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8 Hybrid Wave and Offshore Wind Farms: a Comparative Case Study of Co-located Layouts

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16  
17  
18 **Abstract**

19  
20 Marine energy is one of the most promising alternatives to fossil fuels due to the enormous energy  
21 resource available. However, it is often considered uneconomical and difficult. Co-located offshore wind  
22 turbines and wave energy converters have emerged as a solution to increase the competitiveness of marine  
23 energy. Among the benefits of co-located farms, this work focuses on the shadow effect, i.e. the reduction  
24 in wave height in the inner part of the farm, which can lead to significant savings in operation and  
25 maintenance (O&M) costs thanks to the augmented weather windows for accessing the wind turbines. The  
26 aim of this study is to quantify the wave height reduction achieved within a co-located wave-wind farm.  
27 Different locations and a large number of layouts are analysed in order to define the optimum disposition.

28 **Keywords:** Wave energy; Wind energy; Co-located wind–wave farm; Weather windows for O&M;  
29 Shadow effect; Wave height.

30

31

## 32 **1. Introduction**

33 If wave energy is to become a viable alternative to fossil fuels, its competitiveness must be enhanced.  
34 Combining this promising marine renewable with a more consolidated renewable like offshore wind  
35 energy is a solution of great interest [1]. According to the degree of connectivity between the offshore  
36 wind turbines and Wave Energy Converters (WECs) combined wave-wind systems can be classified into:  
37 co-located, hybrid and islands systems [2]. According to the current state of development of both  
38 technologies, the co-location of WECs into a conventional offshore wind farm is regarded as the best  
39 option [2], which combines an offshore wind farm and a WEC array with independent foundation systems  
40 but sharing: the same marine area, grid connection, O&M equipment, etc.

41 There are many synergies between both renewables [3], such as the more sustainable use of the marine  
42 resource, the reduction in the intermittency inherent to renewables or the opportunity to reduce costs by  
43 sharing some of the most expensive elements of an offshore project. In addition to these powerful reasons  
44 there are a number of technology synergies between wave and wind systems which make their  
45 combination even more attractive, and this paper focuses on one of them: the so-called shadow effect, i.e.  
46 the reduction of the significant wave height in the inner part of the farm. The operational limit of  
47 workboats (the most cost-effective access system for maintenance tasks) is a significant wave height of 1.5  
48 m [4]; when this threshold is exceeded delays in maintenance and repairs ensue, increasing downtime –  
49 with the associated costs. Thus, while modern onshore wind turbines present accessibility levels of 97%  
50 [5], this level can be significantly reduced in offshore installations .

51 On this basis, the aim of this study is to analyse the wave height reduction achieved by deploying co-  
52 located WECs and the influence of the layout in the results. This purpose is carried out through various  
53 cases studies. First, a number of hypothetical co-located farms are analysed in the Wave Hub area. Second,  
54 a real wind farm, Alpha Ventus, is considered in order to obtain more realistic conclusions. Finally, the

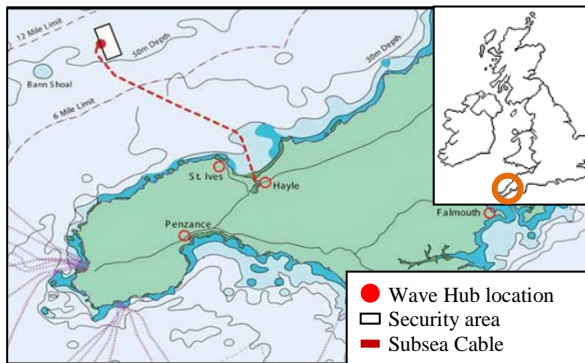
55 study extends to three other wind farms currently in operation (Bard 1, Horns Rev 1 and Lincs) to compare  
 56 the results obtained for each site and draw general conclusions about the benefit of co-located farms and  
 57 the optimum layouts. A state-of-the-art, third generation wave propagation model (SWAN) implemented  
 58 on a high-resolution computational grid is applied and real sea conditions are considered.

59

## 60 2. Methodology

### 61 2.1. Preliminary Case Study

62 This case study was carried out for a hypothetical wind farm at the Wave Hub site, an offshore renewable  
 63 energy (ORE) test centre 20 km to the northwest of St Ives Bay, in SW England (Figure 1).



64 Figure 1. Wave Hub location [6].

66 The water depth at the test site ranges between 40 and 60 m [7]. As regards the sea climate, three wave  
 67 conditions were defined (Table 1) on the basis of the most recent available data [8].

69 Table 1. Case Study (CS):  $H_s$  = significant wave height;  $T_p$  = peak period;  $\theta$  = mean wave direction.

CS	$H_s$ (m)	$T_p$ (s)	$\theta$ (°)
1	1.5	7.57	270
2	2.5	8.14	270
3	3.5	9.33	270

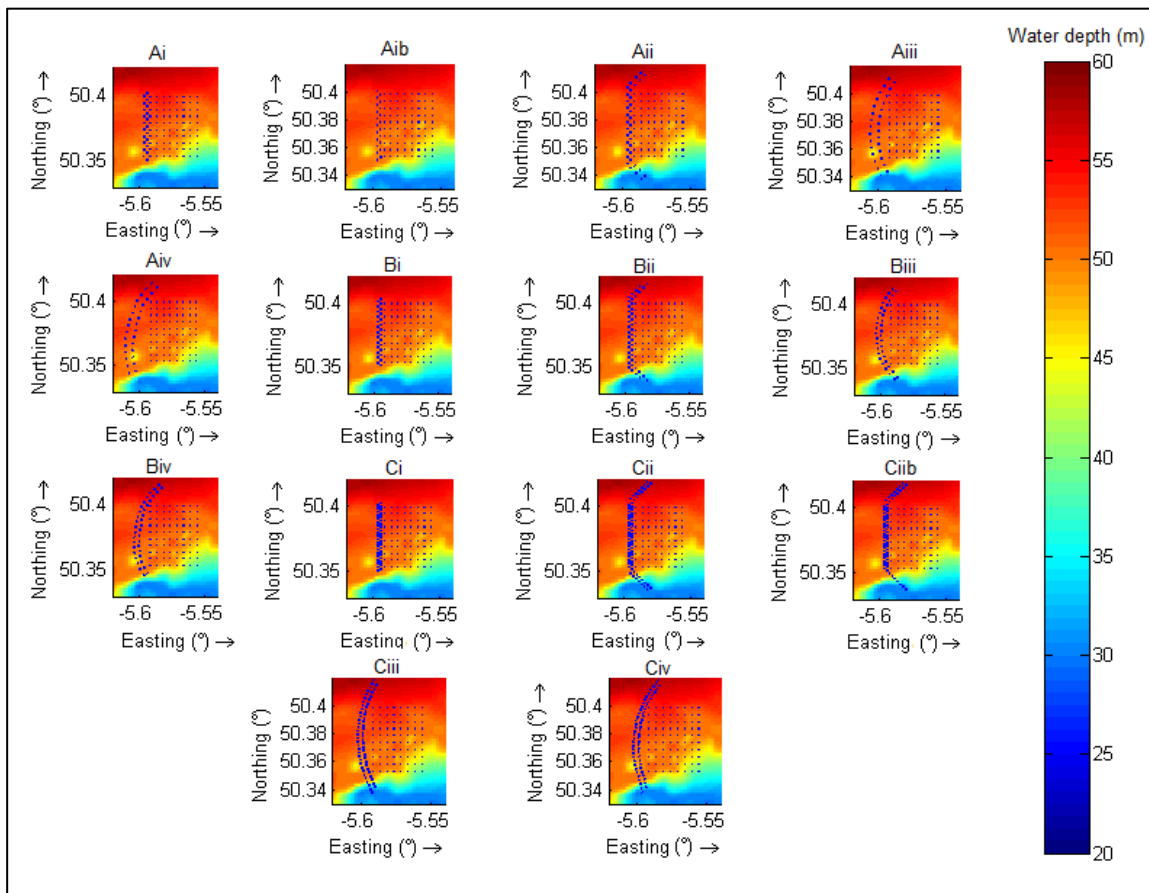
70

71 The wind farm layout is based on that of Horns Rev 1, with 80 turbines (Vestas V80-2MW) erected on a  
72 grid with 10 rows. The spacing between adjacent turbines and rows is 560 m [9]. Thus, the proposed wind  
73 farm would occupy a total area of approximately 20 km<sup>2</sup> with an average water depth of 50 m. The  
74 substructure of the wind turbines is jacket-frames of 18 m x 18 m. The wind farm is staggered and  
75 orientated taking into account the main wind direction in the area in order to maximise the energy output.

76 Having defined the wind farm layout, a Peripherally Distributed Array (PDA) was selected for the co-  
77 location of the WECs. The PDA is a type of co-located system which combines both wind and wave  
78 arrays by positioning the WECs at the periphery of the offshore wind farm.

79 The WEC used in this case study, and in the following cases, is WaveCat: a floating offshore WEC whose  
80 principle of operation is wave overtopping, and with a length overall of 90 m. The minimum distance  
81 between devices is  $2.2D$ , where  $D = 90$  m is the distance between the twin bows of a single WaveCat  
82 WEC [10, 11].

83 14 wave farm configurations were proposed: 3 basic layouts (named A, B, C) with different spacing  
84 between devices: configuration A, with a spacing between WECs equal to that between turbines, 560 m;  
85 configuration B, with a smaller spacing, 345 m; and configuration C, with the minimum spacing allowed,  
86 198 m. For each of these basic configurations, different layouts were considered (Figure 2): (i) two rows of  
87 devices along the west side of the wind farm; (ii) two rows along the west side plus two additional rows of  
88 devices along the north and south sides, at an angle of 45°; (iii) two rows of devices forming an arch; and  
89 (iv) two rows of devices along an arch rotated 11° clockwise. These configurations were used to  
90 investigate the influence of the layout on the wave characteristics within the wind farm, and more  
91 specifically the influence of the spacing between devices and the addition of new lateral rows of devices to  
92 intercept waves from secondary directions (NW and SW), and to ascertain whether an arch layout can  
93 achieve a similar wave height reduction to an angular layout with fewer WECs.



94

95 Figure 2. Co-located farms at the Wave Hub site: configurations  $A_i$  to  $C_{iv}$ .

96

## 97 2.2. Realistic Case Study

97

98 Next, the shadow effect provided by co-located WECs added to an existing wind farm, Alpha Ventus, was  
 99 investigated using one year's worth of buoy data (from January 2013 to December 2013) from the FINO1  
 100 research platform, only 400 m away from the farm (Figure 3) [12]. This park lies about 45 km north of the  
 101 island of Borkum (Germany), in water depths of approx. 30 m [13]. The Alpha Ventus wind farm is  
 102 composed by 12 turbines: 6 AREVA turbines with a tripod substructure and 6 Repower 5M turbines with  
 103 a jacket-frame substructure with a spacing between turbines of around 800 m [14]. In this case, 15 wind-  
 104 wave farms configurations were tested (Table 2, Figure 4) characterised by different spacing between  
 105 WECs, disposition and number of devices ( $N_{WECs}$ ).

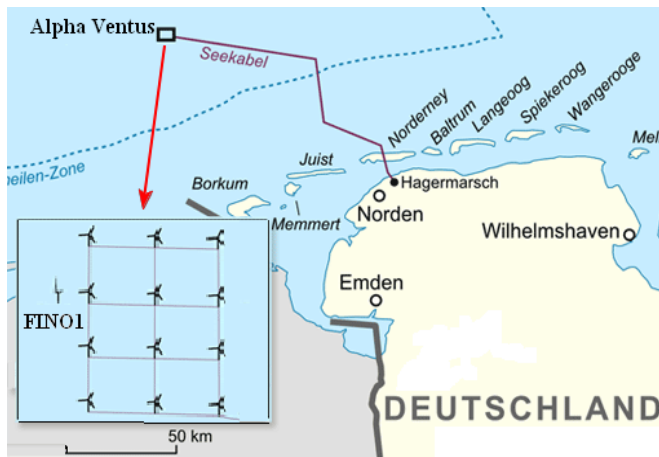
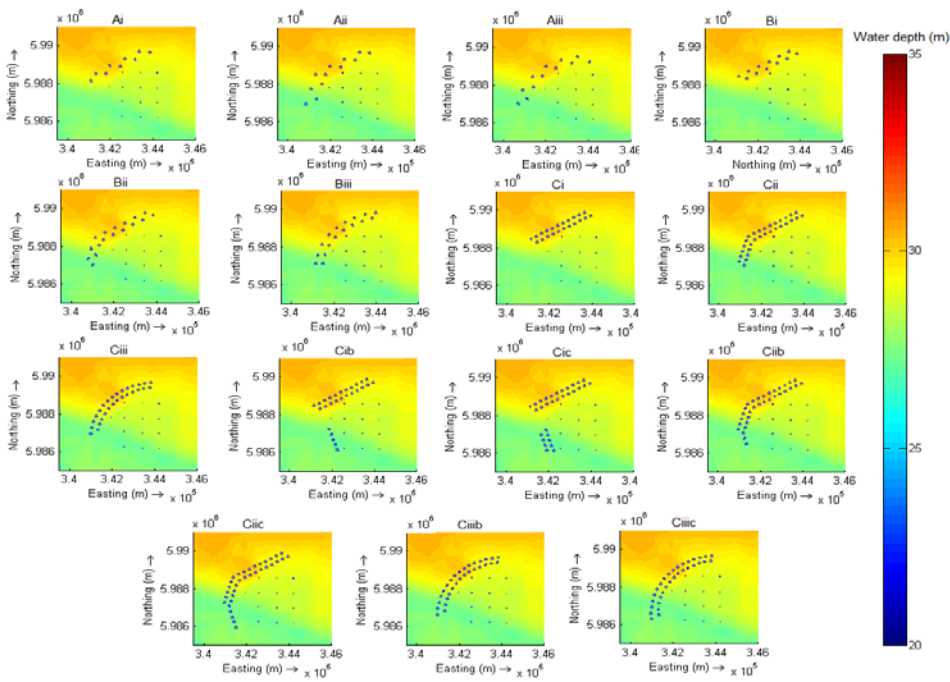


Figure 3. Alpha Ventus location [12].

Table 2. Characteristics of the WEC layouts

Spacing	Name	$N_{WEC}$	Short description
750 m	A <sub>i</sub>	9	Two rows to the NW.
	A <sub>ii</sub>	12	Two rows to the NW and two more rows to the W.
	A <sub>iii</sub>	12	Arch to the NW.
450 m	B <sub>i</sub>	12	Two rows to the NW.
	B <sub>ii</sub>	17	Two rows to the NW and two more rows to the W.
	B <sub>iii</sub>	17	Arch to the NW.
198 m	C <sub>i</sub>	22	Two rows to the NW
	C <sub>ii</sub>	30	Two rows to the NW and two more rows to the W.
	C <sub>iii</sub>	28	Arch to the NW.
198 m	C <sub>ib</sub>	27	Two rows to the NW and one more row to the SW of the farm constituted by 5 additional WECs.
	C <sub>ic</sub>	31	Two rows to the NW and two more rows to the SW of the farm constituted by 9 additional WECs.
	C <sub>iib</sub>	32	Two rows to the NW and two to the W (2 additional WECs).
	C <sub>iic</sub>	34	Two rows to the NW and two to the W (4 additional WECs).
	C <sub>iiib</sub>	30	Arch to the NW (2 additional WECs).
	C <sub>iiic</sub>	32	Arch to the NW with 4 additional WECs.



109

110 Figure 4. Co-located wave-wind farm layouts in Alpha Ventus (configurations A<sub>i</sub> to C<sub>iiic</sub>) and water depth  
 111 (m).

112 **2.3. Comparative Study**

113 The results of the previous study of AlphaVentus were taken as a reference for three further cases,  
 114 corresponding to as many wind farms currently in operation: Bard 1, Horns Rev 1 and Lincs, whose  
 115 locations and characteristics are presented in Figure 5 and Table 3, respectively. These four wind farms  
 116 encompass a wide variety of characteristics on which to establish a comparative analysis.

117



118 Figure 5. Location of the four wind farms used in this study: Alpha Ventus, Bard 1, Horns Rev 1 and  
 119 Lincs.  
 120  
 121  
 122

123 Table 3. Characteristics of the wind farms

Wind farm	Depth (m)	Distance from shore (km)	Installed capacity (MW)	Number turbines	Area (km <sup>2</sup> )
Alpha Ventus	33-45	56	60	12	4
Bard 1	39-41	90-101	400	80	59
Horns Rev 1	6-14	14-20	160	80	21
Lincs	8-16	8	270	75	41

124  
125 Alpha Ventus and Horns Rev have been characterised previously. For their part, Bard 1 is composed of 80  
126 5 MW turbines (Bard 5.0) on tripod substructures [15], and Lincs of 75 3.6 MW Siemens turbines on  
127 monopiles [16]. In Alpha Ventus and Horns Rev 1 the wind turbines are arranged on a Cartesian grid,  
128 whereas in Bard 1 and Lincs they are not organised in clearly defined rows, and the distance between  
129 turbines varies in each case. As regards the sea climate, wave buoy measurements were used, and the main  
130 wave climate parameters are shown in Table 4:  $H_s$  is the significant wave height,  $T_{m01}$  the mean wave  
131 period,  $\theta$  the mean wave direction,  $U_w$  the most frequent wind speed at 10 m, and  $D_w$  the corresponding  
132 wind direction.

133  
134 Table 4. Wave and wind conditions at the wind farm site.

Wind farm	$H_s$ (m)	$T_{m01}$ (s)	$\theta$ (°)	$U_w$ (ms <sup>-1</sup> )	$D_w$ (°)
Alpha Ventus	1.5	4.6	330	10	210-240
Bard 1	0.8-1.5	4.0	320	9.2	330
Horns Rev 1	0.8-1	4-4.6	230-340	9.7	225-315
Lincs	0.6-0.7	3.4-4.4	0-15	8.4	10-70

135  
136 Two co-located WECs layouts (Table 5) were proposed taking into account the wind farm layouts, the  
137 wave climate, and the results of previous studies. In the first case (Figure 6), the co-located WECs  
138 configuration consists of two main rows of WECs with a spacing of 198 m orientated towards the  
139 prevailing wave direction, and other rows of WECs at an angle of 45° to face secondary wave directions  
140 and thus protect a larger wind farm area. With the second configuration (Figure 7) the aim is to check if



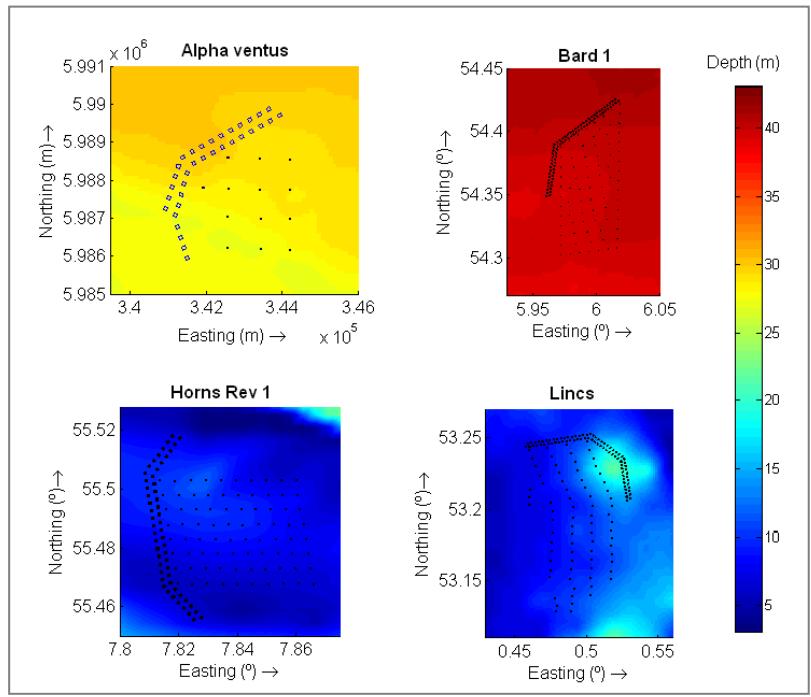
141 deploying WECs in an arch can lead to a wave height reduction similar to that obtained with an angular  
 142 layout with fewer WECs.

143

144 Table 5. Total number of co-located WECs and the rate between the total number of WECs and wind  
 145 turbines ( $r$ ).

Wind farm	Layout in angle		Layout in arch	
	Total	$r$	Total	$r$
Alpha Ventus	34	2.8 3	32	2.6 7
Bard 1	79	0.9 9	79	0.9 9
Horns Rev 1	55	0.6 9	53	0.6 6
Lincs	81	1.0 1	80	1

146



147  
 148 Figure 6. Co-located wind farm layouts with WECs at an angle.  
 149

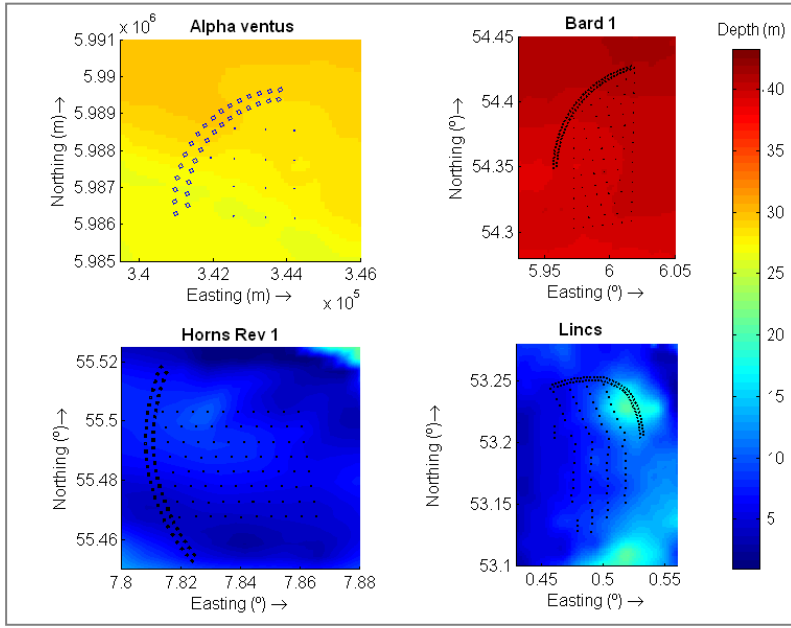


Figure 7. Co-located wind farms layouts with WECs in arch.

## 2.4. The Wave Propagation Model

The assessment of the wave height reduction in the wind farm caused by the co-located WECs was carried out using a third-generation numerical wave model, SWAN (Simulating Waves Nearshore), which was successfully used in previous works (e.g. [17-19]) to model the impact of a wave farm on nearshore wave conditions. The evolution of the wave field is described by the action balance equation, Eq. (1), which equates the propagation of wave action density in each dimension balanced by local changes to the wave spectrum:

$$\frac{\partial}{\partial t} N + \frac{\partial}{\partial x} c_x N + \frac{\partial}{\partial y} c_y N + \frac{\partial}{\partial \sigma} c_\sigma N \frac{\partial}{\partial \theta} c_\theta N = \frac{S_{tot}}{\sigma} \quad (1)$$

where  $t$  is time (s),  $c_x$  and  $c_y$  are spatial velocities in the  $x$  and  $y$  components ( $\text{ms}^{-1}$ ),  $c_\theta$  and  $c_\sigma$  are rates of change of group velocity which describe the directional ( $\theta$ ) rate of turning and frequency ( $\sigma$ ) shifting due to changes in currents and water depth,  $N$  is wave action density spectrum, and  $S_{tot}$  is the energy density source terms which describe local changes to the wave spectrum.

164 In this work the model was implemented in the so-called nested mode, with two computational grids  
 165 (Table 6) in order to obtain high-resolution results without excessive computational cost. The bathymetric  
 166 data, from the UK's data centre Digimap, were interpolated onto this grid.

167 Table 6. Surface area covered by the computational grids and grid size.

Wind farm	Coarse grid		Nested grid	
	Area (km)	Resolution (m)	Area (km)	Resolution (m)
Alpha Ventus	40 × 30	100 × 100	8.5 × 8.5	17 × 17
Bard 1	111 × 111	222 × 222	18 × 22	40 × 40.4
Horns Rev1	42 × 32	70 × 80	9.35 × 9	17 × 20
Lincs	119 × 111	170 × 159	14.4 × 18.2	32 × 33

168  
 169 The wind turbines were represented in the model by a transmission coefficient, whose value can vary in  
 170 theory from 0% (i.e., 100% of incident wave energy absorbed) to 100%. This technique was used in  
 171 previous studies to represent single wind turbines [20] or wind farm arrays [21], and arrays of WECs [22].  
 172 In this study, the transmission coefficient of the offshore wind turbines was calculated by [23]:

$$173 \quad c_t = 4 \left( \frac{d}{H_i} \right) E \left[ -E + \sqrt{E^2 + \frac{H_i}{2d}} \right] \quad (2)$$

$$174 \quad E = \frac{C_d \left( \frac{b}{D+b} \right)}{\sqrt{1 - \left( \frac{b}{D+b} \right)^2}} \quad (3)$$

175 where  $d$  is depth (m),  $H_i$  is incident significant wave height (m),  $D$  is the pile diameter (m),  $b$  is the pile  
 176 spacing (m), and  $C_d$  is the drag coefficient of the piles (1.0 for a smooth pile).

177 As for the co-located WECs, the WEC used was the WaveCat, and its wave transmission coefficient was  
 178 implemented into the wave propagation model based on the laboratory tests reported by Fernandez,  
 179 Iglesias [11].

## 180 2.5. Impact Indicators

181 To compare the results achieved in the proposed co-located farms a series of impact indicators were  
 182 defined: (i) the significant wave Height Reduction within the Farm ( $HRF$ ), (ii) the significant wave Height

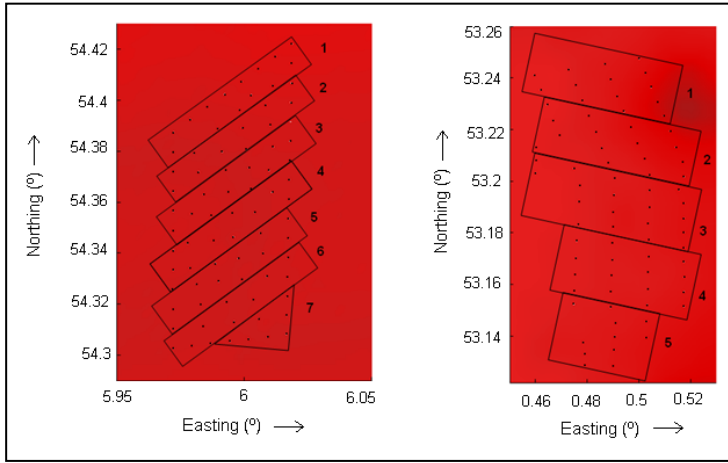
183 Reduction within the  $j$ -th Area of wind turbines ( $HRA_j$ ), and (iii) the increase in access time for O&M  
 184 ( $\Delta T_{O\&M}$ ). The  $HRF$  and  $HRA_j$  indices provide information about the average wave height reduction within  
 185 the wind farm and the wave recovery with increasing distance from the WECs, respectively, and were  
 186 calculated by

$$HRF (\%) = \frac{100}{n} \sum_{i=1}^n \frac{1}{(H_{s,b})_i} [(H_{s,b})_i - (H_{s,w})_i] \quad (4)$$

187  
 188 where the index  $i$  designates a generic turbine of the wind farm,  $n$  is the total number of turbines,  $(H_{s,b})_i$  is  
 189 the significant height incident on the  $i$ -th turbine in the baseline scenario (without WECs), and  $(H_{s,w})_i$  is  
 190 the significant height incident on the  $i$ -th turbine with co-located WECs.

$$HRA_j (\%) = \frac{100}{m} \sum_{i=1}^m \frac{1}{(H_{s,b})_i} [(H_{s,b})_i - (H_{s,w})_i] \quad (5)$$

191  
 192 where the index  $i$  denotes a generic turbine of the  $j$ -th area of the wind farm, and  $m$  is the number of  
 193 turbines in the  $j$ -th area. In the case of Alpha Ventus and Horns Rev 1 each  $j$ -th area corresponds to a  
 194 vertical row of turbines numbered from east to west,  $j = 1, 2, 3$  in Alpha Ventus and  $j = 1, 2 \dots 10$  in Horns  
 195 Rev 1. However, in the other two wind farms, due to the less orderly layout, the division was made into  
 196 different areas with a similar number of turbines, and numbered according to the mean wave direction  
 197 (Figure 8).  
 198



199 Figure 8. The  $j$ -th areas into which Bard 1 (left) and Lincs (right) were divided to calculate the  $HRA_j$  index.

200  
201 The  $\Delta T_{O\&M}$  non-dimensional index allows the assessment of the increase in the timeframe accessibility to  
202 the wind turbines thanks to the co-located WECs, and can be computed from

$$204 \quad \Delta T_{O\&M}(\%) = \frac{T_W - T_b}{T_W} \times 100 \quad (6)$$

205 where  $T_W$  and  $T_b$  are the total number of hours per year when  $H_s$  within the wind farm is lower or equal to  
206 1.5 m with co-located WECs and in the baseline scenario, respectively.

### 207 3. Results and Discussion

#### 208 3.1. Preliminary Study

209 As regards the wave height reduction (Table 7), a value of  $HRF$  between 12% ( $A_{ib}$ ) and 24% ( $C_i$ ) was  
210 obtained for the configurations  $X_i$ , with  $X=A, B, C$ . In the case of 560 m as spacing between devices, two  
211 situations were analysed ( $A_i$  and  $A_{ib}$ ) in order to evaluate the difference between aligning the devices of  
212 the first or second row with the wind turbines.  $HRF$  values were higher in the first case ( $A_i$ ), and therefore  
213 this arrangement was retained for all the other layouts.

214

215

216

217 Table 7. *HRF* (%) values for case studies CS1, CS2 and CS3 and configurations A<sub>i</sub> to C<sub>iv</sub>.

Configuration	CS1	CS2	CS3
A <sub>i</sub>	13	13	13
A <sub>ib</sub>	12	12	12
B <sub>i</sub>	16	16	16
C <sub>i</sub>	24	24	24
A <sub>ii</sub>	14	14	14
B <sub>ii</sub>	18	18	18
C <sub>ii</sub>	26	26	26
C <sub>iib</sub>	25	25	25
A <sub>iii</sub>	11	11	11
B <sub>iii</sub>	17	17	17
C <sub>iii</sub>	25	25	25
A <sub>iv</sub>	15	15	15
B <sub>iv</sub>	17	17	17
C <sub>iv</sub>	27	27	28

218 The configurations with two more rows of 7 WECs at an angle of 45° (X<sub>ii</sub>, with X=A, B, C) led to higher  
 219 *HRF* values than the corresponding X<sub>i</sub> configurations, increasing the wave reduction by 6-8%. Indeed, a  
 220 barrier of WECs to the northwest and southwest of the farm is essential to intercepting the waves from  
 221 these directions, and to retard wave regeneration within the farm. As regards the layout with the smallest  
 222 spacing, 198 m (C<sub>ii</sub>), the average *HRF* value was 26% for C<sub>ii</sub> and 25% C<sub>iib</sub>, indicating that that the second  
 223 row to the south does not contribute to the wave height reduction, and therefore is not worth being  
 224 included.

225 In the X<sub>iii</sub> configurations, with an arched WEC layout, *HRF* values were a little lower than in the X<sub>ii</sub>  
 226 configurations. The explanation may lie in the reduction of the number of converters and in the fact that  
 227 NW waves are not well intercepted. However, when the arch was rotated (X<sub>iv</sub> configurations) the highest  
 228 value of *HRF* was obtained – the C<sub>iv</sub> configuration, with an average value of *HRF* of 27%. This could be  
 229 caused by the refraction of the waves in the vicinity of the wind farm, veering from west to northwest.

230 In brief, the greatest wave height reduction was obtained for the minimum spacing between devices – *HRF*  
 231 values are around 50% greater than those achieved in the configurations with the maximum spacing.

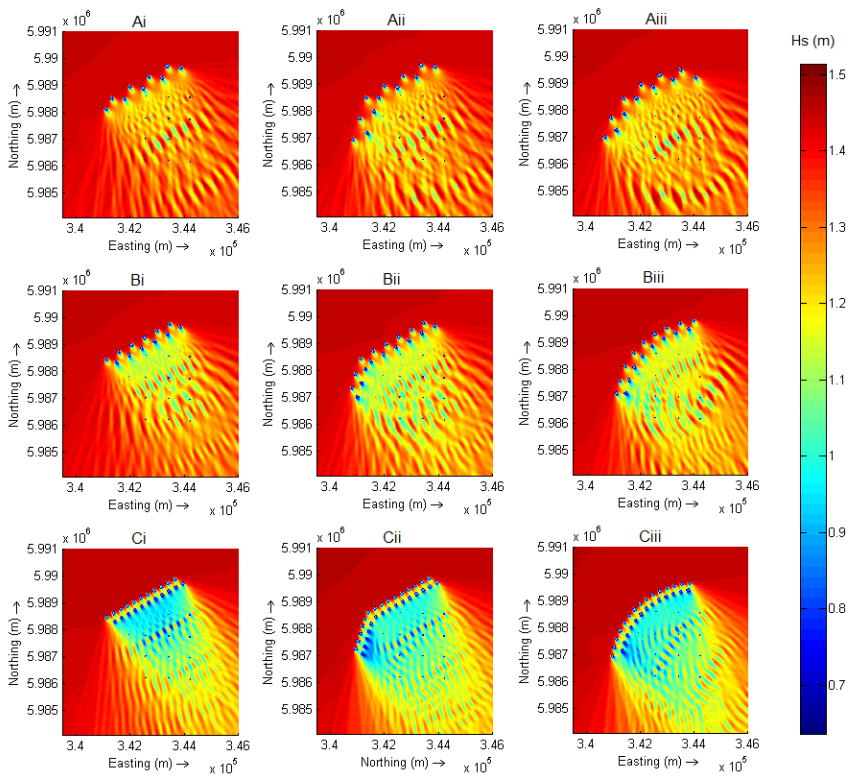
Moreover, deploying WECs not only along the W side of the farm but also along its SW and NW sides reduces the wave height by more than 13%. Finally, arched configurations require fewer WECs for equivalent levels of wave height reduction.

### 3.2. Realistic Case Study

First, the results obtained from the nearshore wave propagation model were successfully validated with the wave data from the FINO1 platform, as demonstrated by the values obtained for the coefficient of determination ( $R^2$ ) and the Root Mean Square Error ( $RMSE$ ):  $R^2 = 0.95$  and  $RMSE = 0.36$  m.

Having validated the numerical model, it was used to analyse the shadow effect caused by the 9 basic wind-wave farm layouts ( $A_i$  to  $C_{iii}$ ). First, the prevailing sea climate was considered in these simulations – Case Study 1 (CS1):  $H_s = 1.5$  m,  $T_p = 6.5$  m and  $\theta = 330^\circ$  – to draw initial conclusions about the configuration that would maximise the weather windows for O&M. Second, and to cover the secondary wave direction, the same simulations were carried out but considering southwesterly waves – CS2:  $H_s = 1.5$  m,  $T_p = 6.5$  m and  $\theta = 250^\circ$ .

The results are shown graphically in Figure 9 and 10, and numerically in Table 8. Comparing the different layouts, there was a small difference between configurations  $X_{ii}$  and  $X_{iii}$ , whereas poorer results were obtained for the configurations  $X_i$ . Regarding the influence of the spacing between devices, the configurations  $C_x$  led to the largest reductions. Based on these assessments and with the objective of a better protection from W and SW waves, 6 new configurations ( $C_{ib,c}$ ,  $C_{iib,c}$  and  $C_{iiib,c}$ ) were analysed, consisting in variants of  $C_x$  layouts.

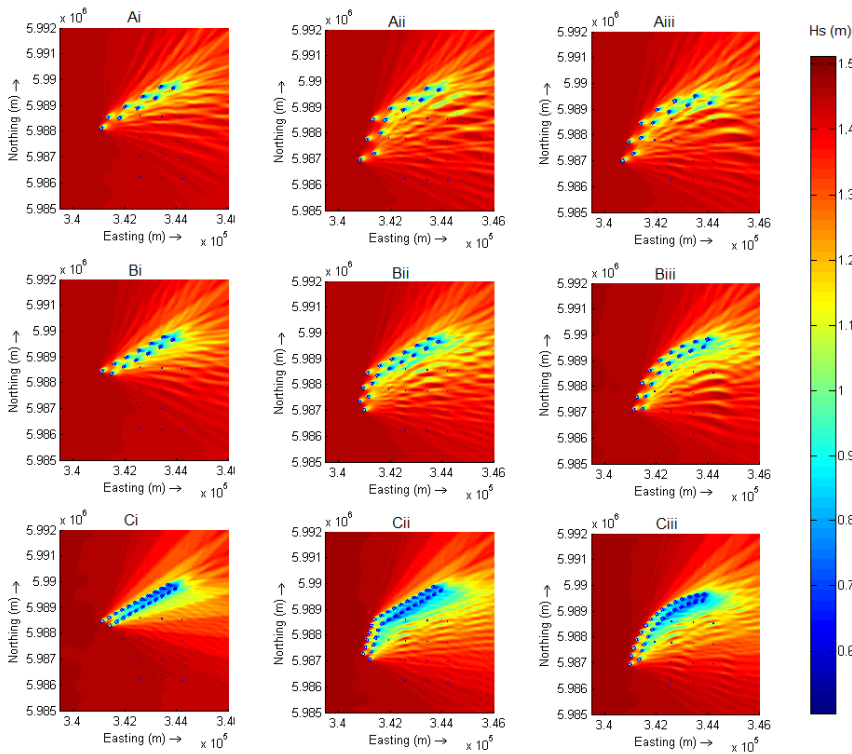


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Figure 9. Wave height reduction within the wind farm (*HRF*) for  $H_s = 1.5$  m,  $T_p = 6.5$  m and  $\theta = 330^\circ$  and configurations  $A_i$  to  $C_{iii}$ .



254

255

256

Figure 10. Wave height reduction within the wind farm (*HRF*) for  $H_s = 1.5$  m,  $T_p = 6.5$  m and  $\theta = 250^\circ$  and configurations  $A_i$  to  $C_{iii}$ .



257 Table 8. *HRF* (%) values for CS1 ( $H_s = 1.5$  m,  $T_p = 6.5$  m,  $\theta = 330^\circ$ ) and CS2 ( $H_s = 1.5$  m,  $T_p = 6.5$  m,  $\theta =$   
 258  $250^\circ$ ), and configurations A<sub>i</sub> to C<sub>iii</sub>.

Configuration	$N_{WECs}$	<i>HRF</i> (%)			
		CS1	CS2	Weighted average	
A	A <sub>i</sub>	9	12	2	9
	A <sub>ii</sub>	12	13	6	11
	A <sub>iii</sub>	12	13	4	11
B	B <sub>i</sub>	12	14	4	11
	B <sub>ii</sub>	17	16	9	14
	B <sub>iii</sub>	17	16	8	14
C	C <sub>i</sub>	22	25	5	19
	C <sub>ii</sub>	30	27	10	22
	C <sub>iii</sub>	28	26	13	22

259 In view of the results (Table 9), *HRF* is greater in the new layouts proposed than in the basic cases – C<sub>i</sub>, C<sub>ii</sub>  
 260 and C<sub>iii</sub>. This is due to the better interception not only of southwesterly waves but also of northwesterly,  
 261 due to the superposition of the shadow effects generated by each individual WEC. The maximum  
 262 reduction was obtained for the configuration C<sub>iiic</sub> (*HRF*= 25%), i.e. the configuration with two rows at an  
 263 angle of 45° and four additional WECs with respect to C<sub>ii</sub>. Configuration C<sub>ic</sub> seems to be a good  
 264 configuration; however, this result is slightly misleading in that it does not reflect the significant  
 265 differences in wave exposure within the farm – indeed, this configuration leaves the wind turbines in the  
 266 northwestern sector of the farm exposed to westerly waves.

267 To sum up, the lower the spacing between devices, the largest the *HRF* values, and therefore C<sub>x</sub>  
 268 configurations generally lead to larger reductions in wave height. Among them, the configurations C<sub>i</sub>, C<sub>ib</sub>  
 269 and C<sub>ic</sub> should be discarded since they leave part of the wind farm unprotected. On the basis of the results,  
 270 the configurations C<sub>iiic</sub> and C<sub>iiic</sub>, with *HRF* = 25% and 23% respectively, were selected for further analysis  
 271 considering the annual data series from January to December 2013. Moreover, *HRF* values considering the  
 272 annual data series were also obtained for C<sub>ii</sub> and C<sub>iii</sub> in order to examine whether adding WECs to the SW  
 273 of the wind farm is worthwhile. The maximum value of *HRF* achieved was 18%, which corresponds to the  
 274 configuration C<sub>iiic</sub> (Table 10). However, the arched configuration C<sub>iiic</sub> yielded a similar wave height

275 reduction, even though this configuration has 2 fewer WECs than  $C_{iic}$ , which is interesting for a future  
 276 analysis in terms of the total cost. Moreover, it was observed that in both cases – configurations with two  
 277 rows at an angle and in arch – the addition of 4 WECs to the SW increases the reduction by almost two  
 278 points.

279 Table 9. *HRF* (%) values for CS1 ( $H_s = 1.5$  m,  $T_p = 6.5$  m,  $\theta = 330^\circ$ ) and CS2 ( $H_s = 1.5$  m,  $T_p = 6.5$  m,  $\theta =$   
 280  $250^\circ$ ) and configurations  $C_i$  to  $C_{iiic}$ .

Configuration	$N_{WECs}$	<i>HRF</i> (%)		
		CS1	CS2	Weighted average
i	$C_i$	22	25	19
	$C_{ib}$	27	28	23
	$C_{ic}$	31	29	25
ii	$C_{ii}$	30	27	22
	$C_{iib}$	32	29	24
	$C_{iic}$	34	29	25
iii	$C_{iii}$	28	26	22
	$C_{iiib}$	30	27	23
	$C_{iiic}$	32	27	23

281 Table 10. *HRF* (%) values for the annual serie Data and configurations  $C_{ii}$  to  $C_{iiic}$ .

Configuration	$N_{WECs}$	<i>HRF</i> (%)
$C_{ii}$	30	16
$C_{iic}$	34	17
$C_{iii}$	28	16
$C_{iiic}$	32	17

283 As for the assessment of the augmented weather windows for O&M with co-located WECs, the  
 284 operational limit for workboats is a significant wave height of 1.5 m. Therefore, the total number of hours  
 285 when  $H_s \leq 1.5$  m was quantified for the study period (Table 11). In the baseline scenario (a standalone  
 286 wind farm) the total number of hours when  $H_s \leq 1.5$  m ( $T$ ) was 5916 h, which represents 67.5% of the year.  
 287 With the co-located layouts analysed, this value was significantly increased (Table 11). According to the  
 288 results of the *HRF* assessment, the best scenario was obtained for configuration  $C_{iic}$ , with an increase in the  
 289 accessibility to the turbines ( $\Delta T_{O\&M}$ ) of approximately 20%. The arched configuration  $C_{iiic}$  shows a very

similar increase with 2 WECs fewer (17.8%). In both cases, the accessibility was above 82%, which is the reference value to maintain the wind farm availability above 90% [24].

Table 11.  $T_{WECs}$ , accessibility and  $\Delta T_{O\&M}$  for configurations  $C_{ii}$ ,  $C_{iic}$ ,  $C_{iii}$ ,  $C_{iiic}$ .

Configuration	$T_{WECs}$ (h)	Accessibility(%)	$\Delta T_{O\&M}$ (%)
$C_{ii}$	7074	80.8	16.4
$C_{iic}$	7212	82.3	18.0
$C_{iii}$	6840	78.1	13.5
$C_{iiic}$	7200	82.2	17.8

The best results were obtained for the configurations with smaller spacing between devices and WECs facing not only the main wave direction (W) but also the secondary wave directions (NW and SW), for these provide a similar wave height reduction in the entire wind farm area. Furthermore, it is worth pointing out that, although the greatest level of accessibility to the wind turbines was obtained for the configuration with WEC rows at an angle, the arched configuration achieved a similar value, despite having two WECs less, which could be an interesting aspect for a future study into cost-effectiveness.

### 3.3. Comparative Study

The proper functioning of the nearshore wave propagation model was validated with wave buoy data. In all cases, a good correlation was observed between the simulated and measured time series, as shown by the values of  $R^2$  and  $RMSE$ , always higher than 0.93 and lower than 0.36 m, respectively.

As regards the wave height reduction achieved throughout the farm ( $HRF$ ), it ranged between 13% and 19% (Table 12) and was always larger for the layouts with WECs deployed at an angle than for those in arch, although the difference between the results of both configurations was small (between 1 and 2%).

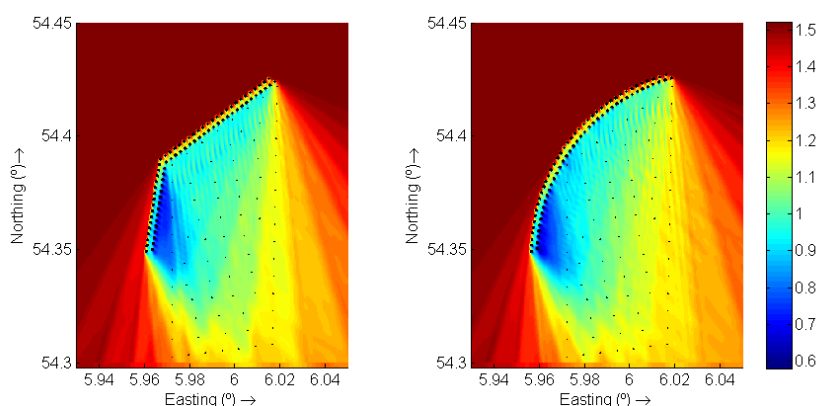
Comparing the results between wind farms (Table 12), the best values were obtained for Bard 1, where a good interception of the incoming waves was achieved for the two layouts of co-located farms (Figure 11). These results were followed very closely by those obtained for Alpha Ventus and Horns Rev 1, whereas the wave height reduction achieved at Lincs was smaller. This was due to three main factors. First, the wind farm layout – this farm has a slightly elongated shape. Second, the wave direction has a greater

311 variability than in the other case studies, and the farm remained unprotected against waves from secondary  
 312 directions (Figure 12). For this reason a larger number of WECs would be required on the east side of the  
 313 farm to achieve better results; however, this would imply an important increase in the ratio between the  
 314 number of WECs and wind turbines, raising the final cost of the co-located farm. Third, the wave climate  
 315 in this park, which was milder than in the other farms and, therefore, less wave energy could be extracted  
 316 by the co-located WECs.

317 Table 12. *HRF* (%) values achieved with co-located WECs deployed in angle or in arch based on the  
 318 annual data series

Wind farm	Layout	$N_{WECs}$	<i>HRF</i> (%)
Alpha Ventus	in angle	34	18
	in arch	32	17
Bard 1	in angle	79	19
	in arch	79	17
Horns Rev 1	in angle	55	17
	in arch	53	15
Lincs	in angle	81	14
	in arch	80	13

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Figure 11. Wave height reduction obtained with co-located WECs at Bard 1 under a sea state with:  $H_s = 1.71$  m,  $T_p = 6.09$  s and  $\theta = 230^\circ$ . The colour scale represents the significant wave weight,  $H_s$  (m).

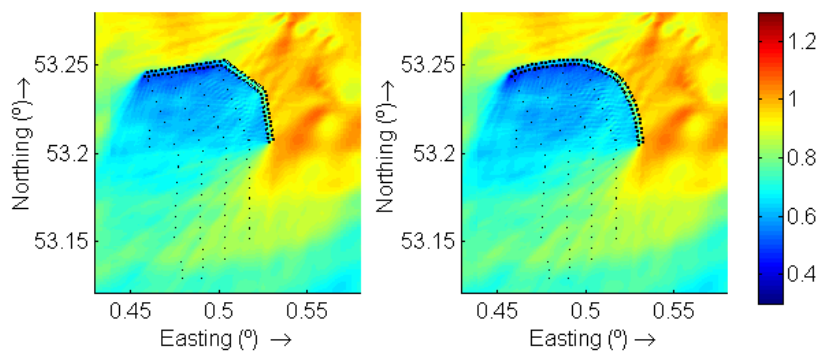


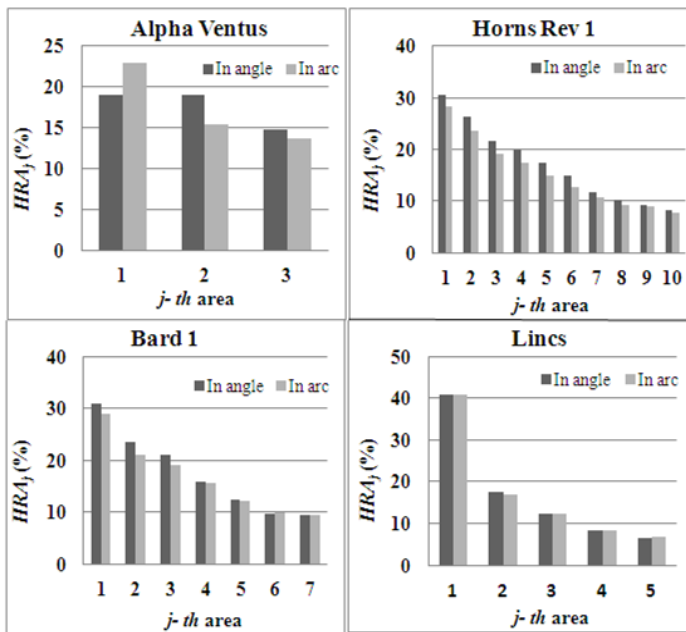
Figure 12. Wave height reduction due to co-located WECs at Lincs under a sea state with:  $H_s = 1.18$  m,  $T_p = 6.03$  s and  $\theta = 60^\circ$ . The colour scale represents the significant wave weight,  $H_s$  (m).

Furthermore, the results of Horns Rev 1 are particularly interesting since they were similar to those of the best scenario, even though the ratio between number of WECs and wind turbines in Horns Rev 1 is much lower than in the other cases – an important consideration for the economic assessment. The explanation lies in the geometry of the wind farms: the layout of Horns Rev 1 is close to a square, whereas Bard 1 or Lincs have a more elongated shape and therefore require more WECs for a similar degree of shelter.

Apart from the average wave height reduction in the farm ( $HFR$ ), it is interesting to analyse the spatial variation in the wave height reduction through its value in different sections ( $HRA_j$ ), since the best WECs layout should achieve not only high values of  $HFR$  but also a fairly homogenous reduction throughout the farm. As may be expected, in all case studies the tendency was for the highest reduction to occur immediately behind the WECs, with  $HRA_j$  decreasing with increasing distance from the co-located WECs (Figure 13). However, the wave height reduction was significant even as the distance from the WECs increased. As with the wave height reduction for the entire farm, greater values of  $HRA_j$  were obtained generally for configurations with WECs deployed at an angle rather than in arch. Lincs presented the highest difference between  $HRA_j$  values in the first and second area of turbines (around 23%), and was also the case with the smallest difference between the wave height reduction with co-located WECs in angle or in arch. Therefore, it may be concluded that in the case of wind farms with a milder wave climate, like Lincs, wave heights are restored more quickly behind the WEC barrier, and the choice between

346 angular or arched layouts for the co-located WECs does not have a significant influence on the  
 347 enlargement of the weather windows for O&M.

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Figure 13.  $HRA_j$  (%) values with co-located WECs deployed in angle or in arch based on the annual data series data.

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As regards the accessibility to the wind turbines, it was below 82% for all the wind farms analysed (Table 13), which corresponds to availability values below 90%. Nevertheless, an important increase of the accessibility was achieved by deploying co-located WECs along the periphery of the farm in the four case studies (Table 14). More specifically, the results for Alpha Ventus and Bard 1 were very similar, the accessibility increased ( $\Delta T_{O\&M}$ ) by 17-18%, whereas in Horns Rev 1 this increased by 13-15% and in Lincs by 8%.

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Table 13. Accessibility to the wind turbines in the baseline scenario for the annual period analysed.

Wind farm	Accessibility (%)
Alpha Ventus	67.5
Bard 1	57.0
Horns Rev 1	59.9
Lincs	74.1

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361 Table 14. Accessibility and  $\Delta T_{O\&M}$  values for the co-located farms considered.

Wind farm	Layout	Accessibility (%)	$\Delta T_{O\&M}$ (%)
Alpha Ventus	in angle	82.3	18.0
	in arch	82.2	17.8
Bard 1	in angle	69.7	18.2
	in arch	69.0	17.5
Horns Rev 1	in angle	70.9	15.6
	in arch	69.5	13.9
Lincs	in angle	81.3	8.9
	in arch	81.1	8.6

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#### 363 4. Conclusions

364 The aim of this study was to analyse and compare the wave height reduction achieved with different co-  
365 located farm layouts and find the configuration that improves the shielding effect of the WECs. To  
366 achieve this purpose a number of case studies were considered, using real wave conditions and a third-  
367 generation wave model (SWAN). First, an important wave height reduction was achieved in all cases,  
368 with significant enlargements of the weather windows for O&M. In fact, in the case of Alpha Ventus and  
369 Lincs, values around 82% were obtained for the accessibility, which would ensure an availability of the  
370 turbines of 90% or higher. With regard to the influence of the co-located farm layout on the results, the  
371 arrays with small spacing between converters achieved the best results of wave height reduction.  
372 Moreover, the best results were obtained for co-located wave arrays that face both the prevailing and  
373 secondary wave directions, either with WECs deployed in angle or arch. Concerning the influence of the  
374 wind farm location, it was found that proximity to land is not a positive factor to implement co-located  
375 WECs, since it normally implies lower water depths and a milder sea climate, and consequently there is  
376 less available wave energy to be extracted by the WECs. The wind farm layout is another key factor – the  
377 largest wave height reduction was achieved for wind farms with square like geometries and smaller  
378 spacing between wind turbines, like Horns Rev 1.

379 In sum, this work: (i) showed that the weather windows regarding wave height are increased as a result of  
380 the presence of the wave farm; and (ii) analysed the main aspects to be taken into account in deploying co-  
381 located WECs for this purpose.

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