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Improving wind farm accessibility for operation & maintenance through a co-located wave farm: Influence of layout and wave climate

S. Astariz [a,*], J. Abanades [b], C. Perez-Collazo [b], G. Iglesias [b]

[a] University of Santiago de Compostela, EPS, Hydraulic Eng., Campus Univ. s/n, 27002 Lugo, Spain
[b] University of Plymouth, School of Marine Science and Engineering, Drake Circus, Plymouth PL4 8AA, UK

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ABSTRACT

One of the challenges of offshore wind energy farms lies in their reduced availability relative to onshore facilities. In effect, with wave heights over 1.5 m impeding workboats access, sea conditions often cause delays to operation & maintenance tasks, and thereby impact on the availability for power production of the farm. The most immediate consequence is larger non-operational periods, which could translate into lower power production and, therefore, a reduction of their economic viability. By deploying wave energy converters along the periphery of the wind farm, wave height within the park can be reduced, and the accessibility for operation & maintenance tasks improved. The aim of this work is to analyse this synergy between wave and wind energy through the comparison of four case studies, and more specifically, to investigate how this synergy can be materialised under different conditions in terms of: (i) location (depth and distance from the coast), (ii) sea climate, and (iii) wind farm layout. It was found that the combination of wave and offshore wind energy results in enhanced accessibility for operation & maintenance tasks in all the cases considered, with accessibility values of up to 82%.

1. Introduction

Offshore wind energy has strongly burst into the energy mix hand in hand with the search of reliable alternatives to fossil fuels [1]. The available resource, larger than in the case of onshore wind, has the potential to supply larger quantities of renewable energy [2], and in this manner harvest wind energy more efficiently. However, offshore installations involve a greater Operation & Maintenance (O&M) demand due to the harsh marine environment, which translates into higher costs and longer down-time periods [3]. In fact, O&M costs of offshore wind farms typically amount to between 20% and 25% of the total lifetime costs of the installation [4]. The savings that can be achieved by enlarging the weather windows for O&M were estimated at 25%; these savings would lead to a reduction in the overall project cost of energy of 2.3% [5].

In this line, a crucial factor in the viability of offshore wind farms is the accessibility to the turbines. The operational limit of workboats (the most cost-effective access system [6]) is a significant wave height of 1.5 m. When this threshold is exceeded delays in maintenance and repairs ensue. Thus, while modern onshore wind turbines presents accessibility levels of 97% [7], this level can be significantly reduced in offshore installations [8]. In this context, co-located wind and wave energy farms [9] have been proposed as a solution to improve accessibility, by deploying Wave Energy Converters (WECs) as a barrier along the periphery of the farm leading to a milder wave climate within [10]. Moreover, the existence of other important synergies between both renewables [11], such as the possibility of sharing common equipment and infrastructure or the smoothing of the variability of the power output [12], which reduce the system integration costs of renewables [13] and increase the capacity credits of the farms [14], turn these combined systems into a more competitive option than wind-only farms. In this vein, the deployment of wave energy devices in offshore wind farms could foster the development of wave energy [15], which, albeit at an initial stage [16], presents extensive possibilities for the future due to the great available resource. In fact, intense efforts are being put into the development of efficient, reliable technologies [17], as well as in the assessment of their performance [18]. Moreover, some recent studies focuses on the associated environmental impact of wave farms, which were to be positive as contributed to reduce the erosion on the coast [19].

Among these synergies between wave and offshore wind, what is incumbent in this paper is the shielding effect of the WECs over the offshore wind farm [20]: WECs are deployed along the periphery of the array, facing the incoming waves [21]. Previous studies showed that this arrangement can enhance accessibility by over

* Corresponding author. Tel.: +34 982823295; fax: +34 982285926.
E-mail address: sharay.astariz@usc.es (S. Astariz).

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Nomenclature

AWT_k	the percentage of Accessible Wind Turbines during the k percentage of time
b	spacing between the piles of the wind turbines (m)
BSH	Bundesamt fuer Seeschiffahrt und Hydrographie
c_x	spatial velocities in the x components (m s^{-1})
c_y	spatial velocities in the y components (m s^{-1})
c_t	transmission coefficient of the offshore wind turbines
c_θ	rate of change of group velocity which describe the directional (θ) rate of turning due to changes in currents and water depth
c_σ	rate of change of group velocity which describe the frequency (σ) shifting due to changes in currents and water depth
C_d	drag coefficient of the wind turbine piles
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
d	water depth (m)
D	distance between the twin bows of a single WaveCat WEC (m)
D_p	diameter of the wind turbine piles (m)
D_w	mean wind direction (°)
EMODnet	European Marine Observation and Data Network
ERDF	European Regional and Development Fund
f	occurrence (%) of the prevailing wind direction
H_i	incident significant wave height (m)
H_s	significant wave height (m)
$(H_{s,}b)_i$	significant height incident on the i-th wind turbine in the baseline scenario, i.e. without WECs (m)
$(H_{s,W})_i$	significant height incident on the i-th wind turbine with co-located WECs (m)
HRA_j	significant wave Height Reduction along the j-th area of wind turbines. This non-dimensional index reflects the wave recovery with increasing distance from the WECs
HRF	wave Height Reduction within the Farm. It is a non-dimensional parameter that provides information about the average wave height reduction within the wind farm
$\bar{J}$	power energy (W/m) generated by all co-located WECs
J_{WEC}	average wave power (W/m) of one WEC
$J_{W,i}$	wave power (W/m) of the i-th WEC
k	percentage of time during which the wind turbines are accessible
m	number of turbines in the j-th column
n	total number of wind turbines
n_W	number of WECs
N	wave action density spectrum (J s)
O&M	Operation & Maintenance
r	rate between the total number of WECs and wind turbines
R^2	coefficient of determination
$RMSE$	Root Main Square Error
S_{tot}	the energy density source terms which describe local changes to the wave spectrum (J s^{-1})
SWAN	Simulating WAves Nearshore
t	a point in time (s)
T	total number of time points considered (s)
T_b	total number of hours per year with $H_s \leqslant 1.5$ m for the baseline scenario, i.e. isolated turbines (h)
T_{m01}	mean wave period (s)
T_p	peak wave period (s)
T_W	total number of hours per year when H_s within the wind farm is lower or equal to 1.5 m with co-located WECs
U_w	wind speed at 10 m (m s^{-1})
VRi	i-th Vertical Row of WECs
WEC	Wave Energy Converter
ΔJ_{WEC}	difference between the average power production per WEC of the 1st and 2nd row
$\Delta T_{O\&M}$	increase in the accessible timeframe for O&M achieved with co-located WECs
θ	wave direction (°)

82% [22], thereby minimising down time and the frequency of sudden breakdowns (and the associated huge maintenance and logistic costs) while providing reliable power generation.

The objective of this paper is to analyse the relationship between the characteristics of the wind farm and the extension of the weather windows for O&M provided by the WECs along its periphery. This objective is achieved through a comparative study between four wind farms currently in operation (Alpha Ventus, Bard 1, Horns Rev1 and Lincs) with different characteristics of distance from land, depth and layout. By comparing the results obtained in each case, conclusions are drawn on the efficacy of combining wave and offshore wind energy as a means towards improved accessibility, and how this efficacy is affected by the particular characteristics of a given wave farm.

This paper is structured in four sections. First, the wind farm characteristics are analysed, as well as the wave climate at the sites considered. Second, with this information and on the basis of previous works, two different layouts of the co-located WECs are proposed for each farm, and wave propagation is modelled by means of SWAN, a state-of-the-art coastal wave model. Third, the results were analysed through impact indicators quantifying the wave height reduction and the power production. Finally, conclusions are drawn.

2. Materials and methods

2.1. Case studies and data

This analysis was carried out through four offshore wind farms: Alpha Ventus, Bard 1, Horns Rev 1 and Lincs, whose locations and characteristics are presented in Fig. 1 and Table 1, respectively. Comparing this information, it can be stated that the Horns Rev 1 and Lincs wind farms are nearer to land than the other two, and consequently these farms are in smaller water depths and have a milder sea climate. With respect to the number of turbines, Alpha Ventus could be considered a small wind farm, with only 12 wind turbines, whereas the other three have around 80 turbines; their total installed capacity, however, is different due to the different nominal power of the wind turbines. Furthermore, their different diameter results in different requirements in terms of spacing between turbines and accordingly a different occupied area and layout (Fig. 2). Therefore, these four wind farms encompass a wide variety of characteristics on which to establish a comparative analysis.

As regards the wind farm layout (Fig. 2), Alpha Ventus is composed of 12 wind turbines: 6 AREVA turbines with a tripod substructure and 6 Repower 5M turbines with a jacket-frame substructure [23] – with a spacing between turbines of around