside the park (with the proper design, e.g., by locating the WECs along the perimeter of the offshore wind park), may lead to more weather windows for accessing the wind turbines for O&M, and to reduced loads on the structures.
- *Environmental benefits.* The environmental impacts of wave and offshore wind energy are a major consideration in the development of these renewables (Abanades et al., 2014). The combined option presents an important advantage in environmental terms in that it is likely to have a reduced impact (relative to independent installations), leading to a better utilisation of the natural resources. Moreover, this could result in a transfer of knowledge on the environmental impacts from one sector to another.

Development Issues

At present there are no co-located or combined wave-wind devices operating in the sea, and only a few prototypes or concepts have been proposed so far. Furthermore, there are no WEC farms or arrays of multiple devices operating in the sea. This technological gap, comparing it with the offshore wind systems, arise a number of challenges or technology development issues which need to be faced to make co-located wave-wind farms becoming a reality. The most relevant of these challenges can be defined as follows:

- *Longer development times.* The early stage of development of WEC technologies could entail longer development times, which would increase project costs.
- *Insurance.* The lack of experience in co-located projects could mean higher insurance costs.
- *Accident or damage risk.* Co-locating floating WECs near OWTs could increase the risk of accident or damage in case of a mooring failure on the WEC.
- *Site-selection compromise.* Optimising the site selection for a combined concept could be not ideal for wave and wind compared with the stand-alone option.

Nevertheless, these challenges present an opportunity to develop new research and technological knowledge which with further development and innovation could lead to an improved future generation of co-located wave-wind farms.

COMBINED WAVE-WIND SYSTEMS

Combined wave-wind systems can be classified according to the technology, water depth (shallow, transition or deep water), or location relative to the shoreline (shoreline, nearshore, offshore). In this work the classification proposed by (Perez-Collazo et al., in press), which is based on the degree of connectivity between offshore wind turbines and WECs is followed. It differences between: co-located, hybrid and islands systems (Fig. 1).

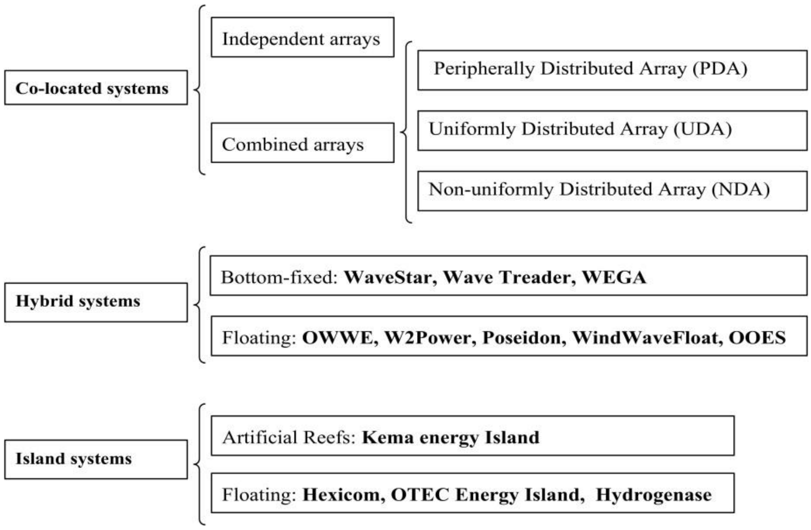

Figure 1. Classification of combined wave-wind technologies (Perez-Collazo et al., in press).

Co-located systems

This is the simplest option at the present stage of development of wave and offshore wind technologies, co-located systems combine an offshore wind farm with a WEC array with independent foundation systems but sharing: the same marine area, grid connection, O&M equipment and personnel, port structures, etc. Co-located systems can be classified into independent arrays and combined arrays. In one hand, co-located independent arrays are those which, while constituting distinct offshore wind and wave farms and occupying different marine areas, are close enough to share the same electric grid connection alongside other services or installation. In the other hand, in co-located combined arrays the offshore wind and wave devices share the same marine area and relevant infrastructures, so that they constitute a single array (Fig. 2).

Figure 2. Artist's impression of a combined array, courtesy of Wave Star AS (Wave Star AS, 2012).

Hybrid systems

A hybrid system combines an offshore wind turbine and a WEC on the same structure, and they are part of a larger family of multipurpose platforms, i.e. offshore structures on which different marine users are combined, such as: ocean energies, offshore wind, aquaculture, transport and marine leisure (Quevedo et al., 2012). According to their substructure, hybrid systems can be classified into bottom fixed and floating. The first are innovative systems based on an evolution of the current substructures used by the offshore wind industry to accommodate a WEC. The second are a novel concept that has emerged in recent years with the raise of floating offshore wind prototypes integrating the WEC into the floating platform, in part to use it as an attenuator of the platform movements (Fig. 3).

Figure 3. Artist's impression of a floating the hybrid systems W2Power, courtesy of Pelagic Power AS (Pelagic Power AS, 2010).

Island systems

The third and final family of combined wave-wind systems comprise the so called island systems. These, as hybrid systems, are offshore multipurpose platforms with the difference that island systems tend to be much larger, and perhaps more importantly, unify the combined exploitation of more than two marine resources at the same platform. Island systems can be classified into artificial or floating islands. Artificial energy islands are typically based on large reefs or dikes and can serve as platforms for large electricity storage, ORE converters and other marine activities. Instead, floating energy islands are large floating multipurpose platforms or barges, usually of smaller dimensions than artificial islands but much larger than hybrid systems, where a combined harnessing of marine resources can be carried out (Energy Island Ltd., 2009).

METHODOLOGY

Once that a complete vision of the different possible combined wave wind systems and their synergies have been seen it is moment to define the main objective of this paper. This objective is to present a preliminary case study of a hybrid array or co-located wave-wind farm, get a better understanding of some of the synergies as the so called "shadow effect" and other possible implications.. The methodology followed to do this research can be structured in three main pillars: i) the location and wave climate; ii) the co-located farms design; and iii) the wave propagation model.

Location and wave climate

The analysis of this case study was carried out by the definition of an hypothetical wind farms at the Wave Hub site. The Wave Hub is an ORE test centre situated approximately 20 km northwest of St Ives Bay in Cornwall, in the southwest of UK (Fig. 4). The water depth at the test site varies from 40 to 60 m (Millar et al., 2007). Regarding to the wave conditions, the most recent available data was considered, in particular the data reported in (Kenny, 2009), which contains values in 8 directional sectors for monthly cases with one year return period, and all year cases with return periods of 1, 10, 50 and 100 years. With this information three sea conditions were defined to proceed with this preliminary case study (Table 1).

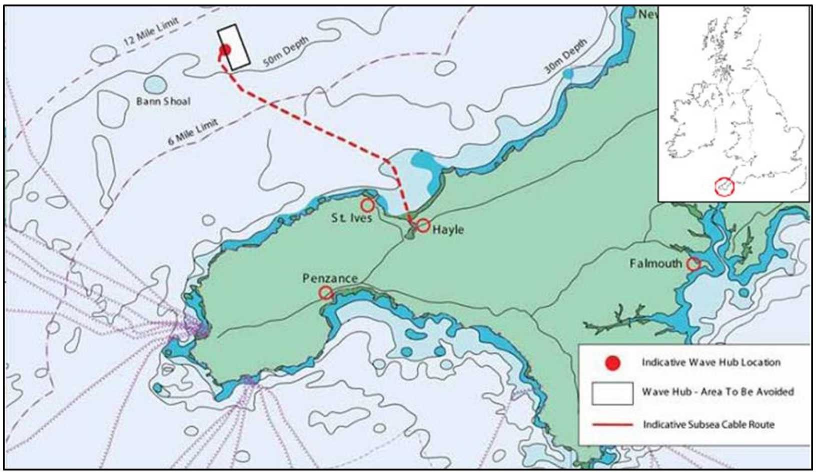

Figure 4. Wave hub location (Wave Hub Ltd., 2014).

Table 1. Parameters of the sea conditions (SC): . H_s = significant wave height; T_p = energy period; θ = mean wave direction.

SE	H_s (m)	T_p (s)	θ (º)
1	1.5	7.57	270
2	2.5	8.14	270
3	3.5	9.33	270

Co-located farm design

To define the co-located wave farm for this case study, first the offshore wind farm layout was defined and then the WEC one was defined considering the restrictions from the wind farm and the predominant wave directions. The conventional and well documented offshore wind farm of Horns Rev 1 in Denmark was used as a model to define the wind farm layout (Wu and Porté-Agel, In press). It is comprised of 80 turbines (Vestas V80-2MW) following a grid pattern with 10 rows. The distance between turbines is 560 m or 7 times the rotor diameter, reaching a total part surface of 20 Km^2 with an average water depth of 50 m. The selected substructure type for this emplacement was a jacket frame of 18 m x 18 m; and finally the layout was staged to the predominant wind direction at the emplacement (315º), in order to maximise the energy output.

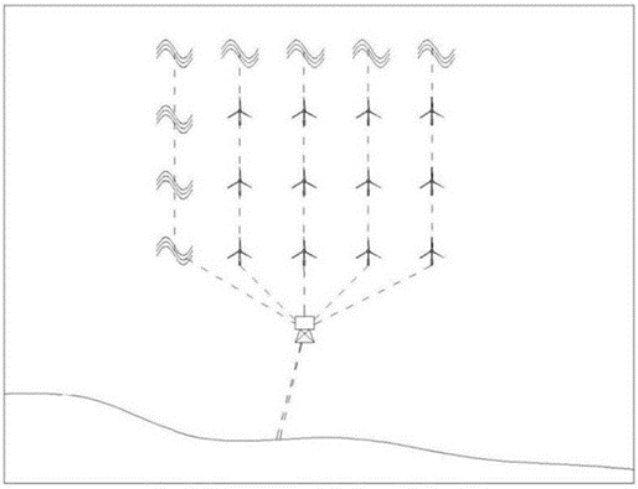

Figure 5. Schematic representation of the Peripherally Distributed Array (PDA), a type of co-located system.

Once that the find farms layout was decided, a Peripherally Distributed Array (PDA) was selected for the co-location of the WEC, the PDA is a type of co-located system which combines both wind and wave arrays by positioning the WEC at the periphery of the offshore wind farm (Fig.5). Considering this distribution and that the predominant wave direction for the Wave Hub is from the West (270º), the array of WEC was decided to be located at the west side of the wind farm. Moreover, The WEC used for this case study was the WaveCat (Fig. 6), a floating offshore WEC whose working principle is the wave overtopping (Fernandez et al., 2012). The WaveCat has an overall length of 90 m and the minimum distance between devices has been prof as 2.2 times *D*, where *D* is the distance between the twin bows of a single WaveCat *D= 90 m* (Carballo and Iglesias, 2013).

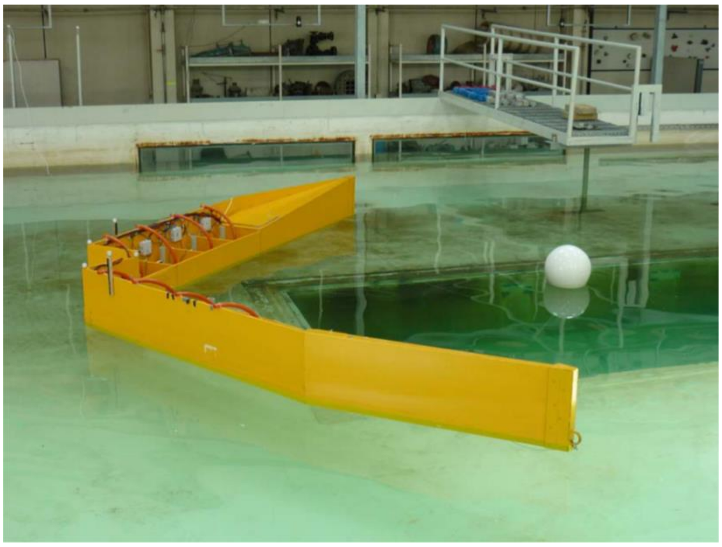

Figure 6. The WaceCat, a novel overtopping type of WEC (Fernandez et al., 2012).

For this case study, three wave farms configurations were tested (A, B and C). A and B have both the same spacing between WEC, and this is the same as the spacing between wind turbines (560 m), while C has the minimum space possible for the WEC (198 m). In addition, the layout for cases A and C was defined in such way that the first row of WEC is parallel to the wind turbines and the second one is positioned in between wind turbines, while the case B is follows the opposite configuration.

The wave propagation model

To simulate the wave propagation, the wave model Simulating Wave Nearshore (SWAN) is used. SWAN is a third generation numerical wave model which computes the evolution of random waves and accounts the refraction, as well as wave generation due to wind, dissipation and non-linear wave-wave interactions (Booij et al., 1999). This model was successfully used to model the propagation of waves, the absorption (transmission) of energy by a wave farm, and the impact of a wave farm on the nearshore wave conditions and the beach profile in its lee (Iglesias and Carballo, 2014).

In this paper, and in order to obtain high-resolution results in the study area without too long computational times, the model was implemented in the so-called "nested mode" with two computational grids: i) a coarse grid from offshore to the coast, covering an area of approx. 120 km x 80 km with a cell resolution of 200 m x 200 m; and ii) a fine (or "nested") grid covering the study site, with an area of 6.8 km x 10.2 km and a cell resolution of 17 m x 17 m (Fig. 7). The high resolution of the nested grid is instrumental to define the position of the wind turbines and WECs and to simulate the individual wakes with accuracy. The bathymetric data, form the UK data centre Digimap, were interpolated onto this grid.

The wind turbines were represented in the model by a transmission coefficient, whose value can vary in theory from 0% (i.e., 100% of incident wave energy absorbed) to 100%. This technique was used to represent single wind turbines, wind farms arrays and arrays of WECs (Ponce de León et al., 2011; Veigas et al., 2014b). In this paper, the transmission coefficient of the offshore wind farm was calculated by (Hayashi and Kano, 2011):

$$c_t = 4\left(\frac{d}{H_i}\right) E\left[-E + \sqrt{E^2 + \frac{H_i}{2d}}\right] \quad (1)$$

$$E = \frac{C_d\left(\frac{b}{D+b}\right)}{\sqrt{1-\left(\frac{b}{D+b}\right)^2}} \quad (2)$$

where *d* is depth (m), *Hi* is incident significant wave height (m), *D* is the pile diameter (m), *b* is the pile spacing (m), and *Cd* is the drag coefficient of the piles (1.0 for a smooth pile).

Diffraction and reflection are significant processes when the ratio between the pile diameter (D) and the wavelength (L) is higher than 0.2 [42]. In this case, D/L is less than 0.1, so reflection and diffraction are negligible. As regards the WaveCat devices, the wave transmission coefficient was implemented on the wave propagation model using the results of the laboratory tests carried out by Fernandez et al. (2012).

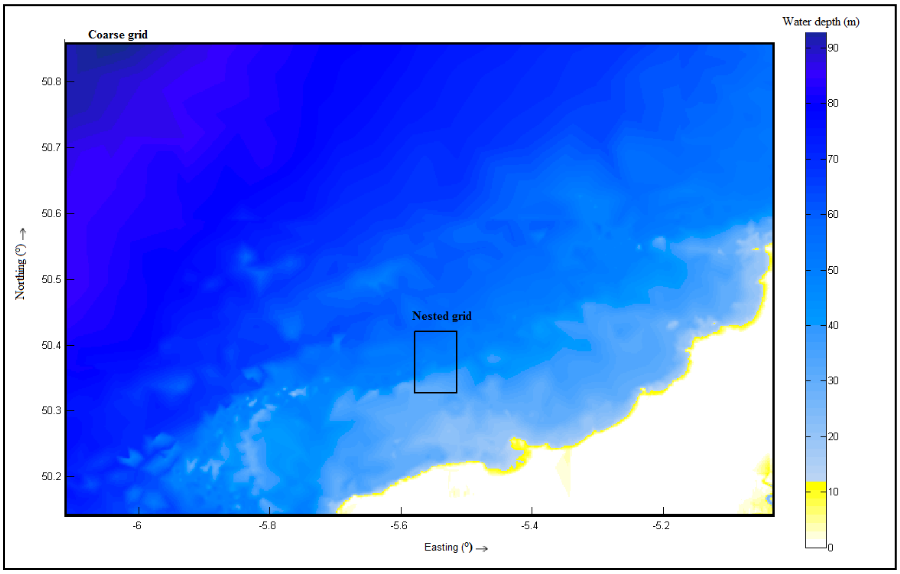

Figure 7. Computational grids of the wave propagation model.

RESULTS

A new impact indicator was developed to compare the impact of the different co-located farm alternatives on the nearshore area. The significant wave Height Reduction within the Farm (*HRF*), which assess the global wave height reduction within the wind farms area. The *HRF* index is calculated by:

$$HRF = \frac{100}{n}\sum_{i=1}^{n}\frac{Hs_i - HsWEC_i}{Hs_i} \quad (3)$$

where the index *i* designates a generic turbine of the wind farm, *n* is the total number of turbines, Hs_i is the significant height incident on the *i-th* turbine in the baseline scenario (without WECs), and $HsWEC_i$ is the significant height incident on the *i-th* turbine with co-located WECs.

The baseline scenario and the results are presented graphically for the sea condition SC 2 and for all cases in Table 2. Fig. 8 presents the baseline scenario, where just the offshore wind farm was considered. This baseline scenario allows the definition of how the near shore area would be affected for a conventional offshore wind farm and to compare with the co-located farm. The three co-located farm configurations are presented in Fig. 9 and Fig. 10. In one hand, Fig. 9 compares configurations A and B, where just the relative position of the WECs is modified and the distance between WECs remains constant (560 m). In the other hand, Fig. 10 compares now configurations A and C, where the distance between WECs is modified but not their relative position with the wind turbines.

From the analysis of the figures it can be seen that Configurations A and B are similar, however it seems that A is slightly better than B, something that can be corroborated from Table 2. In addition to, it is also clear that configuration C is the one that generates a greater shadow area at the inner co-located farm, reaching wave reductions up to the 25.79%.

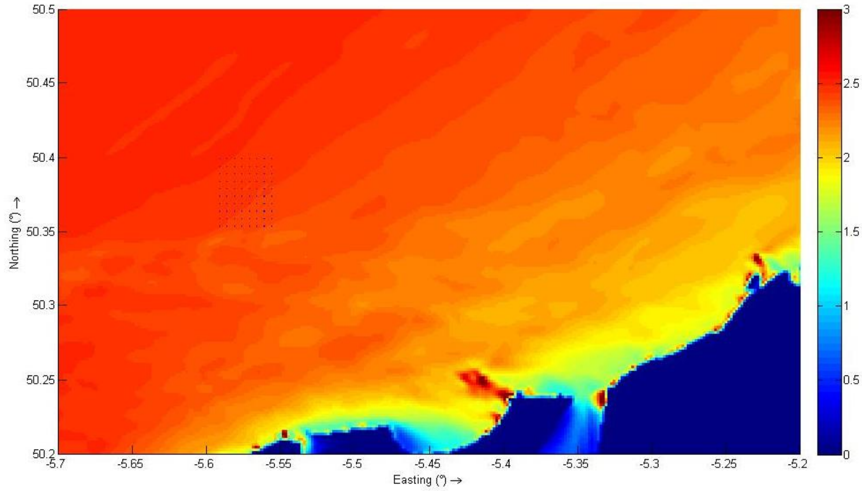

Figure 8. Baseline scenario with just the offshore wind park for the sea condition SC 2.

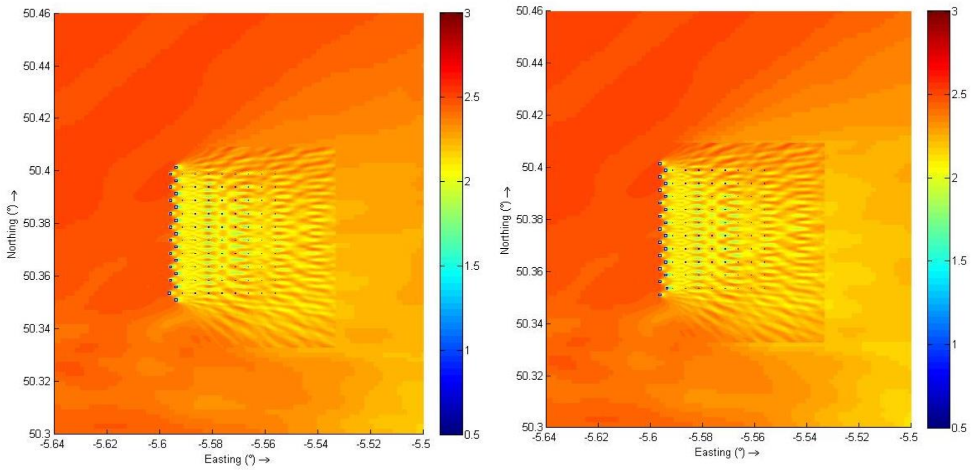

Figure 9. Comparison between configurations A and B for the sea condition SC 2.

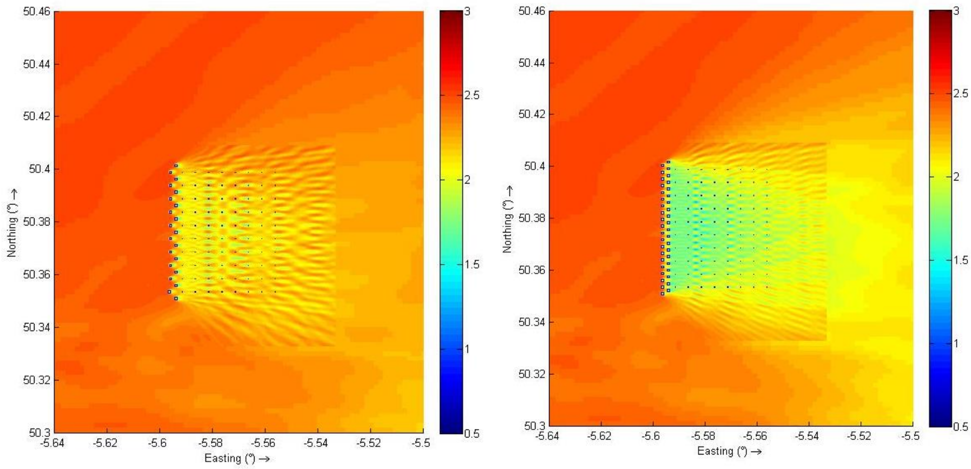

Figure 10. Comparison between configurations A and C for the sea condition SC 2.

Table 2. HRF (%) values for the Sea Conditions SC 1, SC 2 and SC 3 and configurations A, B and C.			
Configuration	CS 1	CS 2	CS 3
A	13.08	13.12	13.21
B	12.06	12.08	12.10
C	25.79	25.77	25.74

In sum, the greater wave reduction was obtained for the smallest distance between WEC and for the configuration where the first row of WEC was deployed parallel to the first row of offshore wind turbines.

CONCLUSIONS AND FUTURE WORK

This paper goes thought the different aspects concerning the co-location of wave and offshore wind farms and finally analyses a preliminary case study of a hybrid array. As a first step, the synergies and technology development issues of combined wave-wind systems was presented. In second place, the different alternatives to combine wave and offshore wind energy systems were presented. Finally, a case study analysing three possible co-located farms was carried out.

Synergies between wave-wind systems are strong and present important points to support the integration of both energies. From these synergies, the one regarding the shadow effect is considered with special detail later at the case study. Furthermore, a number of development issues have been highlighted as the main challenges for WEC to be integrated with offshore wind. These challenges represent some key research lines which need to be addressed in recent years to make co-located farms becoming a reality.

The case study proposed at this paper presents three basic configurations of a peripherally distributed array where two rows of WECs were positioned at the periphery of a conventional offshore wind farm. After the analysis of these three possible configurations for other three possible real sea conditions it was found that significant reduction in wave height are found at the inner farm and that the shadow effect is significantly affected by the relative distance between WECs and between WECs and the wind turbines.

In sum, this paper presents strong facts to support the co-location of wave and offshore wind farms, and in special the so-called “shadow effect”, which takes advantage of the WECs’ wakes to produce an area of lower wave height inside the offshore wind farm to increase the weather windows for O&M of the wind turbines. Furthermore, future research is needed to investigate wave-wind combination alternatives, their interactions with the wave field and the economics benefitof the combination.

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