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CO-LOCATED WAVE AND OFFSHORE WIND FARMS: A PRELIMINARY APPROACH TO THE SHADOW EFFECT

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1. ABSTRACT

In recent years, with the consolidation of offshore wind technology and the progress carried out for wave energy technology, the option of combine both technologies has arisen. This combination rest mainly in two main reasons: in one hand, to increase the sustainability of both energies by means of a more rational harnessing of the natural resources; in the other hand, to reduce the costs of both technologies by sharing some of the most important costs of an offshore project. In addition to these two powerful reasons there are a number of technology synergies between wave and wind systems which makes their combination even more suitable. Co-located projects are one of the alternatives to combine wave-wind systems, and it is specially for these project were so-called *shadow effect* synergy becomes meaningful. 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. This study aims to give a preliminary approach to the shadow effect and its implications for both wave and offshore wind energies.

2. 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 3.8 GW 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– 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 to give a preliminary approach to the so-called *shadow* effect – i.e., the shadow effect is the effect of using a wave energy farm array wake to shield the inner part of a conventional offshore wind farm and reduce so the wave height at its inner part. It is structured as follows: First, the background of combined wave-wind systems and their synergies are described. The methodology followed to study the shadow effect is defined. In fourth place, the results of this research are presented and discussed. Finally, the conclusions and future works are drawn.

3. BACKGROUND

This section pretends to ground the basis of the present work by introducing the different concepts involved on it. First, drafts the different synergies existent between wave and offshore wind energy systems. Secondly, looks at the technology development issues that co-located project face. Finally, gives a glimpse into the different types of combined wave-wind systems. Note that the objective of this section is to present these concepts and not go in depth into them, and Refs. (Pérez-Collazo et al., 2014; Perez-Collazo et al., 2013) can be consulted for additional details.

a. SYNERGIES

As mentioned before at the introduction, apart from the two main reasons to consider the combination of wave and offshore wine energy systems - 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 their combination is considered. The project or technology synergies for combined wave-wind projects can be drafted as follows:

- Enhanced energy yield.
- Better predictability.
- Smoothed power output.
- Common grid infrastructure.
- Shared logistics.
- Common substructure or foundation systems.
- Shared Operation and Maintenance (O&M).
- Shadow effect.
- Environmental benefits.

Among these synergies, the shadow effect one it is of special interest for this paper. 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). Co-locating 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.

b. TECHNOLOGY 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 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 listed as follows:

- Longer development times.
- Difficult insurability.
- Accident or damage risk.
- Site-selection compromise.

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.

c. COMBINED WAVE-WIND SYSTEMS

Combined wave-wind systems can be classified according to their technology, water depth (shallow, transition or deep water), or location relative to the shoreline (shoreline, nearshore, offshore). In this work the classification proposed at (Pérez-Collazo et al., 2014), 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).

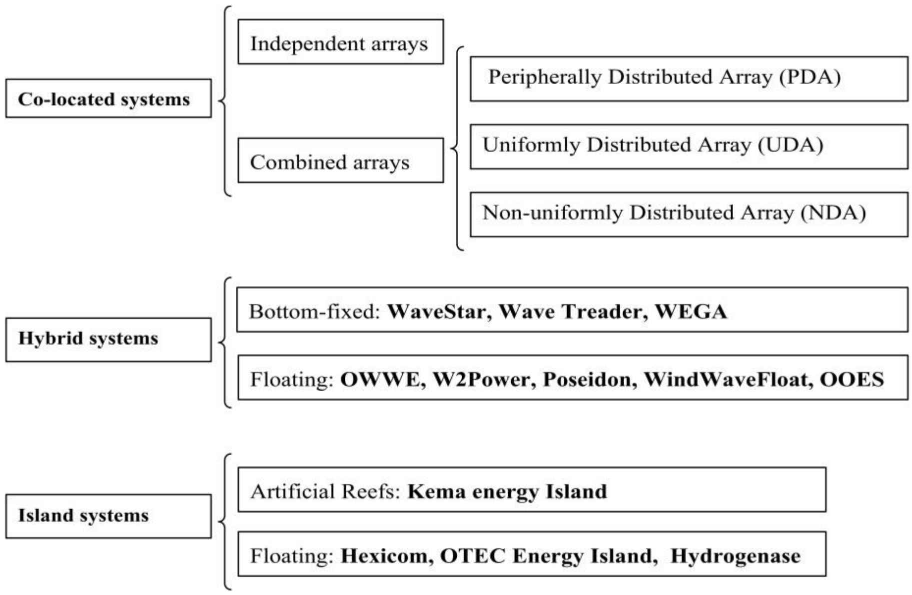

Figure 1. Classification of combined wave-wind technologies (Pérez-Collazo et al., 2014).

Co-located systems are the simplest option at the present stage of development of wave and offshore wind technologies, these 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. For the purposes of this paper only the Peripherally Distributed Array (PDA) is considered.

4. METHODOLOGY

This section describes the methodology followed at this paper to study the shadow effect of a co-located wave-wind farm. This can be structured into three main pillars: (a) the location and wave climate; (b) the co-located farm design; and (c) the wave propagation model.

a. LOCATION AND WAVE CLIMATE

The present research was carried out by means of a hypothetical co-located wave-wind farm located 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. 2). 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 work (Table 1).

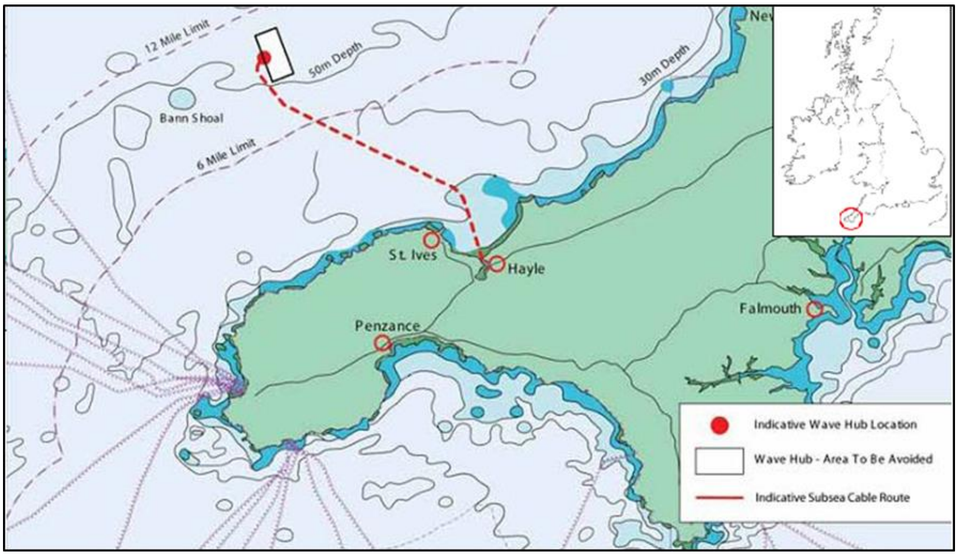

Figure 2. Wave hub location (Wave Hub Ltd., 2014).

SC	Hs (m)	Tp (s)	θ (º)
1a	1.5	7.57	270
2a	2.5	8.14	270
3a	3.5	9.33	270

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

b. CO-LOCATED FARM DESIGN

To define the co-located wave farm for this paper, first the offshore wind farm layout was defined and then the WEC was selected 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 model to define the wind farm layout (Wu and Porté-Agel, In press). This is comprised of 80 turbines (Vestas V80-2MW) following a grid pattern with 10 rows. In addition, the distance between turbines is 560 m or 7 times the rotor diameter, reaching a total park surface of 20 Km2 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.

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.3). 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. 4), 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).

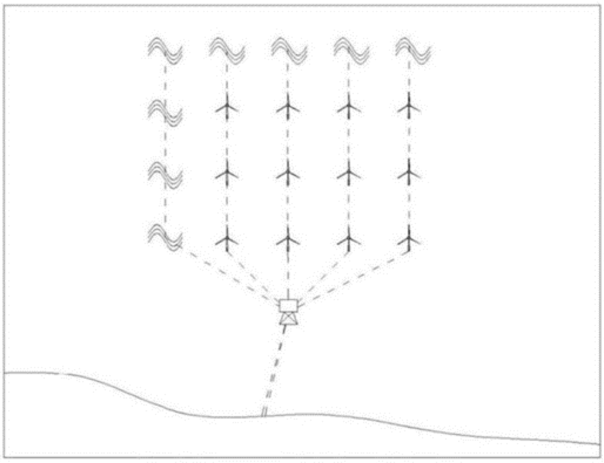

Figure 3. Schematic representation of the Peripherally Distributed Array (PDA), a type of co-located system.

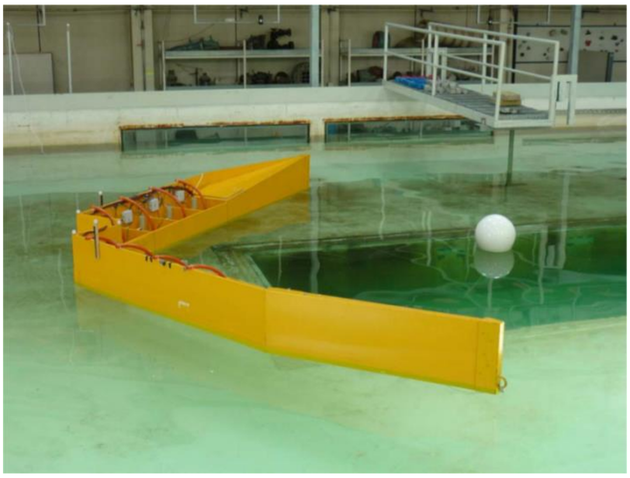

Figure 4. The WaceCat, a novel overtopping type of WEC (Fernandez et al., 2012).

Three wave farms configurations were tested (A, B and C) for this work. 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.

c. 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. 5). 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.

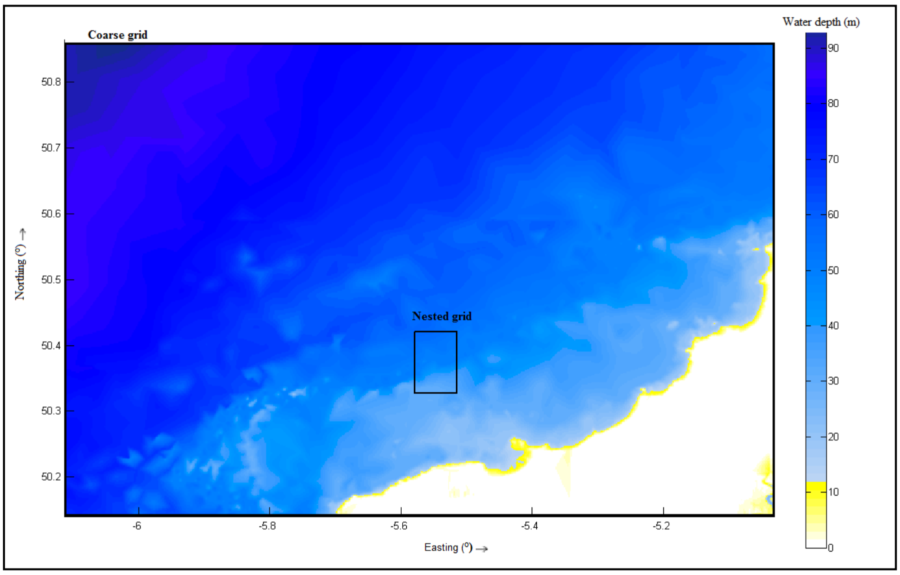

Figure 5. Computational grids of the wave propagation model.

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., 2014). In this paper, the transmission coefficient of the offshore wind farm was calculated by (Hayashi and Kano, 2011):

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

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

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 (Isaacson, 1979). 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).

5. RESULTS

A new impact indicator was developed to analyze the shadow effect at the inner part of the co-located farm. The significant wave Height Reduction along the *j-th* column of wind turbines (HRC_j), which assess the impact of the shadow effect on the different columns of wind turbines as the distance from these increases with respect to the wave farm. The HRC_j index is calculated by:

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

where the index i designates a generic turbine of the *j-th* column of the wind farm, n is the total number of turbines in the respective *j-th* column, Hs_i is the significant incident wave height on the *i-th* turbine in the baseline scenario (without WECs), and $HsWEC_i$ is the significant incident wave height 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. 6 presents the baseline scenario, where just the offshore wind farm was considered. This baseline scenario allows the definition of how sea conditions were at the conventional offshore wind farm and to compare it with the co-located farm. The three co-located farm configurations are presented in Fig. 7 and Fig. 8. In one hand, Fig. 7 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. 8 compares now configurations A and C, where the distance between WECs is modified but not their relative position with the wind turbines.

Case Study	Co-located part vertical row							
	1	2	3	4	5	6	7	8
A	12.24	15.16	13.46	16.63	7.79	16.47	13.01	10.22
B	16.49	13.82	11.98	9.05	17.45	10.32	9.27	8.26
C	27.42	26.45	25.77	26.37	25.14	25.60	24.59	24.81

Table 2. HRC_j (%) values for the Sea Condition SC 2 and configurations A, B and C.

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 and at the same time this reduction persist for longer inside the park, reaching wave reductions up to the 27.42 % at the first row of the co-located park.

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.

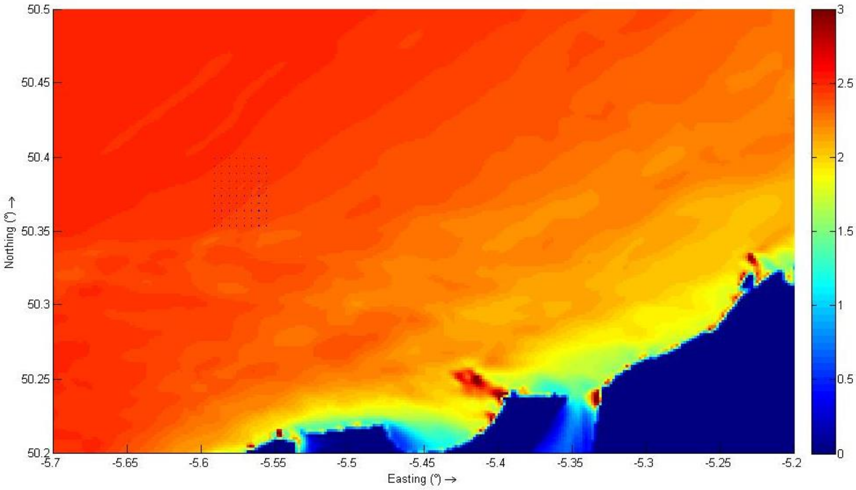

Figure 6. Baseline scenario with just the offshore wind park for the sea condition SC 2.

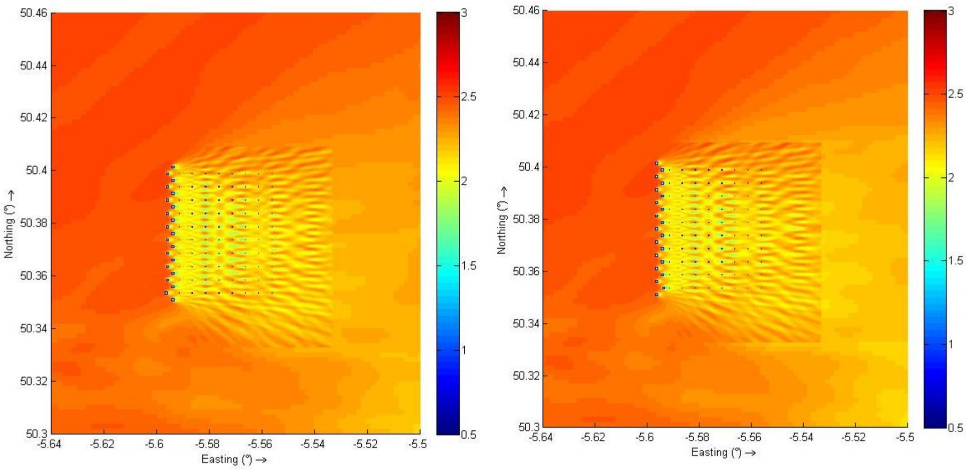

Figure 7. Comparison between configurations A and B for the sea condition SC 2.

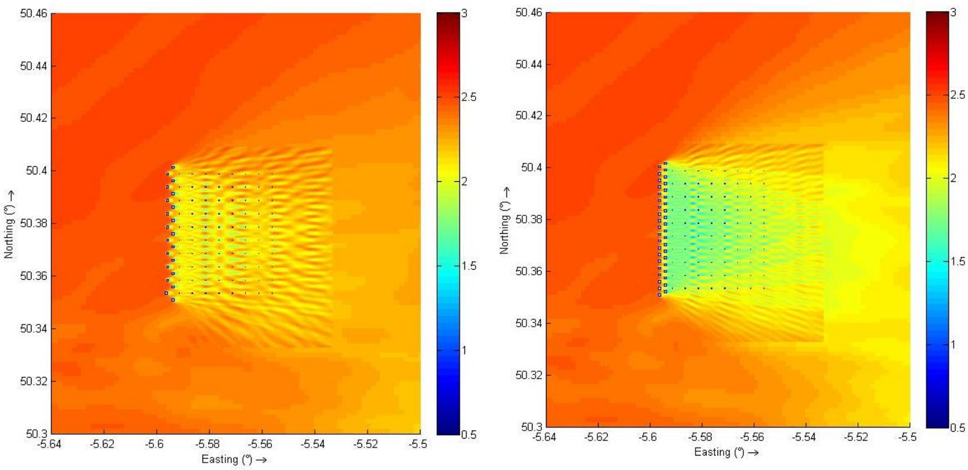

Figure 8. Comparison between configurations A and C for the sea condition SC 2.

6. CONCLUSIONS AND FUTURE WORK

This paper goes thought the different aspects concerning the co-location of wave and offshore wind farms and in particular analyses the shadow effect created by the WECs when these are co-located with a conventional offshore wind farm. As a first step, the synergies, the technology development issues and the different types of combined wave-wind systems were presented. In second place, the methodology followed to study the effects of the shadow effect at a co-located wave-wind farm was described. Finally, the results obtained from this work were presented and discussed.

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. 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 the following years to make co-located farms becoming a reality.

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.

7. ACKNOWLEDGMENTS

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