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Selecting optimum locations for co-located wave and wind energy farms. Part I: The Co-Location Feasibility index

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ABSTRACT

Marine energy is poised to play a fundamental role in meeting renewable energy and carbon emission targets thanks to the abundant, and still largely untapped, wave and tidal resources. However, it is often considered difficult and uneconomical – as is usually the case of nascent technologies. Combining various renewables, such as wave and offshore wind energy, has emerged as a solution to improve their competitiveness and in the process overcome other challenges that hinder their development. The objective of this paper is to develop a new approach to identifying suitable sites for co-located wave and wind farms based on the assessment of the available resources and technical constraints, and to illustrate its application by means of a case study off the Danish coast – an area of interest for combining wave and wind energy. The method is based on an *ad hoc* tool, the Co-Location Feasibility (*CLF*) index, and is based on a joint characterisation of the wave and wind resources, which takes into account not only the available power but also the correlation between both resources and the power variability. The analysis is carried out based on hindcast data and observations from 2005 to 2015, and using third-generation models of winds and waves – WAsP and SWAN, respectively. Upon selection and ranking, it is found that a number of sites in the study region are indeed suited to realising the synergies between wave and offshore wind energy. The approach developed in this work can be applied elsewhere.

1. Introduction

The EU's current policy framework includes the Renewable Energy (RES) Directive (2009/29/EC), which establishes a target of 20% of renewable energy in the total energy consumption by 2020. In order to translate this general policy into concrete action, Member States are to define and publish National Renewable Energy Actions Plans indicating the mix of renewable energy technologies to be implemented. In this context, marine energy [1] has emerged as one of the most promising alternatives to fossil fuels due to the substantial resource and potential for development [2]. Among the different options, this paper is focused on offshore wind and wave energy [3] and their combination [4].

Offshore wind is admittedly more complex and costly than its onshore counterpart; however, it provides higher energy yields thanks to a combination of better resources and larger turbines, and is less contentious. The sea offers more space for deploying energy parks [5]. The installed capacity of offshore wind in the EU reached 6562 MW at the end of 2013, producing 24 TW h in a normal wind year – enough to cover 0.7pc of the EU's electricity consumption [6]. As for wave energy, it presents extensive possibilities for the future thanks to its enormous potential for electricity production [7]. However, it is still in its infancy and the technology has a high levelised cost [8]. The inclusion of co-located Wave Energy Converters (WECs) into wind farms [9] could accelerate the development of wave energy technology, which may be expected to lead to reductions in the cost of wave energy based on the learning curve [10]. Moreover, other synergies [5] can be realised through wave and wind combined energy systems, such as cost savings by common elements [11] and coordinated strategies [12], smoothed power output [13] or a more sustainable use of the natural resources [14].

Finding suitable locations for the development of offshore parks [15] is fundamental to appeal to investors and boost the development of these novel renewables. For that purpose, not only the available resource has to be considered, the water depth or distance to land have to be assessed in a holistic way. The North

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Nomenclature

$c\,(\tau)$	cross-correlation factor between two variables for a time lag τ
$c\,(0)$	instantaneous correlation
c.i.	confidence interval
CLFi	Co-Location Feasibility index of the *i*-th site point
CS	Case Study
E	energy density (J/m^3)
EMODnet	European Marine Observation and Data Network
ERDF	European Regional and Development Fund
g	gravity acceleration (m/s^2)
H	height at which the wind speed is measured (m)
H_{m0}	significant wave height (m)
$\bar{H}_{m0}$	average significant wave height (m)
$H_{m0,\max}$	maximum value of the significant wave height (m)
J	raw wave power (kW/m)
$\bar{J}$	average raw wave power (kW/m)
m_n	spectral moment of order *n*
P	raw wind power (kW/m^2)
$\bar{P}$	average raw wind power (kW/m^2)
R^2	coefficient of determination
RMSE	Root Main Square Error
SWAN	Simulating WAves Nearshore
T_e	energy period (s)
$\bar{T}_e$	average energy period (s)
$T_{e,\max}$	maximum energy period (s)
T_{mo1}	mean wave period (s)
U_w	wind speed (m/s)
U_{10m}	wind speed at 10 m above the sea level (m/s)
$\bar{U}_{10m}$	average wind speed 10 m above the sea level (m/s)
$U_{10m,\max}$	maximum value of the wind speed 10 m above the sea level (m/s)
WAsP	Wind Atlas Analysis and Application Program
WEC	Wave Energy Converter
z	roughness length (m)
α_x	weighted factor of the parameter *x* when calculating the *CLF* index
ρ_a	air density (kg/m^3)
ρ_w	sea water density (kg/m^3)
θ	propagation direction (°)
$\theta_{wav,mean}$	mean wave direction (°)
$\theta_{wind,mean}$	mean wind direction (°)
σ	standard deviation
σ_J	standard deviation of the wave raw power (kW/m)
σ_p	standard deviation of the wind raw power (kW/m^2)
μ	average value

Sea basin has been identified in previous studies as one of the best areas for deploying co-located farms due to the available resource and the existing shallow water [16]. Indeed, recent works such as [16] or [17] identified the Danish coast of the North Sea as a promising area for combined wind and wave energy farms. Denmark has indicated offshore wind energy targets of 1.3 GW [18] and 4.6 GW [19] by 2010 and 2025, respectively. At present, the majority of Members States have not set any targets for the development of marine energy projects in their sea basin, and therefore the elaboration of a plan for marine energy development would be a major step for progress.

The aim of this paper is to characterise the available wave and wind resource in the Danish coast to select a suitable location on the basis of the relevant factors, such as the existing wave and wind resources, water depth or distance to land. Hourly sea data from 2005 to 2015 combined with hindcasts are implemented in 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 commonly used to calculate wave generation and propagation. This paper has a second part where a co-located farm was deployed in the location identified as the optimal site in this first part with the purpose of analysing the benefits of this farm in comparison to two independent wave and wind parks.

This paper is structured in three steps. First, four case studies were defined and simulated on the basis of the available wave and wind data to determine a narrow area suitable for co-located farms within the West Danish coast, taking into account the technical limitations of water depth and distance to coast. Second, annual series of data from February 2005 to January 2015 were run by means of numerical models to identify the best location within the previously defined area through the Co-Location Feasibility (*CLF*) index, which encompasses the available resource, power variability and correlation between waves and winds. Third, the wave and wind resources in the selected location were deeply analysed.

2. Materials and methods

2.1. Study area

This study is focused on the West Danish coast of the North Sea (Fig. 1). It is characterised by fairly long coastline and areas of shallow waters that hold great opportunities for marine energy [19]. Indeed, Denmark has the second largest amount of installed offshore wind energy capacity in Europe, behind the UK, with 1271 MW in 2014 (19% of total European installations) [20].

Nowadays there are technical limitations that prevent offshore installations from being installed in water depths over 50 m [21]. The vast majority of current offshore wind farms are in water depths below 35 m – which is the limit for monopile foundations [22]. Almost the entire study area was under this limit with the exception of the NW corner (Fig. 2). The distance from land is also fundamental when looking for a suitable location for it affects the capital and maintenance costs significantly. The current wind farms in the Danish coast are usually between 10 and 30 km away for the coastline (Fig. 2).

2.2. Wave propagation and wind models

The wind resource assessment and wind farm calculations were carried out by means of the WAsP (Wind Atlas Analysis and Application Program) software [23], which is an implementation of the so-called wind atlas methodology [24]. The program employs a comprehensive list of models for projection of the horizontal and vertical extrapolation of wind climate statistics [25]. It is a linear numerical model based on the physical principles of flows in the atmospheric boundary layer, and it is capable of describing wind flow over different terrains, close to sheltering obstacles and at specific points.

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 impact of wave farms on the wave conditions in their lee in recent studies [26]. It computes the evolution of random waves

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