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Towards the optimal design of a co-located wind-wave farm

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A B S T R A C T

The cost competitiveness of wave energy must be enhanced if it is to become a viable alternative to fossil fuels. This can be achieved by realising the synergies between wave and offshore wind energy through co-located wind turbines and WECs (Wave Energy Converters). First, by using the infrastructure of the wind farm the WECs will be less costly to install and maintain. Second, by deploying the WECs along the periphery of the farm a milder wave climate (*shadow effect*) will ensue within the farm and result in reduced structural loads and enlarged weather windows for Operation & Maintenance. The objective of this work is to investigate the optimum layout for the co-located wind-wave farm with a view to maximising these benefits. This investigation is carried out through a case study: an offshore wind farm consisting of 80 turbines in the Wave Hub area (SW England). To analyse the influence of the farm layout, high-resolution numerical modelling is used, and no fewer than 14 different layouts are compared. We find that the layout does play a fundamental role and that reductions of up to 40% in the significant wave height can be achieved – or up to 64% in terms of energy density.

1. Introduction

The option of combining different renewables in the same area was recently proposed to manage the variability of renewable power and reduce the system integration costs of renewables [1–6]. In this sense, the present work is focused on the integration of two marine energies: offshore wind and wave energy. Marine energy has been undergoing a significant development in the last decades as one of the alternatives to fossil fuels with better perspectives for the future due to its enormous resource [7–15]. The global wave energy potential resource has been estimated at 10 TW [16], and depending on what is considered to be exploitable, this covers from 15% to 66% of the total world energy consumption [17,18].

This increasing interest in marine energy has been reflected in the very active research lines, among which: the characterisation of the resource [10–15,19–33], the development of efficient, reliable technologies and the assessment of their performance [8,17,34–49], and, more recently, the analysis of the environmental impact [16,50–59] and the commercial viability [7,9,60–62].

All this interest notwithstanding, marine energy is still regarded as uneconomical and non-competitive in comparison with other energy sources [62]. For this reason, co-located wave-wind farms and hybrid systems have emerged with force [63–66]. By increasing the energy yield per unit area of marine space occupied, a more sustainable use of the natural resources is achieved [1]. Moreover, this combination brings about a cost reduction owing to the use of common installations, such as the electric grid infrastructure, and common specialized marine equipment, vessels and crews. Last, but not least, an important reduction in the cost of maintenance ensues due to more frequent and longer Access Weather Windows [65].

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 [65]. This work is focused on the first, co-located wave-wind farms [4,67], since this is closer to their commercial development than the other options [6,68,69]. In co-located farms, WECs (Wave Energy Converters) are distributed between the wind turbines along the periphery of the array, facing the incoming waves. This approach takes advantage of the shadow effect of the WECs, which extract wave energy and thereby reduce the significant wave height within the farm. For the case study the selected WEC is WaveCat [40] due to its appropriate dimensions relative to the spacing between wind turbines.

The aim of this paper is to study this shadow effect considering different layouts of the co-located wind-wave farm. Numerical modelling is applied to investigate the interaction between the

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WECs and the offshore wind substructures in a number of array configurations. In this study, real sea conditions are considered. The results for the different layouts are compared with the baseline configuration (the offshore wind farm without WECs), and on these grounds recommendations on the configuration of a co-located wave-wind farm are given.

2. Methods

This paper can be divided into four steps. First, an appropriate location for the case study was defined, along with its characteristic wave conditions, the wind farm configuration and the different layouts for the co-located WECs. Second, the third-generation numerical model SWAN (Simulating Waves Nearshore) was implemented to simulate the surface wave conditions, considering wind turbines and WECs as obstacles. Its application led to valuable results about the wave height reductions that could be achieved with the different layouts. A series of impact indicators were applied to determine the best array configurations. The selected arrays were examined under different wave conditions, assessing the power generated by WECs.

2.1. *Case study: location and wave climate*

The analysis of the shadow effect provided by a wave farm was carried out through a hypothetical wind farm at the Wave Hub site, approximately 20 km northwest of St Ives Bay in Cornwall, in the extreme southwest of the UK (Fig. 1). The water depth is 40–60 m [70].

As regards the wave conditions, the most recent available data were considered, in particular the wave data reported in Ref. [72], which contain values in 8 directional sectors for monthly cases with a one year return period, and all-year cases with return periods of 1, 10, 50 and 100 years. On this ground, 9 case studies were defined as representative of the wave climate in the area (Table 1).

Table 1
Parameters of the CS (case studies): H_s = significant wave height; T_p = energy period; θ = mean wave direction.

CS	H_s (m)	T_p (s)	$\theta(^\circ)$
1	1.5	7.57	270
2	2.5	8.14	270
3	3.5	9.33	270
1b	1.5	7.57	315
2b	2.5	8.14	315
3b	3.5	9.33	315
1c	1.5	7.57	225
2c	2.5	8.14	225
3c	3.5	9.33	225

2.2. *Co-located farm design*

With regard to the co-located farm, recent studies have dealt with the influence of the distance between turbines on the wave field-farm interaction [73–80]. In the present work, the layout of the wind farm of Horns Rev1, currently in operation, was chosen as a case study [81–85]. It is composed of 80 turbines (Vestas V80-2 MW) erected in a grid pattern with 10 rows. The distance between adjacent turbines is 560 m [86,87], or 7 times the rotor diameter; the farm occupies a total area of approximately 20 km^2 (Fig. 2) with an average water depth of 50 m. The substructure of the wind turbines is jackets of 18 m × 18 m. The wind farm is staggered for the main wind direction in this area (Fig. 2) in order to maximise the energy output.

For its parts, the WEC used for the case study was the WaveCat: a floating offshore WEC whose principle of operation is wave overtopping, and with a length overall of 90 m [40]. The minimum distance between devices is 2.2*D*, where $D = 90$ m is the distance between the twin bows of a single WaveCat WEC [51]. In this study, 14 wave farm configurations – specifically designed to face the main wave direction (Section 2.1) – were tested: three basic layouts (named A, B, C) with different spacings between devices:

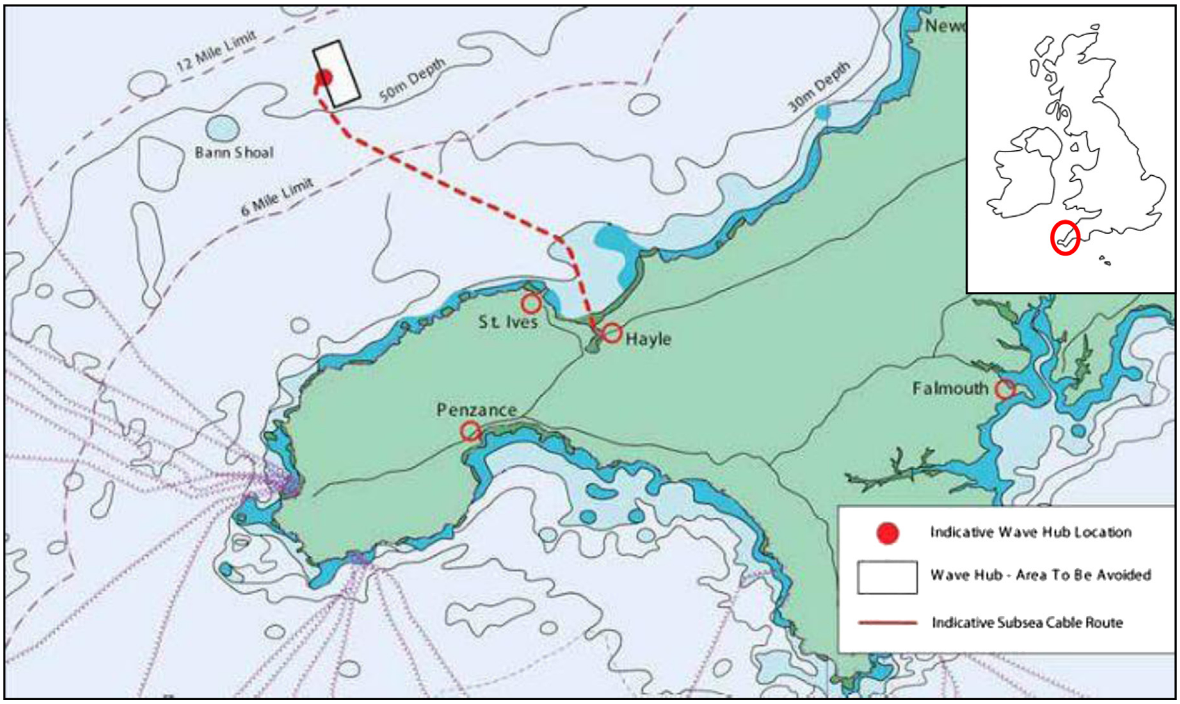

Fig. 1. Wave hub location [71].

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