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1 CO-LOCATED WAVE-WIND FARMS FOR IMPROVED O&M EFFICIENCY

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8 If ocean energy is to become a viable alternative to fossil fuels, its competitiveness vis-
9 à-vis other energy sources must be enhanced. Furthermore, marine space is scarce, and
10 its use should be optimised. On these grounds, the combination of offshore wind and
11 wave energy in the same marine space (co-located) holds promise. This paper focuses
12 on the benefits in terms of O&M efficiency that ensue from the so-called *shadow effect*
13 – the reduction in significant wave height in the inner part of the farm thanks to the
14 presence of the wave energy converters (WECs) – in the form of enlarged weather
15 windows. This investigation is carried out through a case study of four wind farms in
16 the North Sea, including a sensitivity analysis in terms of: (i) location (depth and
17 distance from the coast), (ii) sea climate, and (iii) wind farm layout. Real (observed) sea
18 conditions are considered, and a third-generation wave model (SWAN) is implemented
19 on a high-resolution grid. We find that the combination of wave and offshore wind
20 energy increases the accessibility for O&M tasks in all the cases considered, leading to
21 accessibility values of up to 82%.

22
23 **KEYWORDS:** Wave energy; Wind energy; Co-located wind–wave farm; Weather
24 windows for O&M; Shadow effect.

26 1. INTRODUCTION

27 Marine energy is one of the most promising alternatives to fossil fuels due to the
28 enormous energy resource available. However, it is often considered uneconomical and
29 difficult. Combining this promising marine renewable with a more consolidated
30 renewable like offshore wind energy is a solution of great interest to enhance marine
31 energy competitiveness [1]. According to the degree of connectivity between the
32 offshore wind turbines and Wave Energy Converters (WECs) combined wave-wind
33 systems can be classified into: co-located, hybrid and islands systems [2]. According to
34 the current state of development of both technologies, the co-location of WECs into a
35 conventional offshore wind farm is regarded as the best option (2009/28/EC) [3], which
36 combines an offshore wind farm and a WEC array with independent foundation systems
37 but sharing: the same marine area, grid connection, O&M equipment, etc.

38 There are many synergies between both renewables [4], such as the more sustainable
39 use of the marine resource, the reduction in the intermittency inherent to renewables or
40 the opportunity to reduce costs by sharing some of the most expensive elements of an
41 offshore project. In addition to these powerful reasons there are a number of technology
42 synergies between wave and wind systems which make their combination even more
43 attractive, and this paper focuses on one of them: the so-called shadow effect, i.e. the
44 reduction in the significant wave height in the inner part of the farm. The operational
45 limit of workboats (the most cost-effective access system for maintenance tasks) is a
46 significant wave height of 1.5 m [5]; when this threshold is exceeded delays in
47 maintenance and repairs ensue, increasing downtime – with the associated costs. Thus,
48 while modern onshore wind turbines present accessibility levels of 97% [6], this level
49 can be significantly reduced in offshore installations.

50 On this basis, the aim of this study is to analyse the wave height reduction achieved by
51 deploying co-located WECs and the influence of the layout in the results. This purpose
52 is carried out through various cases studies. Four wind farms currently in operation
53 (Alpha Ventus, Bard 1, Horns Rev 1 and Lincs) are taken as baseline scenarios to
54 analyse the influence of the wind farm characteristics, such as the location, the proximity
55 to coast and the layout, on the results obtained. A state-of-the-art, third generation wave
56 propagation model (SWAN) implemented on a high-resolution computational grid is
57 applied and real sea conditions are considered.

58 2. METHODOLOGY

59 2.1. Case study

60 The study of the shielding effect of the WECs barrier in an offshore wind farm was
61 carried out by considering four wind farms currently in operation at the North Sea: Bard
62 1, Horns Rev 1 and Lincs, whose locations and characteristics are presented in Figure 1
63 and Table 1, respectively. These four wind farms encompass a wide variety of
64 characteristics on which to establish a comparative analysis.



65
66 Figure. 1. Location of the four wind farms used in this study: Alpha Ventus, Bard 1,
67 Horns Rev 1 and Lincs.
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Table 1. Characteristics of the Wind Farms

Wind farm	Depth (m)	Distance from shore (km)	Installed capacity (MW)	Number turbines	Area (km ²)
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

72 Horns Rev 1 has been characterised previously. The Alpha Ventus wind farm is
73 composed by 12 turbines: 6 AREVA turbines with a tripod substructure and 6 Repower
74 5M turbines with a jacket-frame substructure with a spacing between turbines of around
75 800 m [11]. For their part, Bard 1 is composed of 80 5 MW turbines (Bard 5.0) on
76 tripod substructures [12], and Lincs of 75 3.6 MW Siemens turbines on monopiles [13].
77 In Alpha Ventus and Horns Rev 1 the wind turbines are arranged on a Cartesian grid,
78 whereas in Bard 1 and Lincs they are not organised in clearly defined rows, and the
79 distance between turbines varies in each case. As regards the sea climate, wave buoy
80 measurements were used, and the main wave climate parameters are shown in Table 2:
81 H_s is the significant wave height, T_{m01} the mean wave period, θ the mean wave direction,
82 U_w the most frequent wind speed at 10 m, and D_w the corresponding wind direction.

Table 2. Wave and Wind Conditions at the Wind Farm Site.

Wind farm	H_s (m)	T_{m01} (s)	θ (°)	U_w (ms ⁻¹)	D_w (°)
Alpha Ventus	1.5	4.6	330	10	210-240
Bard 1	0.8-1.5	4.0	320	9.2	330
HornsRev 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

84 Having defined the wind farms, a Peripherally Distributed Array (PDA) was selected
85 for the co-location of the WECs. The PDA is a type of co-located system which
86 combines both wind and wave arrays by positioning the WECs at the periphery of the
87 offshore wind farm.. The WEC used in this analysis, is the WaveCat: a floating offshore

88 WEC whose principle of operation is wave overtopping, and with a length overall of 90
 89 m. The minimum distance between devices is $2.2D$, where $D = 90$ m is the distance
 90 between the twin bows of a single WaveCat WEC [10].

91 Two co-located WECs layouts (Table 3) were proposed taking into account the wind
 92 farm layouts, the wave climate, and the results of previous studies [14, 15]. In the first
 93 case (Figure 2a), the co-located WECs configuration consists of two main rows of
 94 WECs with a spacing of 198 m orientated towards the prevailing wave direction, and
 95 other rows of WECs at an angle of 45° to face secondary wave directions and thus
 96 protect a larger wind farm area. With the second configuration (Figure 24b) the aim is to
 97 check if deploying WECs in an arc can lead to a wave height reduction similar to that
 98 obtained with an angular layout with fewer WECs.

99 Table 3. Total Number of Co-located WECs and the Rate Between the Total Number of
 100 WECs and Wind Turbines (r).

Wind farm	Layout in angle		Layout in arc	
	Total	r	Total	r
Alpha Ventus	34	2.83	32	2.67
Bard 1	79	0.99	79	0.99
Horns Rev 1	55	0.69	53	0.66
Lincs	81	1.01	80	1

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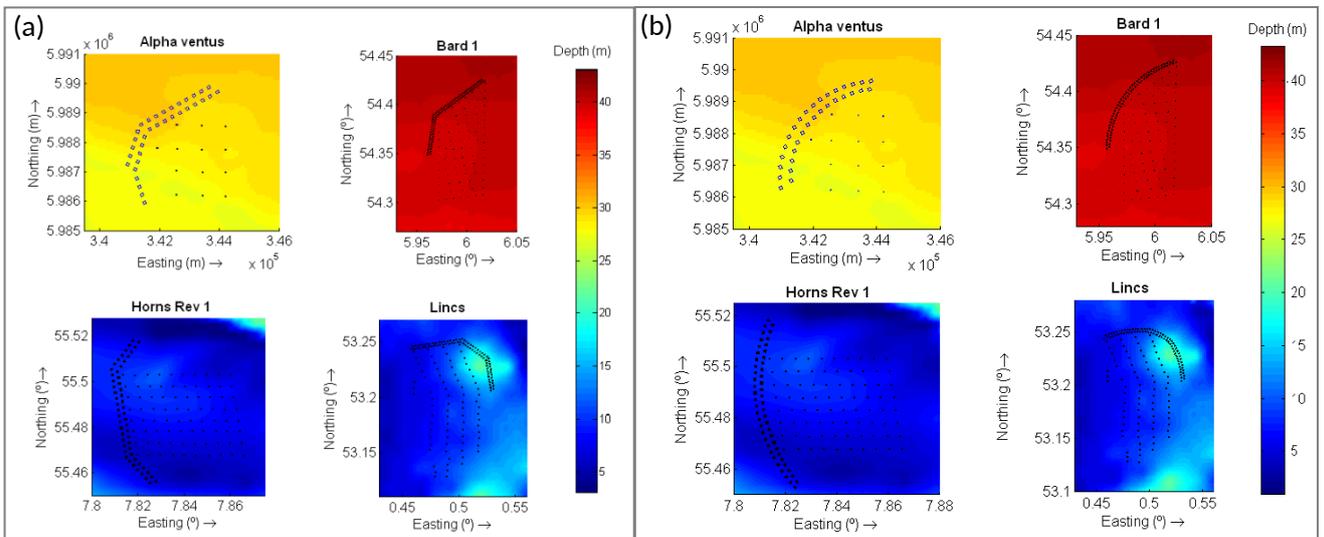


Figure 2. Co-located wind farm layouts with WECs: (a) at an angle. (b) in arc.

113 2.2 The Wave Propagation Model

114 The assessment of the wave height reduction in the wind farm caused by the co-located
 115 WECs was carried out using a third-generation numerical wave model, SWAN
 116 (Simulating WAVes Nearshore), which was successfully used in previous works [16-18]
 117 to model the impact of a wave farm on nearshore wave conditions. The evolution of the
 118 wave field is described by the action balance equation, Equation (1), which equates the
 119 propagation of wave action density in each dimension balanced by local changes to the
 120 wave spectrum:

$$121 \quad \frac{\partial}{\partial t} N + \frac{\partial}{\partial x} c_x N + \frac{\partial}{\partial y} c_y N + \frac{\partial}{\partial \sigma} c_\sigma N \frac{\partial}{\partial \theta} c_\theta N = \frac{S_{tot}}{\sigma} \quad (1)$$

122 where t is time (s), c_x and c_y are spatial velocities in the x and y components (ms^{-1}), c_θ
 123 and c_σ are rates of change of group velocity which describe the directional (θ) rate of
 124 turning and frequency (σ) shifting due to changes in currents and water depth, N is wave
 125 action density spectrum, and S_{tot} is the energy density source terms which describe local
 126 changes to the wave spectrum.

127 In this work the model was implemented in the so-called nested mode, with two
 128 computational grids (Table 4) in order to obtain high-resolution results without
 129 excessive computational cost. The bathymetric data, from the UK's data centre Digimap,
 130 were interpolated onto this grid.

131 Table 4. 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

132 The wind turbines were represented in the model by a transmission coefficient, whose
 133 value can vary in theory from 0% (i.e., 100% of incident wave energy absorbed) to
 134 100%. This technique was used in previous studies to represent single wind turbines [19]
 135 or wind farm arrays [20], and arrays of WECs [21]. In this study, the transmission
 136 coefficient of the offshore wind turbines was calculated by [22]:

$$137 \quad c_t = 4 \left(\frac{d}{H_i} \right) E \left[-E + \sqrt{E^2 + \frac{H_i}{2d}} \right] \quad (2)$$

$$138 \quad E = \frac{C_d \left(\frac{b}{D+b} \right)}{\sqrt{1 - \left(\frac{b}{D+b} \right)^2}} \quad (3)$$

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

142 As for the co-located WECs, they have also been modelled as obstacles characterised by
 143 a transmission coefficient, as in previous works [23-25]. The value of this coefficient is
 144 derived from the results of the physical modelling of the WaveCat [26].

145 2.3. Impact Indicators

146 To compare the results achieved in the proposed co-located farms a series of impact
 147 indicators were defined: (i) the significant wave Height Reduction within the Farm
 148 (HRF), (ii) the significant wave Height Reduction within the j -th Area of wind turbines
 149 (HRA_j), and (iii) the increase in access time for O&M ($\Delta T_{O\&M}$). The HRF and HRA_j
 150 indices provide information about the average wave height reduction within the wind
 151 farm and the wave recovery with increasing distance from the WECs, respectively, and
 152 were calculated by Equations (4) and (5).

153
$$HRF (\%) = \frac{100}{n} \sum_{i=1}^n \frac{1}{(H_{s,b})_i} [(H_{s,b})_i - (H_{s,w})_i] \quad (4)$$

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

158
$$HRA_j(\%) = \frac{100}{m} \sum_{i=1}^m \frac{1}{(H_{s,b})_i} [(H_{s,b})_i - (H_{s,w})_i] \quad (5)$$

159 where the index i denotes a generic turbine of the j -th area of the wind farm, and m is
 160 the number of turbines in the j -th area. In the case of Alpha Ventus and Horns Rev 1
 161 each j -th area corresponds to a vertical row of turbines numbered from east to west, $j =$
 162 1, 2, 3 in Alpha Ventus and $j = 1, 2 \dots 10$ in Horns Rev 1. However, in the other two
 163 wind farms, due to the less orderly layout, the division was made into different areas
 164 with a similar number of turbines, and numbered according to the mean wave direction
 165 (Figure 3).

166 The $\Delta T_{O\&M}$ non-dimensional index allows the assessment of the increase in the
 167 timeframe accessibility to the wind turbines thanks to the co-located WECs, and can be
 168 computed from Equation (6).

169
$$\Delta T_{O\&M}(\%) = \frac{T_w - T_b}{T_w} \times 100 \quad (6)$$

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

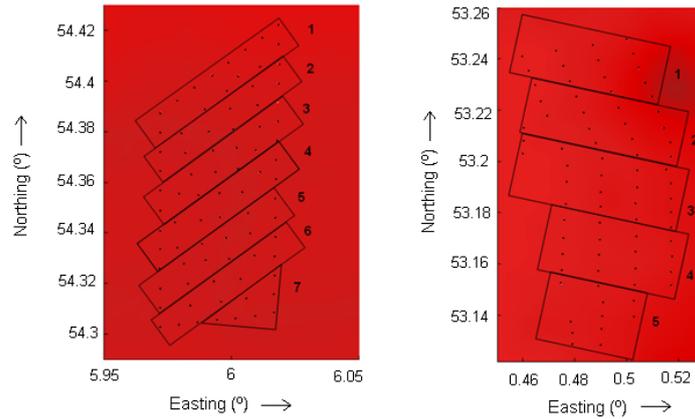


Figure 3. The j -th areas into which Bard 1 (left) and Lincs (right) were divided to calculate the HRA_j index.

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3. RESULTS AND DISCUSSION

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177 The proper functioning of the nearshore wave propagation model was validated with
178 wave buoy data. In all cases, a good correlation was observed between the simulated
179 and measured time series, as shown by the values of R^2 and $RMSE$, always higher than
180 0.93 and lower than 0.36 m, respectively.

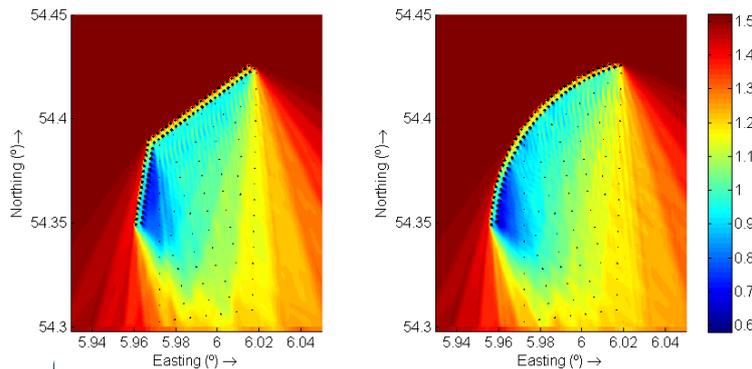
181 As regards the wave height reduction achieved throughout the farm (HRF), it ranged
182 between 13% and 19% (Table 5) and was always larger for the layouts with WECs
183 deployed at an angle than for those in arc, although the difference between the results of
184 both configurations was small (between 1 and 2%). Comparing the results between
185 wind farms (Table 5), the best values were obtained for Bard 1, where a good
186 interception of the incoming waves was achieved for the two layouts of co-located
187 farms (Figure 4). These results were followed very closely by those obtained for Alpha
188 Ventus and Horns Rev 1, whereas the wave height reduction achieved at Lincs was
189 smaller. This was due to three main factors. First, the wind farm layout – this farm has a
190 slightly elongated shape. Second, the wave direction has a greater variability than in the
191 other case studies, and the farm remained unprotected against waves from secondary
192 directions (Figure 5). For this reason a larger number of WECs would be required on

193 the east side of the farm to achieve better results; however, this would imply an
 194 important increase in the ratio between the number of WECs and wind turbines, raising
 195 the final cost of the co-located farm. Third, the wave climate in this park, which was
 196 milder than in the other farms and, therefore, less wave energy could be extracted by the
 197 co-located WECs.

198 Table 5. *HRF (%)* Values achieved with co-located WECs deployed
 199 in angle or in arc based on the annual data series.

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

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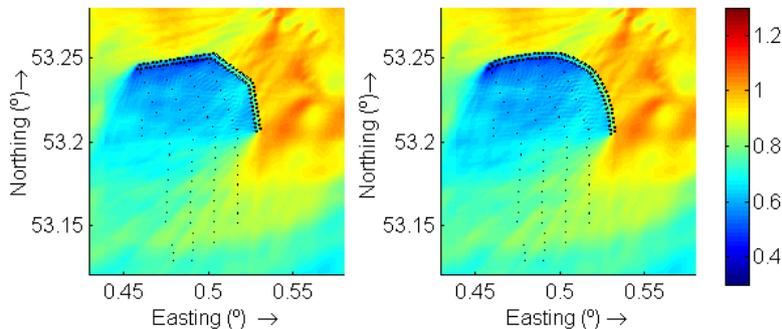
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202 Figure 4. Wave height reduction obtained with co-located WECs at Bard 1 under a sea
 203 state with: $H_s = 1.71$ m, $T_p = 6.09$ s and $\theta = 230^\circ$. The colour scale represents the
 204 significant wave weight, H_s (m).
 205

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207 Figure 5. Wave height reduction due to co-located WECs at Lincs under a sea state with:
 208 $H_s = 1.18$ m, $T_p = 6.03$ s and $\theta = 60^\circ$. The colour scale represents the significant wave
 209 weight, H_s (m).
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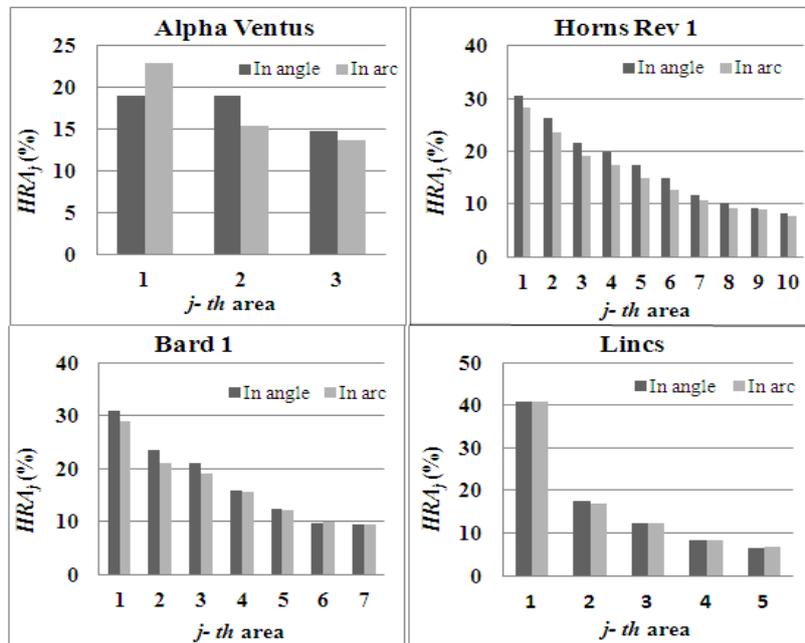
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211 Furthermore, the results of Horns Rev 1 are particularly interesting since they were
212 similar to those of the best scenario, even though the ratio between number of WECs
213 and wind turbines in Horns Rev 1 is much lower than in the other cases – an important
214 consideration for the economic assessment. The explanation lies in the geometry of the
215 wind farms: the layout of Horns Rev 1 is close to a square, whereas Bard 1 or Lincs
216 have a more elongated shape and therefore require more WECs for a similar degree of
217 shelter.

218 Apart from the average wave height reduction in the farm (*HFR*), it is interesting to
219 analyse the spatial variation in the wave height reduction through its value in different
220 sections (*HRA_j*), since the best WECs layout should achieve not only high values of
221 *HFR* but also a fairly homogenous reduction throughout the farm. As may be expected,
222 in all case studies the tendency was for the highest reduction to occur immediately
223 behind the WECs, with *HRA_j* decreasing with increasing distance from the co-located
224 WECs (Figure 6). However, the wave height reduction was significant even as the
225 distance from the WECs increased. As with the wave height reduction for the entire
226 farm, greater values of *HRA_j* were obtained generally for configurations with WECs
227 deployed at an angle rather than in arc. Lincs presented the highest difference between
228 *HRA_j* values in the first and second area of turbines (around 23%), and was also the case
229 with the smallest difference between the wave height reduction with co-located WECs
230 in angle or in arc. Therefore, it may be concluded that in the case of wind farms with a
231 milder wave climate, like Lincs, wave heights are restored more quickly behind the
232 WEC barrier, and the choice between angular or arched layouts for the co-located
233 WECs does not have a significant influence on the enlargement of the weather windows
234 for O&M.

235 As regards the accessibility to the wind turbines, it was below 82% for all the wind
 236 farms analysed, which corresponds to availability values below 90%. Nevertheless, an
 237 important increase of the accessibility was achieved by deploying co-located WECs
 238 along the periphery of the farm in the four case studies (Table 6). More specifically, the
 239 results for Alpha Ventus and Bard 1 were very similar, the accessibility increased
 240 ($\Delta T_{O\&M}$) by 17-18%, whereas in Horns Rev 1 this increased by 13-15% and in Lincs by
 241 8%.



242
 243 Figure 6. HRA_j (%) values with co-located WECs deployed in angle or in arc based on
 244 the annual data series data.
 245

246 Table 6. 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 arc	82.2	17.8
Bard 1	in angle	69.7	18.2
	in arc	69.0	17.5
Horns Rev 1	in angle	70.9	15.6
	in arc	69.5	13.9
Lincs	in angle	81.3	8.9
	in arc	81.1	8.6

247

248 4. CONCLUSIONS

249 The objective of this study was to analyse and compare the wave height reduction and
250 the enlarged weather windows that can be achieved in the inner part of a wind farm by
251 deploying WECs as a barrier. For these purposes, a case study in the North Sea was
252 carried out, considering four wave farms with different characteristics in terms of
253 location and configuration. Two co-located farm layouts were analysed for each of
254 them in order to find the configuration that optimises the shielding effect of the WECs.
255 All the case studies were conducted using real wave conditions and a third-generation
256 wave model (SWAN). It was found that relevant reductions in the significant wave
257 height were achieved in all cases (over 13.5%), resulting in significant enlargements of
258 the weather windows for O&M. Indeed, in the case of Alpha Ventus and Lincs, values
259 around 82% were obtained for the accessibility, which would ensure an availability of
260 the turbines of 90% or higher. With regard to the influence of the co-located farm
261 layout on the results, the arrays with small spacings between converters achieved the
262 best results in terms of significant wave height reduction. Moreover, the best results
263 were obtained for co-located farms in which the WECs face both the prevailing and
264 secondary wave directions, either with WECs deployed forming an angle or arc.
265 Concerning the influence of the wind farm location, it was found that the proximity to
266 land is not favourable in terms of deploying co-located WECs, for it implies lower
267 water depths and, typically, a milder wave climate, and consequently less available
268 wave energy to be extracted by the WECs. As for the wind farm layout, it was found
269 that the greatest reduction in significant wave height, i.e. the most pronounced *shadow*
270 *effect*, was achieved for wind farms with square-like geometries, like Horns Rev. 1.

271 In sum, this work: (i) showed that the weather windows for operation & maintenance
272 tasks as determined by the significant wave height are increased in a relevant manner

273 by the energy-absorbing WECs; and (ii) analysed the main aspects to be taken into
274 account in deploying co-located wave-wind for this purpose.

275

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Figure 1. Location of the four wind farms used in this study: Alpha Ventus, Bard 1, Horns Rev 1 and Lincs.

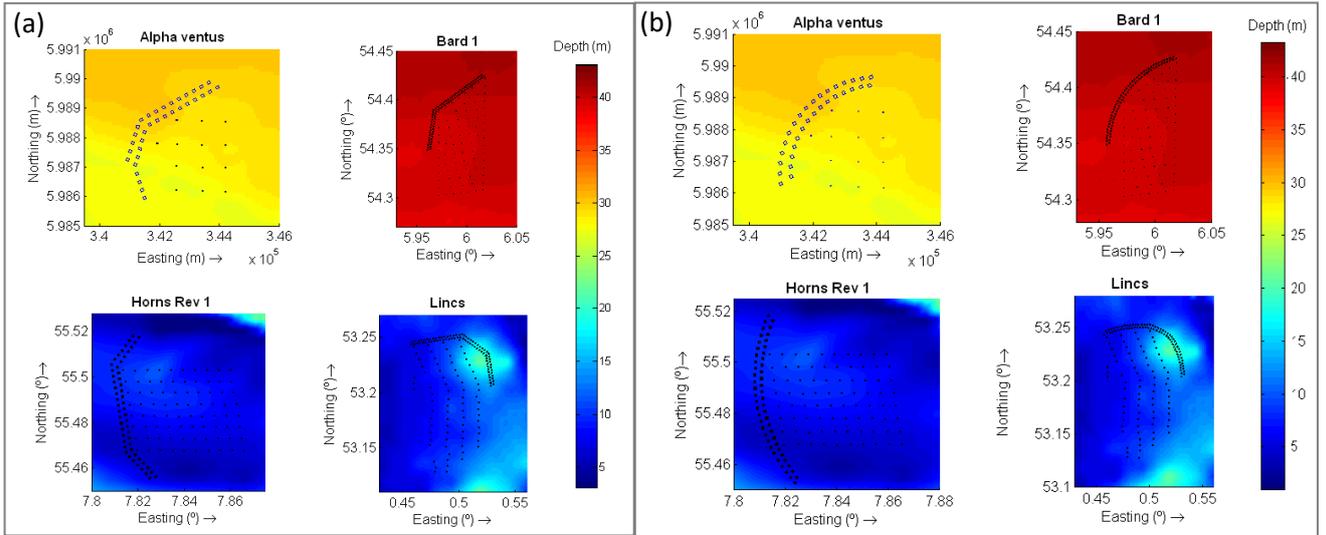


Figure 2. Co-located wind farm layouts with WECs: (a) at an angle. (b) in arch.

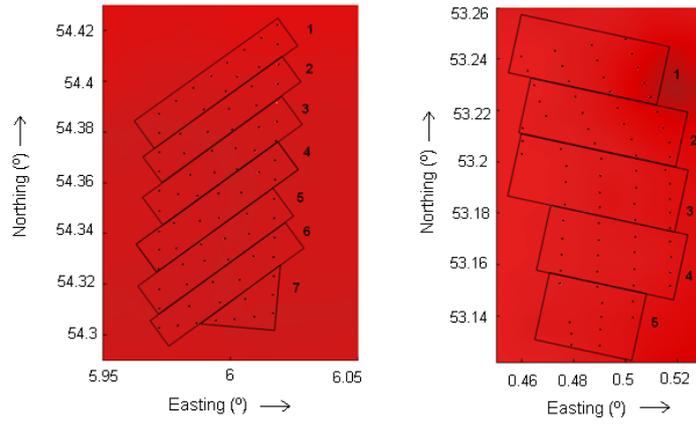


Figure 3. The j -th areas into which Bard 1 (left) and Lincs (right) were divided to calculate the HRA_j index.

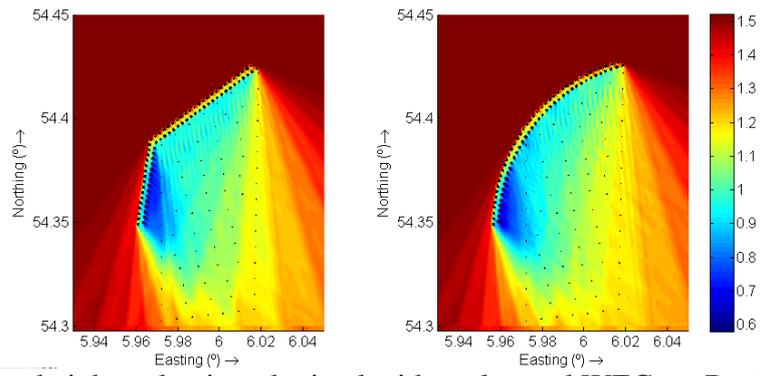


Figure 4. Wave height reduction obtained with co-located WECs at Bard 1 under a sea state with: $H_s = 1.71$ m, $T_p = 6.09$ s and $\theta = 230^\circ$. The colour scale represents the significant wave weight, H_s (m).

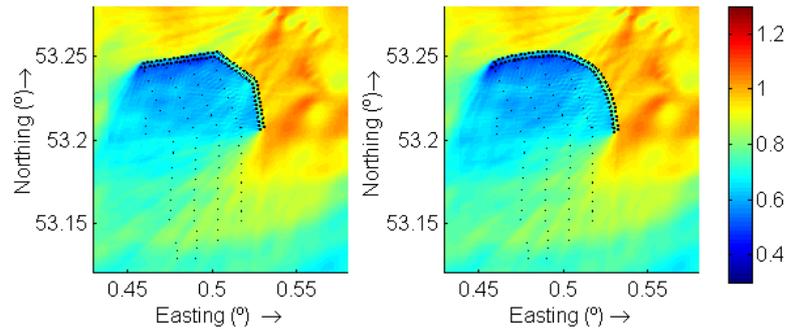


Figure 5. Wave height reduction due to co-located WECs at Lincs under a sea state with: $H_s = 1.18$ m, $T_p = 6.03$ s and $\theta = 60^\circ$. The colour scale represents the significant wave weight, H_s (m).

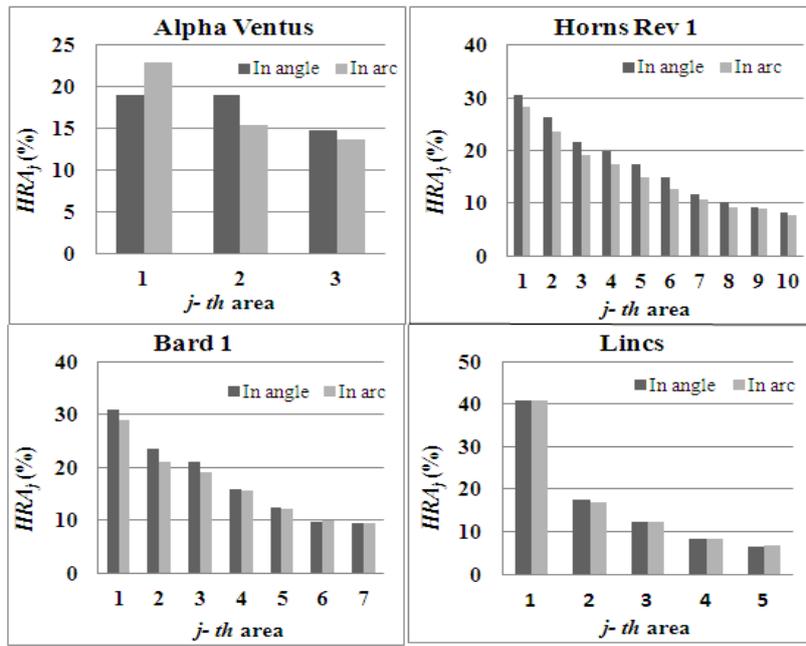


Figure 6. HRA_j (%) values with co-located WECs deployed in angle or in arc based on the annual data series data.

Table 1. Characteristics of the Wind Farms

Wind farm	Depth (m)	Distance from shore (km)	Installed capacity (MW)	Number turbines	Area (km ²)
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

Table 2. Wave and Wind Conditions at the Wind Farm Site.

Wind farm	H_s (m)	T_{mol} (s)	θ (°)	U_w (ms ⁻¹)	D_w (°)
Alpha Ventus	1.5	4.6	330	10	210-240
Bard 1	0.8-1.5	4.0	320	9.2	330
HornsRev 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

Table 3. Total Number of Co-located WECs and the Rate Between the Total Number of WECs and Wind Turbines (r).

Wind farm	Layout in angle		Layout in arch	
	Total	r	Total	r
Alpha Ventus	34	2.83	32	2.67
Bard 1	79	0.99	79	0.99
Horns Rev 1	55	0.69	53	0.66
Lincs	81	1.01	80	1

Table 4. 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

Table 5. *HRF (%)* Values achieved with co-located WECs deployed in angle or in arch based on the 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

Table 6. 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