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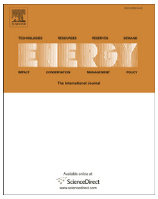

Co-located wind and wave energy farms: Uniformly distributed arrays

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ABSTRACT

Co-located wave and wind energy farms can serve to tackle one of the downsides of offshore wind energy relative to its onshore counterpart: the longer non-operational periods. These are partly caused by delays to maintenance tasks due to energetic sea states preventing access. By co-locating Wave Energy Converters (WECs) in an appropriate configuration it may be possible to reduce the wave heights within the wind farm area (*shielding effect*) and thereby increase the weather windows for maintenance. Previous works analysed the improvements in accessibility obtained by configuring the co-located WECs as a peripheral barrier or interspersed within the farm. However, the former led to an insufficient wave height reduction as the distance to the barrier increased and the latter presented other handicaps, notably in respect of the submarine cable installation and the navigation of workboats. The objectives of this work are: (i) to analyse whether a uniformly distributed array may be more convenient in these respects and (ii) to carry out a comparative economic assessment. This investigation is carried out through a case study at the Horns Rev 1 wind farm by means of a high-resolution spectral wave model. Annual cost savings of up to 900,000 € are found.

1. Introduction

Recently, at the Paris climate conference (COP21) in December 2015, 195 countries adopted the first-ever universal, legally binding global climate deal. The agreement set out a global action plan to put the world on track to avoid dangerous climate change by limiting global warming. In this context, reducing carbon emissions and, therefore, finding alternatives to fossil fuels is fundamental. Marine energy is regarded as a promising energy source due to the vast resource available around the world [1–8]. Already well established commercially, offshore wind energy is the most developed marine renewable, with a relatively mature technology [9–11]. Tidal [12–14] and wave energy [15,16] are less developed. Notwithstanding their environmental benefits, these renewables have to be economically competitive if they are to attract significant investment [17]. Offshore wind energy has a greater resource and better availability than its onshore counterpart [18–21]; on the minus side, it involves higher initial investments and maintenance costs [22,23]. Comparatively frequent maintenance is required in the harsh marine environment [24], yet access to the turbines by workboats – the most cost-effective access system [22] – is only possible when the significant wave height is below 1.5 m [22,25,26]. The resulting downtime [27–30] causes significant costs and raises the power output variability, all of which may hamper the development of offshore wind.

In this context, the co-location of Wave Energy Converters (WECs) in a wind farm [31] has emerged as a solution to increase the accessibility to the wind turbines: the co-located WECs extract energy from the incident waves [32], reducing wave heights in their lee [33,34] and, consequently, improving the accessibility to the wind turbines [35–37]. Moreover, other synergies between offshore wind and wave energy can be realised through the co-located WECs [35,38], including a more sustainable use of the scarce marine space [39], a reduction in the intermittency inherent to renewables [40,41] or the opportunity to reduce costs by sharing some of the most expensive elements of an offshore project [34,42].

Within these co-located arrays, different options may be considered [43]: (i) a Peripherally Distributed Array (PDA), where WECs are placed along the perimeter of the wind farm, forming a barrier; (ii) a Uniformly Distributed Array (UDA), with WECs deployed uniformly throughout the wind farm; or (iii) a Non-uniformly Distributed Array (NDA). Previous studies [31,44] demonstrated that co-located farms increase considerably the accessibility to the wind turbines for maintenance. However, in the

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Nomenclature

A_{TR}	rated power of transformer (MVA)
AWT_k	percentage of Accessible Wind Turbines during the k percentage of time
b	the pile spacing (m)
c_x	spatial velocities in the x component (ms^{-1})
c_y	spatial velocities in the y component (ms^{-1})
c_t	transmission coefficient of the offshore wind turbines
c_θ	rate of change of group velocity which describe the directional rate of turning
c_σ	rate of change of group velocity which describe the frequency shifting due to changes in currents and water depth
C_d	drag coefficient of the piles
C_{cable}	cost of the electricity transmission cable (€/m)
$C_{MV/HV}$	cost of the MV/HV transformer (k€)
C_t	total costs (€)
CALM	Catenary Anchor Leg Mooring
d	depth (m)
D	distance between the twin bows of a single WaveCat WEC
D_c	catenary diameter (m)
D_p	pile diameter (m)
EMODnet	European Marine Observation and Data Network
ERDF	European Regional and Development Fund
H_i	incident significant wave height (m)
H_s	significant wave height (m)
H_{si}	significant wave height incident on the i-th turbine in the baseline scenario without WECs (m)
$H_{s,WECi}$	significant height incident on the i-th turbine with co-located WECs (m)
HRA_j	significant wave Height Reduction along the j-th Area of wind turbines with co-located WECs
HRF	wave Height Reduction within the Farm with co-located WECs (m)
$I_{n,}$	maximal current in the medium voltage cable (A)
J_{farm}	average power output of all co-located WECs (W/m)
$J_{W,i}$	power production of the i-th WEC (W/m)
J_{WEC}	average power production per WEC generated by the co-located (W/m)
k	percentage of time during which the wind turbines are accessible
K	constant with a value 0.02 kg/(m·mm^2) for studless chain and 0.0219 kg/(m·mm^2) for stud-link chain
m	number of turbines in the j-th area
n	total number of wind turbines
n_W	total number of WECs
N	wave action density spectrum (Js)
NDA	Non-uniformly Distributed Array
L	total length of the catenary (m)
$LCOE$	Levelised Cost of Energy
O_t	electricity generation (MWh)
O&M	Operation & Maintenance
PDA	Peripherally Distributed Array
PTO	Power Take-off System
r	discount rate
S_{tot}	energy density source terms which describe local changes to the wave spectrum (Js^{-1})
SWAN	Simulating WAves Nearshore
t	a point in time
T	total number of time points considered
T_p	peak wave period (s)
U_w	wind speed at 10 m.
UDA	Uniformly Distributed Array
W_{CALM}	weight of the mooring system (N)
WEC	Wave Energy Converter
WF	Wind Farm
α	cost coefficient to calculate the electricity transmission cable that depends on the operating voltage of the cable (€/m)
β	cost coefficient to calculate the electricity transmission cable that depends on the operating voltage of the cable (€/m)
γ	cost coefficient to calculate the electricity transmission cable that depends on the operating voltage of the cable (1/A)
θ_{wave}	wave direction (°)
θ_{wind}	wind direction (°)

first case (PDA array) the wave height reduction achieved in the area farthest from the barrier of WECs was not enough to ensure an appropriate level of accessibility [45]. The NDA configuration, with part of the WECs forming a peripheral barrier and the remaining WECs interspersed between the wind turbines to counter wave regeneration by diffracted energy overcomes this downside, resulting in a more uniform wave height reduction [46]. However, this configuration presents other shortcomings, notably in relation to the installation of the moorings and submarine cables and the manoeuvrability of workboats for access to wind turbines and WECs, which are not facilitated by the non-uniform layout [47].

With this in view, the aim of this work is to assess the option of uniformly distributed arrays (UDAs), and in particular to determine whether this configuration may achieve similar values of wave height reduction while facilitating the circulation through the farm. For this purpose, a case study at the Horns Rev offshore wind farm is carried out in which four UDA layouts are considered. A third-generation wave model, SWAN (Simulating WAves Nearshore) and real (observed) wave data are used for estimating the wave conditions within the farm.

This paper is structured in four steps. First, on the basis of previous results obtained at Horns Rev 1 with PDA and NDA configurations, four UDA configurations are proposed and tested for a representative sea state. Second, the two best configurations are simulated with real annual sea data by means of the wave model. Third, the results obtained are analysed in terms of wave height reduction within the wind farm area and power production by means of indicators defined *ad hoc*. These results are then translated into monetary terms by means of the levelised cost. Finally, the results for the UDA co-located farms are compared with those for PDAs and NDAs, and conclusions are drawn.

2. Methodology

2.1. Study area

The assessment of the UDAs was carried out by considering an offshore wind farm currently in operation: Horns Rev 1. Located off the Danish North Sea coast (Fig. 1), the water depth and distance to shore are in the ranges 6–14 m and 14–20 km, respectively. Horns Rev 1 is composed by 80 turbines (Vestas V80-2 MW) with a