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Selecting optimum locations for co-located wave and wind energy farms. Part II: A case study

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ABSTRACT

Combined energy systems present an opportunity to enhance the competitiveness of renewables and overcome other challenges of these novel renewables by realising the synergies between them. Among the different possibilities for combined systems, this work focuses on wave and wind co-located farms with the aim of assessing their benefits relative to standalone wind farms. To this end we estimate the energy production, investigate the power smoothing and shadow effect, and quantify the reduction in downtime achieved by the co-located farm through a case study off the Danish coast – a promising area for co-located farms based on the available resource and other considerations including technical constraints. The analysis is carried out based on hindcast data and observations extending from 2005 to 2015, and by means of state-of-the-art numerical models of the wind and wave fields – WAsP and SWAN, respectively. It is found that the energy yield per unit area with the combined wave-wind farm increases by 3.4% relative to a standalone wind farm, the downtime periods decrease by 58% and the power output variability reduces by 12.5%. Moreover, the capital and operational expenditures (CAPEX and OPEX, respectively) would also be significantly reduced thanks to the synergies realised through the combination of wind and wave power.

1. Introduction

The Renewable Energy (RES) Directive (2009/29/EC) established an EU target of a 20% share of renewable energy in the total energy consumption by 2020. 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 to well below 2 °C. The agreement is due to enter into force in 2020. In this context, marine energy [1] emerges as one of the most promising alternatives to fossil fuels due to its substantial potential for electricity production [2], not least through the combination of various renewables in the same marine space [3], which can significantly enhance marine energy competitiveness [4]. Co-located projects are a solution to simultaneously tackle two major challenges: reducing technology costs [5] and achieving a more sustainable use of natural resources [6]. In particular, this research deals with the co-location of Wave Energy Conversion (WEC) technologies into a conventional offshore wind farm [7]. The addition of co-located Wave Energy Converters (WECs) to wind farms [8] is supported by a number of synergies ranging from an increase in the energy yield [9] to a reduction in the operation and maintenance cost [10] and smoothed power output [11].

In Part I of this work, the wave resource off the Danish coast was characterised in order to determine the best location for a co-located wave and wind energy farm. The aim of Part II is to define a co-located wave and wind farm at this location and assess its benefits relative to a standalone, conventional offshore wind farm. The co-located farm is designed on the basis of the current offshore farms characteristics and the results of previous studies concerning the most convenient co-located farm layout [12]. Hourly wave and wind observations from 2005 to 2015 combined with hindcast data are implemented on two numerical models: WAsP (Wind Atlas Analysis and Application Program) and SWAN (Simulating WAves Nearshore). The former is an industry-standard software for predicting the wind climate, wind resource, and power production from wind farms; and the latter is a third-generation numerical model that calculates wave generation and propagation.

The differences between the combined system and the conventional wind farm are quantified in terms not only of the global power production but also the performance of the devices, the downtime periods and the power variability. Moreover, the

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Nomenclature

AWT_k	percentage of Accessible Wind Turbines during k % of time
b	spacing between the piles of the wind turbines (m)
$c\ (\tau)$	cross-correlation factor between two variables for a time lag τ
c_t	transmission coefficient of the offshore wind turbines
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 describes the directional (θ) rate of turning due to changes in currents and water depth
c_σ	rate of change of group velocity which describes the frequency (σ) shifting due to changes in currents and water depth
C_d	drag coefficient of the wind turbine piles
d	water depth (m)
D	rotor diameter (m)
D_p	diameter of the wind turbine piles (m)
E	energy density (J m^{-3})
EMODnet	European Marine Observation and Data Network
ERDF	European Regional and Development Fund
f	wave frequency (s^{-1})
g	gravity acceleration (ms^{-2})
H	height at which the wind speed is measured (m)
H_{m0}	significant wave height (m)
$\overline{H}_{m0}$	average significant wave height (m)
$H_{m0,max}$	maximum value of the 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)
HRC_j	significant wave height reduction along the j-th row 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
IA	increase in the accessible timeframe for O&M achieved with co-located WECs
J	raw wave power (kW m^{-1})
$\overline{J}$	average raw wave power (kW m^{-1})
$\overline{J}_{farm}$	time-averaged power generated by the WECs (kW)
$J_{W,i}$	is the power generated by the i-th WEC (kW)
k	percentage of time during which the wind turbines are accessible
L	distance between the twin bows of a single WaveCat WEC (m)
m	number of turbines in the j-th row
m_n	spectral moment of order n
n_T	total number of time points
n_W	total number of WECs or wind turbines
N	wave action density spectrum (J s)
O&M	operation & maintenance
P	raw wind power (kW m^{-2})
$\overline{P}$	average raw wind power (kW m^{-2})
$\overline{P}_{farm}$	time-averaged power generated by the wind turbines (kW)
$\overline{P}_{w,i}$	is the power generated by the i-th wind turbine (kW)
PDA	Peripherally Distributed Array
R^2	coefficient of determination
RES	Renewable Energy Directive (2009/29/EC)
$RMSE$	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 Hs $\leqslant$ 1.5 m for the baseline scenario, i.e. isolated turbines (h)
T_e	energy period (s)
$\overline{T}_e$	average energy period (s)
$T_{e,max}$	maximum energy period (s)
T_{mo1}	mean 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
THD	Total Harmonic Distortion
U_w	wind speed (ms^{-1})
U_{10m}	wind speed at 10 m above the sea level (ms^{-1})
U_{10m}	average wind speed 10 m above the sea level (ms^{-1})
$\overline{U}_{10m,max}$	maximum value of the wind speed 10 m above the sea level (ms^{-1})
WAsP	Wind Atlas Analysis and Application Program
WEC	Wave Energy Converter
z	roughness length (m)
ρ_a	air density (kg m^{-3})
ρ_w	sea water density (kg m^{-3})
θ	propagation direction (°)
σ	standard deviation
μ	average value

enlarged weather windows for O&M (Operation and Maintenance) thanks to the shadow effect of the co-located WECs are determined.

2. Materials and methods

2.1. Wave and wind numerical models

The wind resource assessment and wind farm calculations were carried out by means of the WAsP (Wind Atlas Analysis and Application Program) software [13], which is an implementation of the so-called wind atlas methodology [14]. The program employs a comprehensive list of models for projection of the horizontal and vertical extrapolation of wind climate statistics [15]. It is a linear numerical model based on the physical principles of flows in the atmospheric boundary layer, capable of describing wind flow over different terrains, close to sheltering obstacles and at specific points. Moreover, WAsP models the estimated power loss in wind farms due to the wind speed reduction in wakes from up-wind turbines [16]. In terms of wind farm modelling, the wake model in the commercial version is based on Katic et al. [17], using a linear expansion of the wake diameter set with a wake decay coefficient – a value of 0.04 or 0.05 is recommended for offshore applications [18]. The model has been amply validated through a number of comparisons between measured and modelled wind statistics and wind farm production [19].

The available wave resource was assessed through the third-generation numerical wave model SWAN (Simulating WAves Nearshore). This model was successfully applied to examining the