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The collocation feasibility index – A method for selecting sites for co-located wave and wind farms

S. Astariz [a, *], G. Iglesias [b]

[a] University of Santiago de Compostela, EPS, Hydraulic Eng., Campus Univ. s/n, 27002 Lugo, Spain
[b] University of Plymouth, School of Marine Science and Engineering, Drake Circus, Plymouth PL4 8AA, UK

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A B S T R A C T

Marine energy is one of the most promising solutions to attempt the ambitious renewable energy target of 20% by 2020 due to its very substantial energy resource. However, it is often considered uneconomical and difficult, and this may hinder its development. Combined energy systems, such as co-located offshore wind turbines and wave energy converters, have recently emerged as a solution to increase the competitiveness of marine energy by taking advantage of the synergies between renewables; which would lead to reductions in the energy cost and improvements in the power output variability and security. On this basis, finding viable locations for combined offshore renewable energies is fundamental to boosting their development. The objective of this paper is to determine suitable locations for deploying a co-located wind and wave energy farm in the North Sea - an area with several characteristics that make large-scale integration of renewable energy sources attractive. In this assessment we investigate not only the existing resource but also other parameters such as its variability and the correlation between waves and winds by means of the *CLF* index. In addition, inter- and intra-national user conflicts are considered, while balancing environmental conservation and economic development.

1. Introduction

Marine energy, carried by ocean waves, tides, salinity, ocean temperature differences and also offshore winds [1], has emerged as one of the most attractive solutions to meet the major energy challenge of transforming Europe into a highly energy-efficient and low-GHG economy [2]. The main argument that supports the substantial use of this energy is its enormous potential for electricity production [3,4]. Nevertheless, there are several barriers that may hinder the development of marine energies, such as the early stage of technology development of some marine renewables such as wave energy [5–7], the higher costs involved relative to onshore installations [8–10] or uncertainties regarding the environmental impacts [11–13].

Among the different alternatives of marine energy, this work focuses on two of them: offshore wind and wave energy. As for the former, investment in offshore wind systems has been growing rapidly throughout Europe in order to achieve EU targets for renewable energy in 2020 [2], due to the powerful available resource [14] and its similarities to its onshore counterpart. However, there exist some limitations that could hinder its introduction into the energy mix, such as the higher investment implied, more demanding maintenance tasks or power variability. For its part, wave energy presents extensive possibilities for the future thanks to its enormous potential for electricity production [15,16]. In fact, the global gross wave energy resource has been estimated at about 4TW [17]. Nevertheless, wave energy is still in its infancy and its levelised cost is high [18–20].

In recent years, taking advantage of various marine renewables at the same time through combined systems has been regarded as a good solution to promote and accelerate the development of marine energy [21–23]. There are many synergies to be realised, such as the more rational use of the marine resource [24], the reduction in the intermittency inherent to renewables [25–28] or the opportunity to reduce costs by sharing some of the most expensive elements of an offshore project [29]; as well as other technology synergies such as the so-called shadow effect [30,31].

According to the degree of connectivity between the offshore wind turbines and Wave Energy Converters (WECs) combined wave-wind systems can be classified into: co-located, hybrid and islands systems [32]. Due to the current state of development of

* Corresponding author.
E-mail address: sharay.astariz@usc.es (S. Astariz).

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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
E	energy density (Jm^{-3})
EEZs	Exclusive Economic Zones
g	gravity acceleration (ms^{-2})
GHG	Green House Gas
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)
ICZM	Integrated Coastal Zone Management
IMO	international shipping lanes
J	raw wave power (kWm^{-1})
$\bar{J}$	average raw wave power (kWm^{-1})
m_n	spectral moment of order n
MSP	Maritime Spatial Planning
P	raw wind power (kWm^{-2})
P	average raw wind power (kWm^{-2})
R^2	coefficient of determination
RMSE	Root Main Square Error
T_e	energy period (s)
$\overline{T}_e$	average energy period (s)
$T_{e,max}$	maximum energy period (s)
T_p	peak wave period (s)
U_w	wind speed (ms^{-1})
U_{10m}	wind speed at 10 m above the sea level (ms^{-1})
$\overline{U}_{10m}$	average wind speed 10 m above the sea level (ms^{-1})
$U_{10m,max}$	maximum value of the wind speed 10 m above the sea level (ms^{-1})
UNCLOS	United Nations Convention on the Law of the Sea
WECs	Wave Energy Converters
α	coefficient depending on the shape of the wave spectrum that relates T_e and T_p
α_x	weighted factor of the parameter x when calculating the *CLF* index
γ	peak enhancement factor in the standard JONSWAP spectrum
ρ_a	air density (kgm^{-3})
ρ_w	sea water density (kgm^{-3})
σ	standard deviation
σ_J	standard deviation of the wave raw power (kWm^{-1})
σ_p	standard deviation of the wind raw power (kWm^{-2})
θ	wave propagation direction
$\theta_{wave,mean}$	mean wave direction (°)
$\theta_{wind,mean}$	mean wind direction (°)
μ	average value

both technologies, the co-location of WECs into a conventional offshore wind farm is regarded as the best option [32], which combines an offshore wind farm and a WEC array with independent foundation systems but sharing the same marine area, grid connection, crafts and crews involved in operation and maintenance tasks, etc.

As was proved in Ref. [33], the possibility of taking advantage of the above synergies will depend on the location considered for the deployment of the co-located farm. Therefore, finding adequate locations is a prerequisite to the large scale deployment of these combined systems [34]. This work focuses on the Central and Southern North Sea, one of the most promising areas for offshore marine energy parks [35] thanks to the large available resource and the relatively shallow waters – about 40% of this area has a water depth below 50 m [36] in line with the current technological limit and helps to keep costs down. However, significant portions of the North Sea are already used by traditional non-wind functions such as shipping or military activities. This can, in effect, create competition for space between the comparatively new marine space user that is offshore marine energy and existing users.

On this basis, the aim of this study is to find the most convenient area to deploy a co-located wind and wave energy farm in the North Sea with a view to maximising the benefits of the combination of the marine resources while minimising effects on other uses. Previous studies (e.g. Refs. [35,37]) analysed the available wind and wave energy resource in the North Sea, but as independent renewables. Only a few works, e.g. Ref. [34], assess both resources in conjunction and these are focused on a specific area of the North Sea, e.g. Ref. [21]. In the present study, different parameters are considered in determining the best location: (i) the available wave and wind resource, their variability and the correlation between them, (ii) the bathymetry and distance to land, (iii) restricted and protected areas such as shipping routes, fishing zones, military areas or natural protected sites, and (iv) economic considerations resulting from factors such as distance to land and grid connection or distance from the meanest suitable port.

2. Methodology

This paper is structured in three steps. First, the available wave and wind resource is assessed through buoy data and numerical hindcasts along the North Sea coast. The best 10 locations in terms of potential power output, variability and correlation between waves and winds are identified. Second, economic considerations, overlap with other uses of the marine space and natural protected areas are considered in selecting the most suitable locations. Third, a thorough analysis of these sites is carried out in order to determine the best location for a co-located wind-wave farm in the Central and Southern North Sea.

2.1. Study area

The Central and Southern North Sea – approaching half a million square kilometres in size [38] – is bordered by 6 countries: Belgium, Denmark, Germany, the Netherlands, Norway and the UK (Fig. 1). It is one of the most promising areas for large scale deployment of offshore marine energy. In fact, a capacity of 135 GW of offshore wind energy might be feasible by 2030 while the current capacity of operational offshore energy is lower than 5 GW [39]. The total capacity of the study area is divided into 44% in the UK, 27% in Germany, 13% in the Netherlands, 7% in Denmark, 6% in Norway and 3% in Belgium [40].

Among the reasons that make the North Sea a great area for offshore projects, the abundant wind and wave resource are maybe the most important [39]. Moreover, the water depth and soil conditions are in line with the current technological requirements. Besides, this sea basin has numerous ports and harbours situated on its coasts, which is important for the construction of the offshore farms and their maintenance tasks during their lifetime. Nevertheless, currently marine renewable energy is still a marginal sector