Energy Conversion and Management 91 (2015) 63–75

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Co-located wind-wave farm synergies (Operation & Maintenance): A case study

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ARTICLE INFO

Article history:
Received 9 September 2014
Accepted 29 November 2014

Keywords:
Wave energy
Wind energy
Co-located wind-wave farm
Weather windows
O&M
Shadow effect

ABSTRACT

Operation and maintenance can jeopardise the financial viability of an offshore wind energy project due to the cost of downtime, repairs and, above all, the inevitable uncertainties. The variability of wave climate can impede or hinder emergency repairs when a failure occurs, and the resulting delays imply additional costs which ultimately reduce the competitiveness of offshore wind energy as an alternative to fossil fuels. Co-located wind turbines and Wave Energy Converters (WECs) are proposed in this paper as a novel solution: the reduction of the significant wave height brought about by the WECs along the periphery of the wind farm results in a milder wave climate within the farm. This reduction, also called *shadow effect*, enlarges weather windows for Operation & Maintenance (O&M). The objective of this paper is to investigate the increase in the accessibility time to the turbines and to optimise the layout for the co-located wind-wave farm in order to maximise this time. The investigation is carried out through a case study: Alpha Ventus, an operating offshore wind farm. To maximise the reduction of wave height in the turbine area no fewer than 15 layouts are tested using high-resolution numerical modelling, and a sensitivity analysis is conducted. The results show that, thanks to the wave energy extraction by the WECs, weather windows (access time) can increase very significantly – over 80%. This substantial effect, together with other benefits from the combination of wave and offshore wind power in a co-located farm (common electrical infrastructures, shared O&M equipment and crews, etc.) will enhance the economic viability of these marine renewables, and hence their potential to reduce our carbon footprint on the planet.

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1. Introduction

Investment in offshore wind systems has been growing rapidly throughout Europe in order to achieve EU targets for renewable energy in 2020 [1]. The main advantage of offshore wind over wind energy projects on land is the greater availability and power of resource [2–5], which in turn implies a higher capacity credit, and thus smaller back-up costs [6]. In exchange, the costs of offshore wind farms are much higher, driven partly by the distance from the coast and partly by the harsh conditions of the marine environment [7], which imply higher investment and Operation and Maintenance (O&M) expenditures [8,9]. Indeed, O&M costs of offshore wind farms typically constitute between 20% and 25% of the total lifetime costs of the installation [10–12]. Apart from the typical cost components of O&M (regular maintenance, insurance, repairs, spare parts and administration) [12], the accessibility to the turbines is key [13]. In this sense, the operational limit of workboats – the most cost-effective access system [10] – is a significant wave height of 1.5 m [10,14,15]. When this threshold is exceeded delays in maintenance and repairs ensue, and the resulting down time causes earnings to be missed. In previous works the savings that can be achieved by enlarging the weather windows for O&M were estimated at 25%; which would lead to an reduction in the overall project cost of energy of 2.3% [16]. Therefore, the relevance of the weather windows and their eventual enlargement to the overall viability of a project is clear.

This extension of the weather windows for O&M is one of the synergies that can be realised by combining wave and offshore wind energy thanks to the wave energy extraction of the WECs (Wave Energy Converters) that are placed appropriately in relation to the offshore wind turbines and the prevailing waves. This is the focus of this work, in which a sensitivity analysis of the key parameters in the design of the wave farm layout (e.g., array configuration, intra- and inter-row spacing) is carried out to establish the best layout. Moreover, combining both renewables may strengthen

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http://dx.doi.org/10.1016/j.enconman.2014.11.060
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Nomenclature

b	spacing between the piles of the wind turbines (m)
BSH	Bundesamt fuer Seeschiffahrt und Hydrographie
c_x	spatial velocities in the x components (ms^{-1})
c_y	spatial velocities in the y components (ms^{-1})
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
CSi	case study i-th
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)
EU	European union
H_s	significant wave height (m)
Hs_i	significant height incident on the i-th wind turbine in the baseline scenario, i.e. without WECs (m)
$HsWEC_i$	significant height incident on the i-th wind turbine with co-located WECs (m)
HRC_j	significant wave height reduction along the j-th Column of wind turbines. This nondimensional index reflects the wave recovery with increasing distance from the WECs
HRF	wave height reduction within the farm. It is a nondimensional 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_{WECi}	wave power (W/m) of the i-th WEC
m	number of turbines in the j-th column
n	total number of wind turbines
n_{WECs}	number of WECs
N	wave action density spectrum (Js)
O&M	Operation & Maintenance
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 (Js^{-1})
SWAN	simulating WAves nearshore
t	a point in time (s)
T	total number of time points considered (s)
T_{BS}	total number of hours per year with $H_s \leqslant 1.5$ m but for the baseline scenario, i.e. isolated turbines (h)
T_p	peak wave period (s)
T_{WECs}	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
VRi	i-th vertical row of WECs
WEC	Wave Energy Converter
$\Delta T_{O\&M}$	increase in the accessible timeframe for O&M achieved with co-located WECs
θ	wave direction (°)

wave energy development, a renewable in its infancy but with substantial available resource in some areas [17]. In fact, the characterisation of the available resource is currently one of the most active research lines [18–22], along with the development of efficient and reliable technology [23–29] and, more recently, the analysis of the environmental impact [30–35] and commercial viability [36–40]. The multiple synergies that can be realised by combining wave and offshore wind energy were brought to light by Refs. [41–45]. In particular, the shielding effect of WECs over the offshore wind farm is mentioned in Refs. [46–48], and is one of the reasons why co-located wave-wind farms and hybrid systems have emerged with force in recent years [46,49–51].

On this basis, the objective of this paper is to investigate how the synergy between wave and offshore wind energy, by virtue of the reduction of the significant wave height caused by the WECs extracting part of the energy of the incoming waves, leads to enlarged weather windows for O&M. This objective is achieved through a case study: Alpha Ventus, an operating offshore wind farm.

2. Materials and methods

This paper is structured as follows. First, the case study (the Alpha Ventus wind farm) and the wave climate in this area are described. Second, the numerical model of wave propagation in the coastal zone, SWAN, is validated. Third, the shadow effect is analysed in a comparative study involving 15 different layouts under typical wave conditions, for the purpose of determining their effectiveness in reducing the wave height within the farm. Fourth, the duration of time during which the turbines can be accessed for O&M (weather windows) is determined for the best WECs layouts based on annual wave climate data. Finally, the power generated by the WECs is examined.

2.1. Case study: location and wave climate

As discussed in the previous section, the analysis of the shadow effect provided by a wave farm was investigated through a real wind farm, Alpha Ventus (Fig. 1). This park lies about 45 km north of the island of Borkum (Germany), in water depths of approx. 30 m [52].

Wave data were obtained from the FINO1 research platform, located at a distance from the farm of only 400 m [53]. Since 2003 this platform has been supplying half-hourly weather data. The wave buoy data were used in conjunction with hindcast data from WaveWatch III, a third-generation offshore wave model consisting of global and regional nested grids with a resolution of 100 km [54], to validate the high-resolution nearshore wave propagation model. The period selected for the study is January 2013 to December 2013 (Fig. 6). The mean values in this period of significant wave height (H_s), peak wave period (T_p) and mean wave direction (θ_m) were 1.5 m, 6.5 s and 330° (Fig. 2). As for the wind, the average wind speed at the site was 10 ms^{-1} and the prevailing wind direction was 210–240° (southwest) [52].

2.2. 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 [55–60] 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 [61], Eq. (1), which equates the propagation of wave action density in each dimension balanced by local changes to the wave spectrum. The wave model was set up to account the following wave processes: shoaling, refraction due to current and

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