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Accessibility for operation and maintenance tasks in co-located wind and wave energy farms with non-uniformly distributed arrays

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A B S T R A C T

Operation and maintenance is a particularly challenging aspect of offshore wind energy. First, the harsh marine environment requires more frequent tasks relative to onshore wind turbines; and second, these labours can be delayed by difficult sea conditions – in particular, large wave heights – leading to down time and, consequently, increased costs. This can be offset in part by combining offshore wind and wave energy systems: wave energy converters adequately deployed extract part of the incoming wave energy, resulting in a milder wave climate within the wind park, and hence better accessibility for maintenance tasks and reduced down time. The actual results depend on the layout of the co-located wave-wind energy farm. Previous works showed that peripherally distributed arrays, i.e., co-located wave energy converters deployed along the periphery of the wind farm to act as a barrier, bring about good results in terms of wave height reduction and average accessibility. However, important differences between the accessibility to the wind turbines located directly behind the barrier and the other turbines in the farm were found. On this basis, the objective of this paper is to analyse whether non-uniformly distributed arrays can lead to a more uniform wave height reduction throughout the farm. The analysis is based on 4 offshore wind farms currently in operation: Alpha Ventus, Bard 1, Horns Rev 1 and Lincs. It was found that non-uniformly distributed arrays lead to a more significant average wave height reduction (by over 4.7%) and more uniformly distributed throughout the farm, as well as a greater power output from the co-located devices (by up to 16.5%).

1. Introduction

Marine renewables have been growing rapidly [1] throughout Europe in order to achieve the EU targets for renewable energy in 2020 [2]. Already well established commercially, offshore wind energy is the most developed marine renewable, with a relatively mature technology. Its pace of growth over the last years is also explained by a greater resource [3] and a better availability [4] compared to its onshore counterpart. Nevertheless, wind energy is not without downsides which could hamper its development, such as the higher initial investment and maintenance costs [5], which is an inherent feature of installations located in a marine environment. As regard the latter, not only more frequently maintenance and repair tasks are required due to the harsh conditions, but also the existing sea climate in the area may cause delays in these works turning this renewable in less economic-competitive due to the resulting down time [6]. Indeed, the operational limit of workboats – the most cost-effective access system [7] – is a significant wave height of 1.5 m [8].

In view of the above, the combination of offshore wind farms with wave energy technology [9] has been regarding as a solution to achieve a milder wave climate in the inner part of the wind farm: Wave Energy Converters (WECs) deployed within the wind farm area extract energy from the incident waves, reducing their height [10] and, consequently, improving the accessibility to the wind turbines. Therefore, the shielding effect of WECs over the offshore installation [11] is translated into enlarged weather windows for Operation & Maintenance (O&M) tasks [12]. Previous studies [13] showed that with this combination the availability of the wind turbines can be raised more than 15%, which would lead to a reduction in the overall project cost by 2.3% [14]. Moreover, taking advantage of different marine resources in the same area has recently emerged as a viable option to improve the economic viability of marine renewable because of the existing synergies [15]. Besides, this combination may result in a boost for the development of wave energy, which albeit in its infancy, as shows the stage of development of the technology [16], is a

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Nomenclature

A_{NDA}	accessibility to the wind turbines in a non-uniformly distributed array (%)
A_{PDA}	accessibility to the wind turbines with WECs deployed as a barrier at the periphery of the farm (%)
A_{WF}	accessibility to the wind turbines in the baseline scenario with the wind turbines as stand-alone systems (%)
AWT_k	percentage of accessible wind turbines during the k percentage of time
BSH	Bundesamt fuer Seeschiffahrt und Hydrographie
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CS	case study
EMODnet	European Marine Observation and Data Network
ERDF	European Regional and Development Fund
H_s	significant wave height (m)
H_{si}	significant wave height incident on the ith turbine in the baseline scenario without WECs (m)
H_{sWECi}	significant height incident on the ith turbine with co-located WECs (m)
H_{sNDAi}	significant height incident on the ith turbine with co-located WECs deployed in a NDA (m)
HRA_j	significant wave Height Reduction along the jth Area of wind turbines
HRF_{NDA}	wave Height Reduction within the Farm with non-uniformly distributed co-located WECs (m)
HRF_{PDA}	significant wave Height Reduction within the Farm with peripherally distributed co-located WECs (m)
J	average power output of all co-located WECs (W/m)
$J_{W,i}$	power production of the ith WEC (W/m)
$J_{WEC\text{-}NDA}$	average power production per WEC generated by the co-located WECs deployed in a NDA (W/m)
$J_{WEC\text{-}PDA}$	average power production per WEC generated by the co-located WECs deployed in a PDA (W/m)
k	percentage of time during which the wind turbines are accessible
m	number of turbines in the jth area
n	total number of wind turbines
n_W	total number of WECs
NDA	Non-uniformly Distributed Array
O&M	Operation & Maintenance
PDA	Peripherally Distributed Array
SWAN	Simulating WAves Nearshore
t	a point in time
T	total number of time points considered
T_p	peak wave period (s)
UDA	Uniformly Distributed Array
WEC	Wave Energy Converter
WF	Wind Farm
$\Delta A_{NDA\text{-}PDA}$	non-dimensional index that compares the accessibility achieved in NDAs with regard to PDAs
$\Delta A_{NDA\text{-}WF}$	non-dimensional index that compares the accessibility achieved in NDAs with regard to the baseline scenario
ΔHRF	non-dimensional index that compares the wave height reduction achieved in PDA and NDA
ΔJ_{WEC}	difference in the power production per WEC with regard to the PDA configurations
θ	wave direction (°)

promising renewable with extensive possibilities for the future [17] due to the large available resource [18].

There are different possibilities for a combined wave and wind array: (i) co-located wave and offshore wind turbines; (ii) hybrid energy converters; and (iii) energy islands [19]. The former, which is the direct option at the current stage of development of both technologies [20], consists in combining 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, etc. This way, no major technology developments are required and the integration consists essentially in appropriate grid planning [21]. Among this combined arrays, different options can be considered [21]: (i) a Peripherally Distributed Array (PDA), where WECs are placed on the perimeter of the wind farm as a barrier; (ii) an Uniformly Distributed Array (UDA), with WECs deployed uniformly throughout the wind farm; or (iii) a Non-uniformly Distributed Array (NDA). Previous works, as [22,23], have analysed the *shadow effect* of PDAs, and in general great results of wave height reduction were achieved, even when the accessibility increases were translated into monetary terms [24]. However, in the case of large wind farms waves have enough space to be regenerated behind the peripheral barrier of WECs and, consequently, the wave height reduction achieved in the more distant rows of wind turbines is lower and sometimes insufficient [25].

On this basis, the aim of this paper is to analyse if placing some WECs among the wind turbines (NDA) instead of deploying them as a unique barrier at the periphery would lead to a more uniform wave height reduction within the entire wind farm site. This objective was carried out through 4 wind farms currently in operation: Alpha Ventus, Bard 1, Horns Rev1 and Lincs, considering real sea conditions and using a third-generation wave model, SWAN (Simulating WAves Nearshore), for obtaining realistic estimates of the wave climate.

This paper is structured as follows. First, the co-located farm layouts with WECs placed among the wind turbines (NDA) are defined and tested on the basis of the results obtained in previous works with PDAs [22]. Second, simulations with real annual sea data are carried out through the third-generation wave numerical model SWAN. Third, the results are analysed by means of several impact indicators that quantify the wave height reduction and the power production. Finally, these results are analysed and compared to that obtained for PDAs. On this basis, conclusions about the more convenient layout are drawn.

2. Methodology

2.1. Baseline scenarios: offshore wind farms

The detailed description of the 4 offshore wind farms taking as baseline scenarios – Alpha Ventus, Bard 1, Horns Rev 1 and Lincs (Fig. 1) – and their corresponding wave climate can be consulted in the previous work of which this study is a continuation [22]; as well as, the grounds of the third-generation wave model used and its validation for each case study. All the same, Table 1 summarises the most relevant characteristics of the wind farms; and Fig. 2 shows the significant wave height rose at the study sites.

2.2. Impact indicators

Three groups of parameters were defined to analyse the results: (i) parameters to determine the wave height reduction; (ii) indices to quantify the increase in the accessibility; and (iii) indicators to analyse the average power production.

The first group includes the significant wave Height Reduction within the Farm with non-uniformly distributed co-located WECs