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The Collocation Feasibility Index – a method for selecting sites for co-located wave and wind farms

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Abstract

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.

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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)

$\bar{H}_{m0}$: 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})

$\bar{P}$: 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 (º)

$\theta_{wind,mean}$: mean wind direction (º)

μ: average value

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.

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 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 [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. [35], [37]) analysed the available wind and wave energy resource in the North Sea, but as independent renewables. Only a few works , e.g. [34], assess both resources in conjunction and these are focused on a specific area of the North Sea, e.g. [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 (Figure 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].

Figure 1. The North Sea and its bordering countries. The red framed area represents the area considered in this study [from (50º N, -4º W) to (59º N, 11º E)].

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 in the North Sea waters. In fact, only wind power is commercially developed (Figure 2), while there are only some not commercial wave energy installations for research and development.

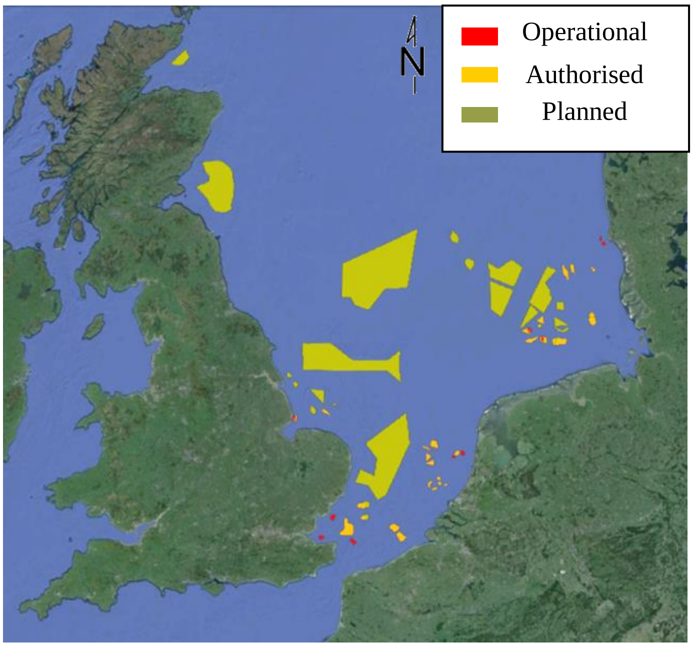

Figure 2. Planned, authorised and operational wind farms in the North Sea area (source: adapted from [41]).

2.2. Available wind and wave resource

The wave and wind data was obtained from a combination of hindcast data from WaveWatch III, a third generation wave model [42], and buoy data along the North Sea coast, encompassing the period from February 2005 to January 2015 with an hourly temporal resolution – in wind energy applications, 5 or more years of data are suggested to give a reasonable wind energy assessment [43]. These data sets were implemented into the third generation models SWAN (Simulating WAves Nearshore) [44] and WAsP (Wind Atlas Analysis and Application Program) [45] to simulate wave and wind propagation within the study area, respectively.

The former model (SWAN) computes the evolution of random waves accounting for refraction, wave generation due to wind, dissipation and non-linear wave-wave interactions [44]. It was successfully applied in recent studies such as [46] or [47]. The evolution of the wave field is described by the action balance equation,

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}c_x N + \frac{\partial}{\partial y}c_y N + \frac{\partial}{\partial \sigma}c_\sigma N \frac{\partial}{\partial \theta}c_\theta N = \frac{S_{tot}}{\sigma}\ , \qquad (1)$$

where t is time (s), c_x and c_y are spatial velocities in the x and y components (ms^{-1}), c_θ and c_σ are rates of change of group velocity which describe respectively the directional (θ) rate of turning and frequency (σ) shifting due to changes in currents and water depth, N is wave action density, and S_{tot} are the energy density source terms which describe local changes to the wave spectrum.

For its part, the WAsP software is an implementation of the so-called wind atlas methodology [48]. The program employs a comprehensive list of models for projection of the horizontal and vertical extrapolation of wind climate statistics [49]. 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 [50]. In terms of wind farm modelling, the wake model in the commercial version is based on Katic et al. [51], 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 [52].The model has been amply validated through a number of comparisons between measured and modelled wind statistics and wind farm production [53].

Both models (SWAN and WAsP) were implemented in conjunction on a computational grid encompassing an area of approx. 10.6 × 10.6 º with a 0.025 º spatial resolution and the North as the open boundary. Bathymetric data from the European Marine

Observation and Data Network (EMODnet) were interpolated onto this grid. The study of the available wave and wind resource was focused on 60 points along the North Sea coast (Figure 3, Table 1). The model output was calibrated with measured wave and wind data provided by buoys along the North Sea coast (Figure 3, Table 2).

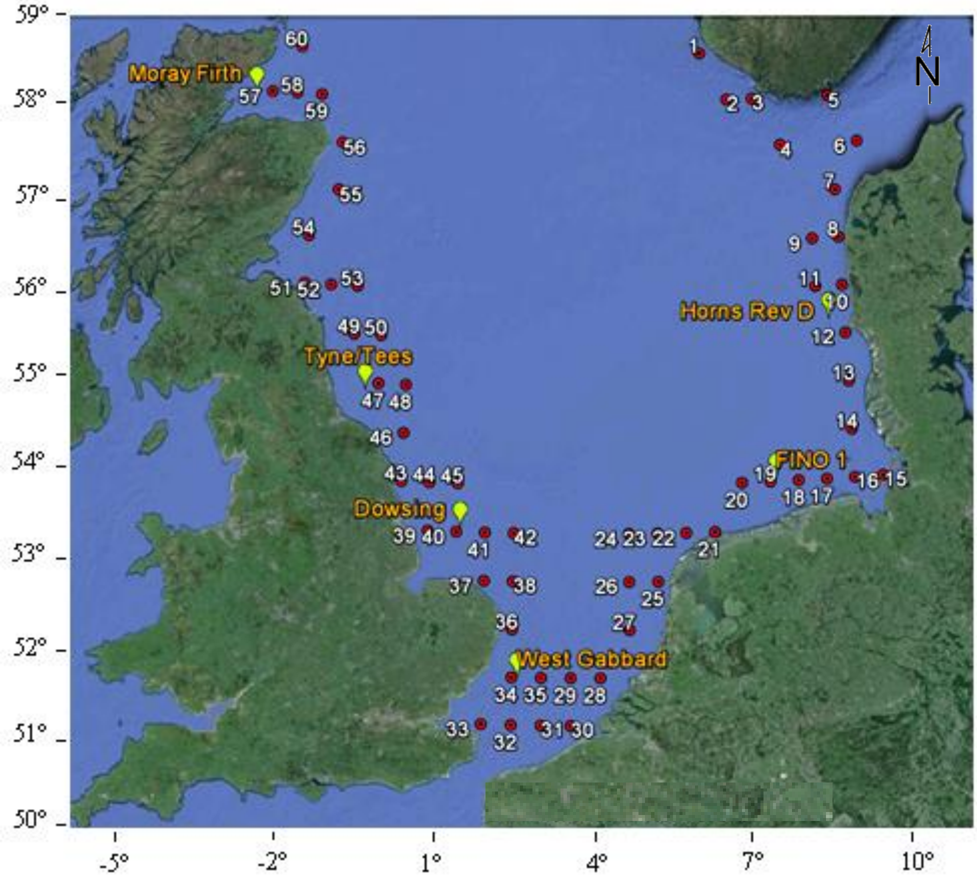

Figure 3. Location of the 60 points (red circles) considered in this study and the 6 buoys (green beacon) used to validate the hindcasts.

Table 1. Coordinates, distance to coast and water depth of the 60 points considered in this study.

Site no.	Coordinates	Distance to coast (km)	Water depth (m)	Site no.	Coordinates	Distance to coast (km)	Water depth (m)
1	58.5º N, 5.5º E	11.7	266	31	51.5º N, 2.5º E	39.9	27
2	58.0º N, 6.0º E	38.2	295	32	51.5º N, 2.0º E	41.1	43
3	58.0º N, 6.5º E	11.0	327	33	51.5º N, 1.5º E	12.9	18
4	57.5º N, 7.0º E	53.5	149	34	52.0º N, 2.0º E	36.7	28
5	58.0º N, 8.0º E	5.3	185	35	52.0º N, 2.5º E	64.2	30
6	57.5º N, 8.5º E	47.1	77	36	52.5º N, 2.0º E	15.8	26
7	57.0º N, 8.0º E	22.0	33	37	53.0º N, 1.5º E	12.9	21
8	56.5º N, 8.0º E	7.5	20	38	53.0º N, 2.0º E	37.0	26
9	56.5º N, 7.5º E	39.4	31	39	53.5º N, 1.0º E	18.9	11

10	56.0º N, 8.0º E	7.5	19	40	53.5º N, 1.0º E	51.4	18
11	56.0º N, 7.5º E	41.1	27	41	53.5º N, 1.5º E	65.8	21
12	55.5º N, 8.0º E	19.0	8	42	53.5º N, 2.0º E	76.5	20
13	55.0º N, 8.0º E	21.3	16	43	54.0º N, 0.0º E	12.5	19
14	54.5º N, 8.0º E	29.8	15	44	54.0º N, 0.5º E	44.9	47
15	54.0º N, 8.5º E	13.7	10	45	54.0º N, 1.0º E	73.0	40
16	54.0º N, 8.0º E	21.7	28	46	54.5º N, 0.0º E	33.7	59
17	54.0º N, 7.5º E	26.9	30	47	55.0º N, 0.5º W	55.1	68
18	54.0º N, 7.0º E	34.3	29	48	55.0º N, 0.0º E	85.7	70
19	54.0º N, 6.5º E	46.0	28	49	55.5º N, 1.0º W	36.6	99
20	54.0º N, 6.0º E	59.0	32	50	55.5º N, 0.5º W	69.4	57
21	53.5º N, 5.5º E	6.5	12	51	56.0º N, 2.0º W	17.0	67
22	53.5º N, 5.0º E	23.1	23	52	56.0º N, 1.5º W	41.8	72
23	53.5º N, 4.5º E	38.6	24	53	56.0º N, 1.0º W	66.6	69
24	53.5º N, 4.0º E	66.4	28	54	56.5º N, 2.0º W	33.6	47
25	53.0º N, 4.5º E	11.3	22	55	57.0º N, 1.5º W	36.0	67
26	53.0º N, 4.0º E	49.5	26	56	57.5º N, 1.5º W	16.1	73
27	52.5º N, 4.0º E	38.7	20	57	58.0º N, 3.0º W	34.2	56
28	52.0º N, 3.5º E	38.0	23	58	58.0º N, 2.5º W	35.8	61
29	52.0º N, 3.0º E	56.7	29	59	58.0º N, 2.0º W	32.1	82
30	5º.5º N, 3.0º E	29.5	22	60	58.5º N, 2.5º W	30.7	66

Table 2. Location of the 6 buoys situated along the North Sea coast used in this work.

Name	**Coordinates**	**Country**	**Provider**
Dowsign	53.5310º N, 1.0528º E	UK	Cefas
Fino 1	54.0143º N, 6.5877º E	Germany	Alpha Ventus
Horns Rev D	55.6500º N, 7.7000º E	Denmark	Horns Rev 3
Moray Firth	57.9663º N, 3.3332º W	UK	Cefas
Tyne/Tees	54.9188º N, 0.7488º W	UK	Cefas
West Gabbard	51.9828º N, 2.0818º E	UK	Cefas

The most relevant parameters during the study period are shown in Tables 3 and 4 for waves and wind, respectively, on the basis of the model output – these are shown for 15 representative points of the total 60 points analysed in this study.

Table 3. Most relevant statistics of wave energy resource for 15 representative sites of the total considered in this study ($\overline{H}_{mo}$: average significant wave height, σ: standard deviation, $H_{m0,max}$: maximum value of the significant wave height, $\overline{T}_e$: average energy period, $T_{e,max}$: maximum energy period and $\theta_{wave,mean}$: mean wave direction).

Site no.	Location	$\overline{H}_{mo} \pm \sigma$ (m)	$H_{m0,max}$ (m)	$\overline{T}_e$ (s)	$T_{e,max}$ (s)	$\theta_{wave,mean}$ (º)
2	58.0ºN, 6.0ºE	1.56 ± 1.03	8.31	6.71	19.57	233.21
7	57.0ºN, 8.0ºE	1.82 ± 1.66	15.78	5.86	19.52	230.45
11	56.0ºN, 7.5ºE	1.56 ± 0.95	8.14	6.03	19.56	237.87
12	55.5ºN, 8.0ºE	1.35 ± 0.87	7.21	5.76	18.44	247.49

14	54.5ºN, 8.0ºE	1.26 ± 0.75	6.17	5.41	16.43	239.74
19	54.0ºN, 6.5ºE	1.41 ± 0.83	6.93	5.75	17.46	237.04
22	53.5ºN, 5.0ºE	1.21 ± 0.71	5.54	5.63	13.56	238.98
27	52.5ºN, 4.0ºE	1.15 ± 0.72	5.37	5.26	17.40	226.64
30	51.5ºN, 3.0ºE	0.95 ± 0.60	4.33	4.89	16.36	220.50
33	51.5ºN, 1.5ºE	0.84 ± 0.53	3.83	4.37	24.69	153.10
38	53.0ºN, 2.0ºE	1.14 ± 0.64	4.49	5.44	16.01	189.18
44	54.0ºN, 0.5ºE	1.20 ± 0.69	4.95	5.97	25.13	149.81
49	55.5ºN, 1.0ºO	1.29 ± 0.79	6.53	6.53	24.56	121.43
55	57.0ºN, 1.5ºO	1.38 ± 0.83	6.53	6.74	24.47	120.70
60	58.5ºN, 2.5ºO	1.33 ± 0.81	6.70	6.16	24.58	144.28

Table 4. Most relevant statistics of wind energy resource for 15 representative points of the total considered in this study ($\overline{U}_{10m}$: average wind speed at 10 m above the sea level, σ: standard deviation, $U_{10m,max}$: maximum wind speed at 10 m above the sea level and $\theta_{wind,mean}$: mean wind direction).

Site no.	Location	$\overline{U}_{10m} \pm \sigma$ (m s^{-1})	$U_{10m,max}$ (m s^{-1})	$\theta_{wind,mean}$ (º)
2	58.0ºN, 6.0ºE	8.31 ± 4.06	29.55	191.02
7	57.0ºN, 8.0ºE	7.90 ± 3.54	27.73	176.96
12	55.5ºN, 8.0ºE	7.81 ± 3.52	25.46	173.82
14	54.5ºN, 8.0ºE	8.45 ± 3.77	25.72	171.88
19	54.0ºN, 6.5ºE	8.41 ± 3.75	26.54	168.24
22	53.5ºN, 5.0ºE	7.69 ± 3.50	22.88	164.45
27	52.5ºN, 4.0ºE	7.44 ± 3.64	26.52	161.91
30	51.5ºN, 3.0ºE	7.01 ± 3.34	22.67	156.24
33	51.5ºN, 1.5ºE	7.47 ± 3.48	23.35	152.88
38	53.0ºN, 2.0ºE	7.36 ± 3.50	23.75	160.98
44	54.0ºN, 0.5ºE	7.66 ± 3.58	25.96	154.79
49	55.5ºN, 1.0ºO	7.68 ± 3.63	26.65	158.60
55	57.0ºN, 1.5ºO	7.60 ± 3.77	29.26	156.03
60	58.5ºN, 2.5ºO	8.56 ± 3.98	30.13	162.63

The available resource was quantified in terms of wind (P) and wave (J) raw power, which can be calculated according to the following expressions [56, 57]:

$$P = \frac{1}{2}\rho_a U_w^3 \qquad (2)$$

where U_w is the wind speed, and ρ_a is the air density, assumed as equal to 1.23 kg/m^3, considering an average air temperature of 5 °C; and

$$J = \frac{\rho_w g^2 H_{m0}^2 T_e}{64\pi} \tag{3}$$

where ρ_w is the sea water density (it was assumed equal to 1027 kg/m^3 considering an average water salinity concentration of 33 ppm and an average water temperature of 7 °C), g is the gravity acceleration (g = 9.82 m/s^2), H_{m0} is the significant wave height, and T_e is the energy period which is defined in terms of spectral moments as:

$$T_e = \frac{m_{-1}}{m_0} \tag{4}$$

where m_n represents the spectral moment of order n, which is given by

$$m_n = \int_0^{2\pi} \int_0^{\infty} f^n E(f,\theta) df d\theta \tag{5}$$

where f is the wave frequency and $E = E(f, \theta)$ is the energy density with θ the propagation direction.

The energy period T_e can be estimated based on the peak period (T_p) as [58]:

$$T_e = \alpha T_p \tag{6}$$

The coefficient α depends on the shape of the wave spectrum. For instance, α = 0.86 for a Pierson–Moskowitz spectrum, and α increases toward unity with decreasing spectral width [58]. In this study, the assumption of α = 0.90 or $T_e = 0.9T_p$ was adopted, which is equivalent to assuming a standard JONSWAP spectrum with a peak enhancement factor of γ = 3.3.

The variability of the available power was analysed through statistical indicators such as the standard deviation (σ) or confidence intervals [59]. The variability of waves and winds is relevant in choosing a location since the peak-to-average ratio has been identified as a major cost driver in renewable energy systems [60]. Moreover, the correlation between wave and wind energy farms, the analysis of the existing correlation between waves and winds was analysed through the cross-correlation factor, $c(\tau)$, which gives the correlation between two generic signals $x(k)$ and $y(k)$ at a time lag τ (Eq. 7) [33]. The instantaneous correlation, $c(0)$, is of particular interest in this study, since it focuses on the opportunity to smooth the power output and avoid downtime periods through co-located wind-wave energy farms.

$$c(\tau) = \frac{1}{N}\sum_{k=1}^{N-\tau} \frac{[x(k)-\mu_x][y(k-\tau)-\mu_y]}{\sigma_x \sigma_y} \tag{7}$$

where μ_x, μ_y and σ_x, σ_y are the mean and the standard deviation of x and y, respectively. In this work, $x(k)$ and $y(k)$ are, respectively, the wind and wave raw power , P and J.

To encompass all these factors when searching for the best location for a co-located wave and wind energy farm, the *CLF* index (Co-location Feasibility index) was defined (Eq. 8). Since these factors are not equally important, different weighting factors were assigned for each parameter: $\alpha_{\bar{J}}$ and $\alpha_{\bar{P}}$ = 0.35 for the available wind and wave power – the most relevant parameters, $\alpha_{c(0)}$= 0.2 for the instantaneous correlation, and $\alpha_{\sigma_{\bar{J},\bar{P}}}$= 0.05 for the wave and wind power variability:

$$CLF_i = \alpha_{\bar{J}} \frac{\bar{J}_i - \bar{J}_{min}}{\bar{J}_{max} - \bar{J}_{min}} + \alpha_{\bar{P}} \frac{\bar{P}_i - \bar{P}_{min}}{\bar{P}_{max} - \bar{P}_{min}} + \alpha_{c(0)} \frac{c(0)_{max} - c(0)_i}{c(0)_{max} - c(0)_{min}} + \alpha_{\sigma_{\bar{J}}} \frac{\sigma_{\bar{J},max} - \sigma_{\bar{J},i}}{\sigma_{\bar{J}max} - \sigma_{\bar{J},min}} + \alpha_{\sigma_{\bar{P}}} \frac{\sigma_{\bar{P},max} - \sigma_{P,i}}{\sigma_{\bar{P}max} - \sigma_{\bar{P},min}} \tag{8}$$

where x_i is the value of the parameter x in the point i for the study period, x_{max} corresponds to the value of the parameter x at the point where it enhances the maximum value, and the same for x_{min} but for the minimum. The general parameter x could correspond to the mean wave power during the study period ($\bar{J}$), the mean wind power ($\bar{P}$), the instantaneous correlation ($c(0)$) or the standard deviation of wave and wind power (σ_J and σ_P, respectively). For instance, the site with the maximum mean wave power will correspond to a value of 1 in the first term of the right-hand side of the equation, whereas the site with the greatest power variability will have a zero value in the last term.

Once the best locations for a co-located wave and wind energy farm have been identified on the basis of the CLF index's results, the assessment of the available resource can be extended by analysing the wave and wind roses, the correlation between waves and winds for different time lags (τ) and the variation in the mean raw power on inter- and intra-annual time scales for the study period.

2.3. Overlap with other activities, restricted areas and other considerations

The North Sea, surrounded by densely populated and highly industrialised countries, is under increasing pressure on the marine space. In fact, this is one of the most crowded marine areas in the world [61], and marine energy projects will have to share space with other activities such as shipping, fishing, sand and gravel extraction, military activities and the exploitation of oil and gas reserves [39]. Not only do the characteristics of each use of the marine space differ, but many of these uses overlap with each other. Besides, the different uses are not stable but change from year to year (e.g. fishing depends on the available resource), and their future development is uncertain. At the same time, energy farms have to deal with the conservation of the marine environment and its living natural resources.

Therefore, establishing a management strategy for the marine space is fundamental to avoiding conflicts between offshore parks and other sea uses. However, there is no EU legislation that directly regulates offshore energy. All marine legislation is dependent on the United Nations Convention on the Law of the Sea (UNCLOS), which defines the different maritime zones at sea and the legal status of these zones. UNCLOS authorises coastal states to extend their jurisdiction up to 200 nm to create Exclusive Economic Zones (EEZs), in which the coastal state is allowed to deploy offshore renewable energy projects. It is worth specifying that UNCLOS provides only general rules. Detailed regulation is organised through specialised bodies and specific agreements [62]. In this sense, the European Commission has recently proposed directives for Maritime Spatial Planning (MSP) and Integrated Coastal Zone Management (ICZM), which should be cross-cutting policy tools for public authorities and stakeholders to apply a coordinated and integrated approach [63]. In September 2012, the Commission presented the Communication Blue Growth as part of the EU Integrated Maritime Policy. The Communication stated that the Commission will assess options for giving industry the confidence to invest in marine renewable energy [41] .

Moreover, the sea use functions are commonly present near shore or in shallow depths, which are at the same time the suitable areas for low cost offshore renewable farms. The majority of offshore wind projects have been installed using monopile foundations, which currently is feasible for water depths of up to 35 m. For deeper water other foundations, including floating systems have been tested and used, but remain a costly option and still require development. In this study, a maximum water depth of 50 m was considered as in [64] or [65]. This limit restricts the available area for deploying a co-located farm considerably, especially in some countries of the study area such as Norway (Figure 4).

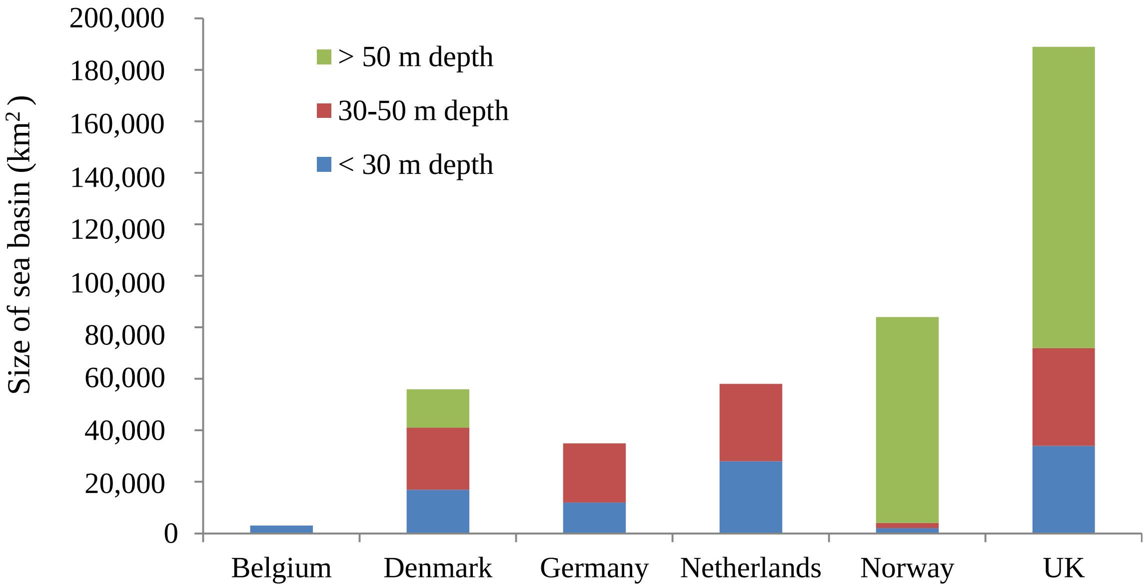

Figure 4. Size of sea basin by country and depth (source: adapted from [39]).

Therefore, the challenge is to find space for offshore renewable projects that balances the need for low cost renewable energy against the needs of these other, so called, non-wind sea uses.

3. Results and discussion

3.1. Wave and wind available resource

The models used in this study were validated with real data provided by buoys located along the North Sea coast (Section 2.1) in terms of the significant wave height (H_{m0}) and wind speed at 10 m above the sea level (U_{10m}). In all cases, a good correlation was observed (Figure 5) as shown by the values of the coefficient of determination (R^2) and the Root Main Square Error (*RMSE*) (Table 5).

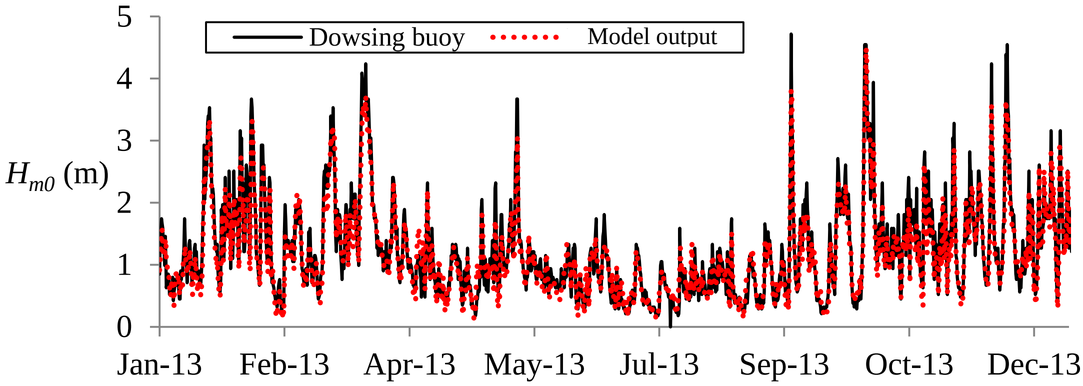

Figure 5. Correlation between simulated and observed data from Dowsing buoy in terms of significant wave height (H_{mo}) from January to December 2013.

Table 5. The coefficient of determination (R^2) and Root Main Square Error (*RMSE*) between simulated and observed significant wave height (H_{m0}) and wind speed at 10 m above the sea level (U_{10m}) from February 2005 to January 2015. The average value of H_{m0} and U_{10m} is included.

Buoy	H_{m0}			U_{10m}		
	Mean (m)	R^2	*RMSE* (m)	Mean (m)	R^2	*RMSE* (m/s)
Dowsign	1.23	0.96	0.22	8.02	0.95	0.28
Fino 1	1.44	0.94	0.31	8.43	0.94	0.29
Horns Rev D	1.39	0.93	0.31	8.71	0.94	0.32
Moray Firth	1.07	0.90	0.32	7.89	0.92	0.30
Tyne/Tees	1.34	0.91	0.36	8.12	0.91	0.34
West Gabbard	1.15	0.90	0.29	7.32	0.91	0.31

When validating the models, the results of the simulations were used to analyse the available wind and wave resource (Table 6) in the 60 points along the North Sea coast considered in this study. With regard to the wave energy resource, the largest available power corresponded with the site no. 7 with a mean value over 16 kW/m, whereas the worst location was the site no. 15 with only 1.59 kW/m. A value of 4−5 kW/m is commonly set as the limit for possible location of an offshore wave farm [17, 66]. In this study, approx.. 70% of the points analysed exceeded this value, and even more, the 10 best locations in terms of $\bar{J}$ (Table 7) had values of wave power greater than 8.8 kW/m. These points were located in the Danish and Norwegian coasts of the North Sea and in the northern coast of the UK, which is in accordance with the highest values of significant wave height due to its exposure to the large fetch from North. The other sites are sheltered by the coast itself so the potential decreases clearly. As for the mean wind power density, $\bar{P}$, it ranged between 0.26 and 0.71 kW/m^2 (Table 6). The 10 best locations (Table 7) had values over 0.58 kW/m^2 and 5 of them – around the Norwegian and Danish coasts – were at the same time good locations in terms of wave power.

Although the potential power production is one of the most important parameters when selecting the best location, there are other factors to be considered. One of them is the correlation between both resources; if there is phase shift between them the inherent variability of the power output may be smoothed and the non-operational periods may be avoided. The points with greater variability with regard to wave power corresponded to the Norwegian part of the North Sea and the North of Denmark, which were important areas in terms of the available resource, as noted previously. The same applies to wind power, whose largest standard deviation was found in the points of the northern coast of the UK. Therefore, the locations with the greatest resource had also the largest power variability, implying high balancing costs to connect the co-located farm to the electric grid. In view of the values obtained for the instantaneous correlation, $c(0)$, in some of these areas this challenge could be overcome with co-located farms by combining both resources. This was the case of some points in the Danish coast and the North coast of UK, e.g. the site no. 51 and 54, that presented very low values of $c(0)$: 25% and 28%, respectively. The largest correlation values, around 80% were found in areas of Germany and the Netherlands characterised by a soft wave climate. The time required for waves to develop is relatively shorter for low energies and, thus, the time lag between waves and winds is also low, increasing the correlation between them.

Table 6. Main statistics of wave (J) and wind (P) power: mean, median, standard deviation (σ) and 90% confidence interval (*c.i.* 90%). The instantaneous correlation $c(0)$ between wave and wind power is also included.

Site no.	J (kW m^{-1})				P (kW m^{-2})				c (0)
	Mean	Median	σ	*c.i.* 90%	Mean	Median	σ	*c.i.* 90%	
1	10.01	4.05	16.30	± 0.158	0.40	0.17	0.62	± 0.006	0.52
2	10.89	4.85	17.40	± 0.169	0.63	0.31	0.90	± 0.009	0.61
3	8.68	3.61	15.23	± 0.156	0.46	0.22	0.65	± 0.006	0.47
4	10.48	5.33	15.12	± 0.147	0.71	0.42	0.88	± 0.009	0.71
5	2.99	1.22	5.36	± 0.052	0.31	0.17	0.40	± 0.004	0.61
6	6.29	2.72	10.56	± 0.102	0.62	0.36	0.79	± 0.008	0.39
7	16.04	4.20	35.80	± 0.366	0.50	0.28	0.66	± 0.006	0.27
8	7.12	3.24	10.76	± 0.104	0.44	0.23	0.61	± 0.006	0.74
9	9.63	4.87	13.75	± 0.133	0.61	0.34	0.79	± 0.008	0.76
10	15.37	4.10	32.80	± 0.336	0.44	0.24	0.61	± 0.006	0.15
11	9.16	4.71	12.60	± 0.122	0.62	0.35	0.80	± 0.008	0.76
12	6.80	3.22	9.92	± 0.096	0.49	0.26	0.65	± 0.006	0.74
13	6.20	3.29	8.35	± 0.081	0.58	0.32	0.76	± 0.007	0.77
14	5.32	2.81	7.20	± 0.070	0.60	0.35	0.77	± 0.007	0.77
15	1.59	0.78	2.31	± 0.022	0.35	0.19	0.49	± 0.005	0.10
16	3.50	1.84	4.81	± 0.047	0.47	0.26	0.62	± 0.006	0.76
17	5.25	2.59	7.61	± 0.074	0.50	0.28	0.63	± 0.006	0.72
18	6.52	3.33	9.11	± 0.088	0.55	0.31	0.71	± 0.007	0.71
19	7.00	3.75	9.38	± 0.091	0.60	0.33	0.77	± 0.007	0.73
20	7.77	4.28	10.22	± 0.099	0.61	0.34	0.79	± 0.008	0.72
21	3.29	1.88	4.29	± 0.042	0.46	0.24	0.64	± 0.006	0.74
22	5.22	2.90	6.67	± 0.146	0.47	0.25	0.63	± 0.014	0.76
23	6.87	3.80	8.62	± 0.084	0.56	0.30	0.75	± 0.007	0.74
24	7.02	3.97	8.64	± 0.084	0.53	0.28	0.72	± 0.007	0.77
25	4.63	2.47	5.96	± 0.058	0.47	0.24	0.66	± 0.006	0.79
26	5.11	2.64	6.77	± 0.067	0.52	0.26	0.72	± 0.007	0.67
27	4.32	2.26	5.71	± 0.055	0.45	0.22	0.67	± 0.007	0.78
28	3.85	2.07	5.05	± 0.049	0.48	0.23	0.69	± 0.007	0.78
29	4.33	2.46	5.41	± 0.052	0.55	0.29	0.73	± 0.007	0.79
30	2.73	1.45	3.73	± 0.036	0.37	0.18	0.53	± 0.005	0.74
31	3.27	1.81	4.29	± 0.042	0.48	0.26	0.65	± 0.006	0.75
32	2.79	1.58	3.53	± 0.034	0.54	0.29	0.72	± 0.007	0.80
33	1.91	1.04	2.46	± 0.024	0.44	0.23	0.59	± 0.006	0.77
34	3.12	1.81	3.88	± 0.038	0.49	0.26	0.65	± 0.006	0.45
35	4.16	2.38	5.12	± 0.050	0.55	0.30	0.72	± 0.007	0.51
36	3.03	1.73	3.88	± 0.038	0.34	0.18	0.47	± 0.005	0.40
37	2.72	1.46	3.85	± 0.037	0.31	0.16	0.44	± 0.004	0.38
38	4.22	2.43	5.31	± 0.051	0.42	0.22	0.60	± 0.006	0.43
39	2.96	1.56	4.23	± 0.041	0.39	0.19	0.55	± 0.005	0.35
40	4.35	2.36	6.07	± 0.059	0.47	0.24	0.66	± 0.006	0.40
41	5.01	2.83	6.49	± 0.063	0.48	0.25	0.66	± 0.006	0.44
42	5.96	3.42	7.50	± 0.073	0.48	0.25	0.66	± 0.006	0.45
43	3.42	1.71	5.23	± 0.051	0.26	0.13	0.38	± 0.004	0.32
44	5.24	2.80	7.34	± 0.071	0.47	0.24	0.66	± 0.006	0.37
45	6.44	3.55	8.80	± 0.085	0.52	0.28	0.71	± 0.007	0.41
46	6.07	3.01	9.33	± 0.090	0.38	0.20	0.54	± 0.005	0.32
47	6.94	3.46	10.65	± 0.103	0.50	0.26	0.72	± 0.007	0.31
48	8.62	4.48	12.75	± 0.124	0.55	0.30	0.75	± 0.007	0.37
49	6.90	3.40	10.63	± 0.103	0.48	0.25	0.70	± 0.007	0.32
50	8.90	4.62	12.98	± 0.126	0.58	0.31	0.81	± 0.008	0.36
51	3.58	1.72	5.81	± 0.056	0.40	0.19	0.60	± 0.006	0.25
52	6.60	3.32	9.82	± 0.095	0.52	0.27	0.76	± 0.007	0.32
53	8.85	4.60	12.68	± 0.123	0.59	0.31	0.82	± 0.008	0.35
54	5.00	2.50	7.64	± 0.074	0.47	0.22	0.73	± 0.007	0.28
55	8.28	4.14	12.25	± 0.119	0.49	0.23	0.73	± 0.007	0.33
56	8.82	4.33	13.10	± 0.127	0.42	0.21	0.60	± 0.006	0.40
57	3.52	1.59	6.07	± 0.059	0.48	0.22	0.75	± 0.007	0.32
58	5.79	2.72	8.97	± 0.087	0.56	0.27	0.82	± 0.008	0.37
59	8.26	4.05	12.23	± 0.119	0.57	0.30	0.81	± 0.008	0.40
60	7.02	3.40	10.99	± 0.106	0.65	0.35	0.88	± 0.009	0.41

Table 7. Best locations in terms of: mean wave power $(\bar{J})$, mean wind power $(\bar{J})$, instantaneous correlation ($c(0)$) and standard deviation of wave and wind power (σ_J and σ_P, respectively).

Parameter	10 best locations (site no.)
$\bar{J}$	7, 10, 2, 4, 1, 9, 11, 50, 53, 56
$\bar{P}$	4, 60, 2, 11, 6, 9, 20, 14, 19, 53
c (0)	15, 10, 51, 7 54, 47, 52, 43, 57, 46
σ_J	15, 33, 32, 30, 37, 34, 36, 39, 31, 21
σ_P	43, 5, 37, 36, 15, 30, 46, 39, 33, 38

In view of the above, there was not a location with optimal conditions with regard to all the parameters considered. Assessing the results with the *CLF* index (Figure 6), the 10 best locations were found to be in the northern coast of the UK and the Norwegian and Danish areas (Figure 7). Site no. 7 was the best location with CLF_i = 0.75, followed by site no. 10 with CLF_i = 0.68.

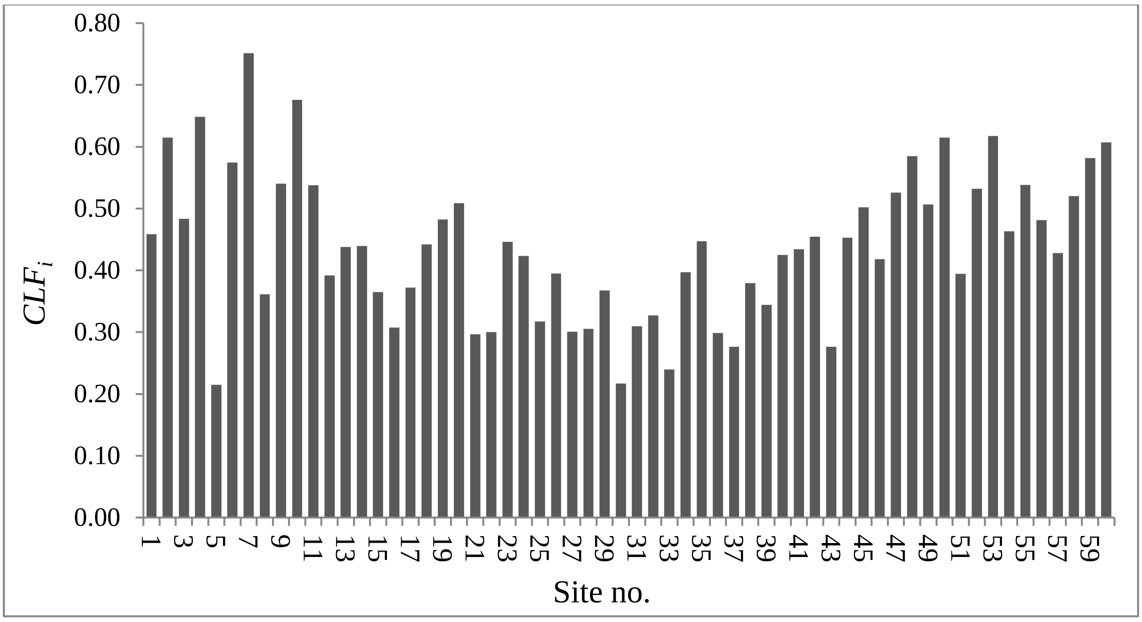

Figure 6. CLF_i of the 60 sites along the North Sea coast considered in this study.

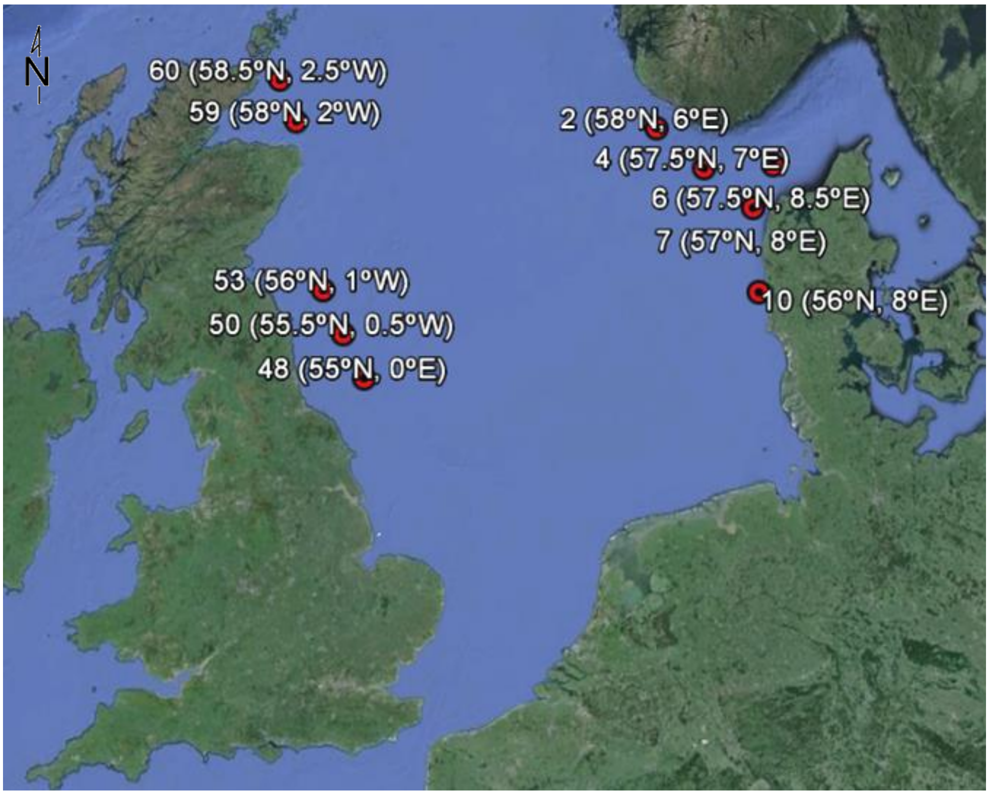

Figure 7. The 10 best sites for a co-located farm in the North Sea with based on the *CLF* index.

3.2. Technological and economic limitations

As explained in Section 2.3, current commercial substructures are limited to maximum water depths of 50 m (Figure 8). There are prototypes suitable for depths up to 200 m [67], but this technology is still at a very early stage of development. For that reason, the sites of the Norwegian coast were discarded in this study. When the technology for deep waters becomes a reality the feasible areas for offshore farms will increase considerably, especially in Norway and the UK (Figure 8).

Apart from the technical limitations, the water depth and distance to land are fundamental for the economic assessment of the installations. On this basis different zones were distinguished in the North Sea (Figure 9). It was found that the more convenient areas for co-located offshore installations were the Southern and Eastern North Sea. The westerly sites were discarded for their high levelised cost values (Figure

9). Instead, the sites along the Danish coast corresponded to areas where the deployment of an co-located offshore park would be more economical.

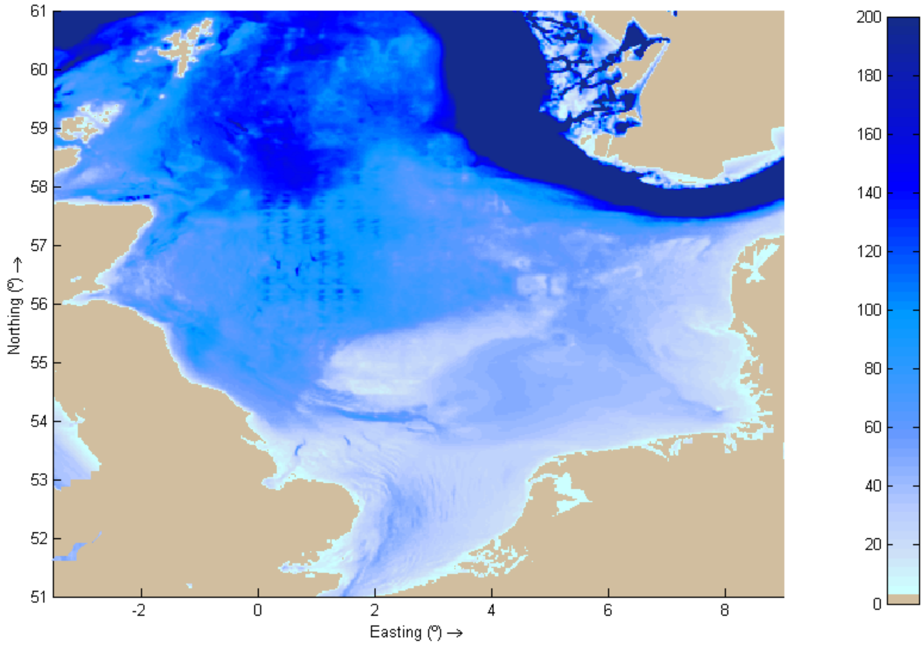

Figure 8. Water depth (m) in the study area.

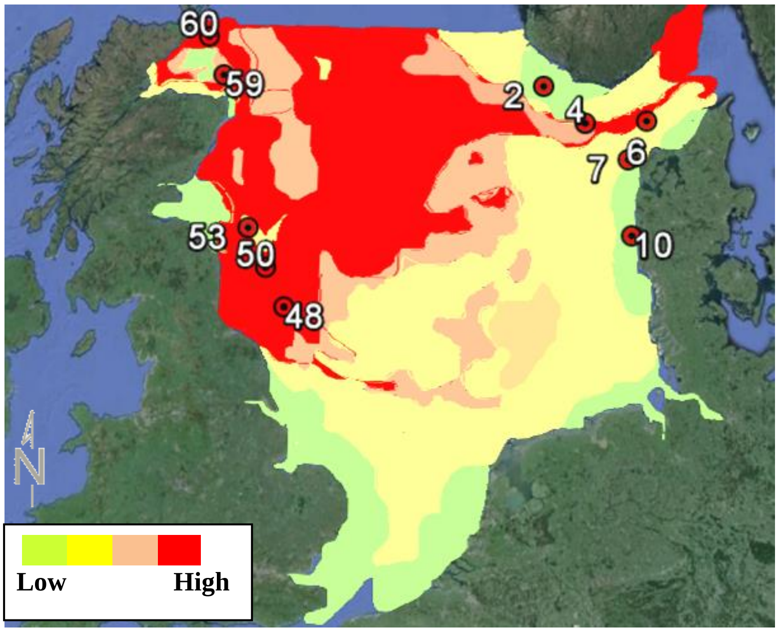

Figure 9. Location of the 10 best sites for a co-located farm in terms of resource in a distribution map of the levelised cost (source: adapted from [38]).

3.3. Overlap with other activities and nature protected areas

Shipping takes up 10-25% of the North Sea [39] with some routes with important traffic density (Figure 10(a)) and it is expected to undergo significant growth over the next decades [39]. In International shipping lanes (IMO) a 2 nm safety zone is considered, which constitutes an exclusion area for offshore energy farms. Similarly, anchorage areas involve exclusions zones, and in this case a 4 nm margin is required. Major shipping routes are also exclusion zones [68, 69]. Moreover, it is of particular interest for the offshore wind farm operators to minimise the cable length in the area of shipping routes. In many cases conflicts of interest could be resolved by measures such as altering maritime routes or establishing corridors between wind turbines [62].

For their part, *military areas* cover 14% of the North Sea (Figure 10(b)). Munitions dumping areas are not available for offshore parks. All remaining military use categories are possibly available for coexisting with energy farms. In the case of zones designated for military aircraft manoeuvres the offshore farm should not use more than 20% of the area [64].

With regard to *cables and pipelines* (Figure 10(c)), a 500 m safety zone to either side cable or pipelines is considered as an exclusion zone for offshore installations [70] to protect them and provide maintenance access. *Sand extraction* is a minor and stable sea use function (Figure 10(d)), but it represents access limited areas that have to be considered when deploying an offshore farm. *Oil and gas extraction activities* (Figure 10(e)) are declining through decommissioning, but nowadays still cover 11% [39] of the sea area. Around sub-surface installations a 500 m safety zone is considered [64], as well as in the case of surface installations not accessible by helicopter. As for *fishing activities* (Figure 10(f)), they are present in almost all the North Sea in some form or another, but the greatest conflict with offshore projects would come from heavy fishing, especially for the cables of the energy parks.

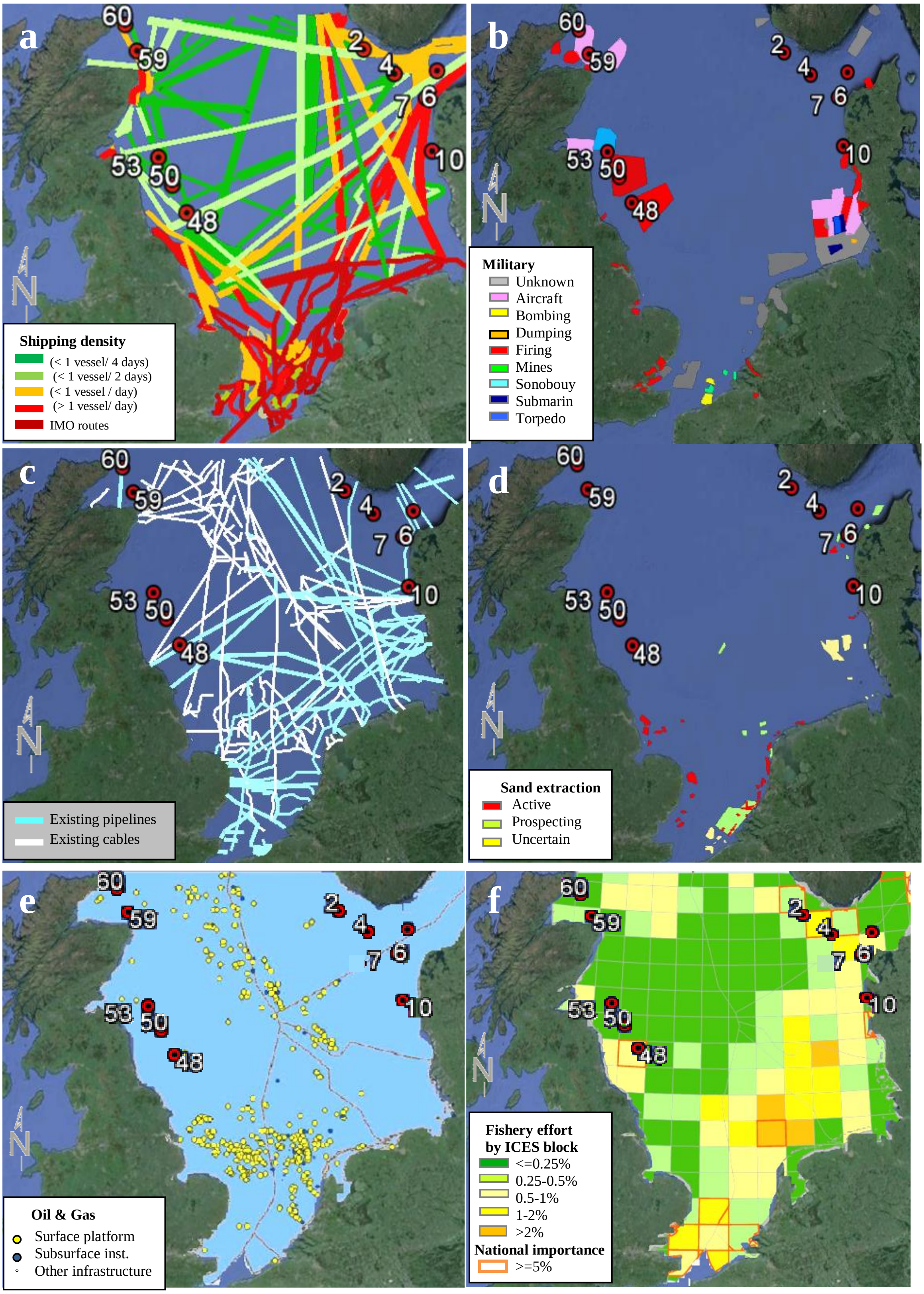

Figure 10. Location of the 10 best sites for a co-located farm in terms of resource in distribution maps of: (a) shipping routes, (b) military activities, (c) cables and pipelines, (d) sand extraction activities, (e) oil and gas platforms and (f)fishing. (source: adapted from [62, 64, 71]).

Therefore, with all these activities in the development of offshore renewable projects requires the compatibility of some of these sea use functions (Figure 11). In this sense, the need for including regeneration corridors between wind parks to avoid turbulence and inter-park effects [39] provides opportunities for co-use/co-existence with other sea uses such as shipping and fishing.

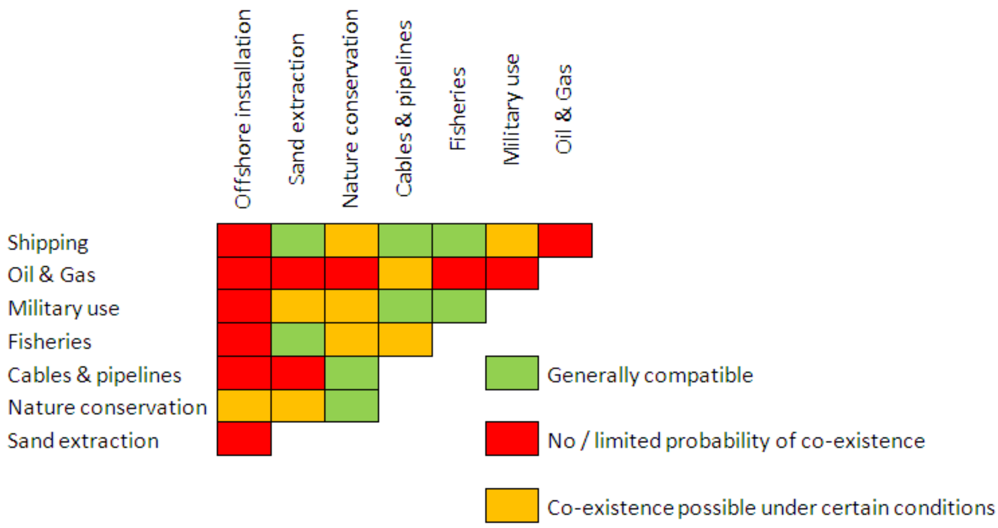

Figure 11. Interactions between sea use functions (source: adapted from [72]).

Among the 10 best locations identified previously by means of the *CLF* index (see Section 3.1), some of them were rejected (Section 3.2.) for technical limitations and/or economic considerations. At this point of the study, sites no. 7 and 10 remain as the best locations for deploying a co-located farm. When they were analysed with regard to the overlap with other sea activities (Figure 10), it was found that site no. 7 was near a major shipping route, but with a good design of the co-located farm both activities could coexist without disturbing each other. The same applied to sand extraction areas. In the case of site no. 10 there were no interferences with shipping routes or sand extraction; however, this location was close to a military zone designated for firing activities – which is not an exclusion area, but far enough to avoid conflicts between both activities. Furthermore, both sites did not interfere with any oil and gas platforms or pipelines in the near vicinity, while they were close to offshore cables that could be harnessed to the electrical installation of the co-located farm, particularly site no. 10.

As for nature conservation, EU countries are required by the EIA Directive to conduct environmental impact assessments before developing offshore renewable energy installations. Several protected areas were defined through directives and initiatives such as Natura 2000 (Figure 12). These directives do not exclude offshore renewable energy installations within protected areas; however, the developer must show that the activity will not harm the conservation goals set out for the particular area [62], and this may slow down the approval process. The distribution of the protected areas is not equitable (Figure 12). Indeed, in Germany about 45% [61] of the waters in the North and Baltic Seas are marine protected areas, whereas there are no special protection areas designated entirely in the Scottish marine environment. Even, if all Natura 2000 and other areas designated for nature protection were theoretically excluded from marine energy development, there would still be enough wind energy available to supply 3-7 times the total estimated energy demand in 2020 and 2030 [73]. Furthermore, offshore energy farms must be in accordance with the EU Marine Strategy Framework Directive, whose aim is to ensure good environmental status for the EU’s marine waters by 2020; and with the Guidance on Environmental Considerations for Offshore Wind Farm Development published by the OSPAR Commission [41].

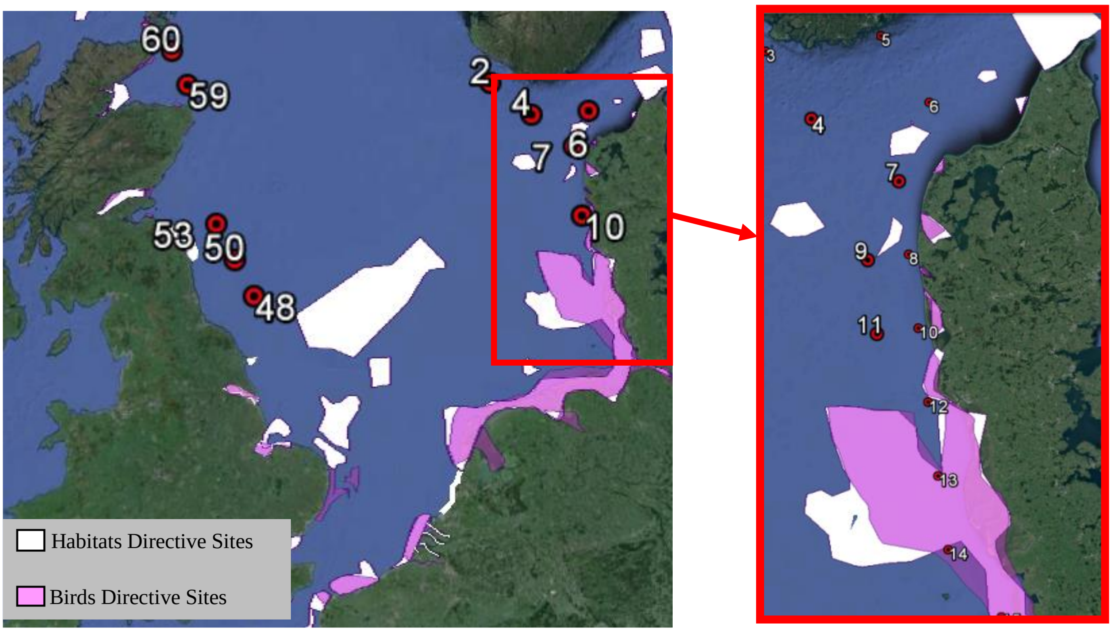

Figure 12. Nature 2000 sites (source: adapted from [74]). The ref framed area represents a zoom of the Danish coast.

In light of Figure 12, site no. 7 and 10 were not in natural protected areas, although a detailed environmental impact assessment is advisable since they are near Habitats Directive Sites.

3.4. Best location for a co-located farm

With regard to the wave and wind resource site no. 7 emerged as the best location for deploying a co-located farm, followed by site no. 10. These points were located in the Danish coast in water depths around 20-30 m, and with distances to shore of 10 km and 35 km for sites no. 10 and 7, respectively, which is similar to operational wind farms. Both sites are in line with current technical and economic limitations, and do not overlap with traditional sea activities, which is important for avoiding conflict between users. Moreover, these sites are close to a number of Danish ports (Figure 13), e.g. Esbjerg, which is important both for construction and maintenance.

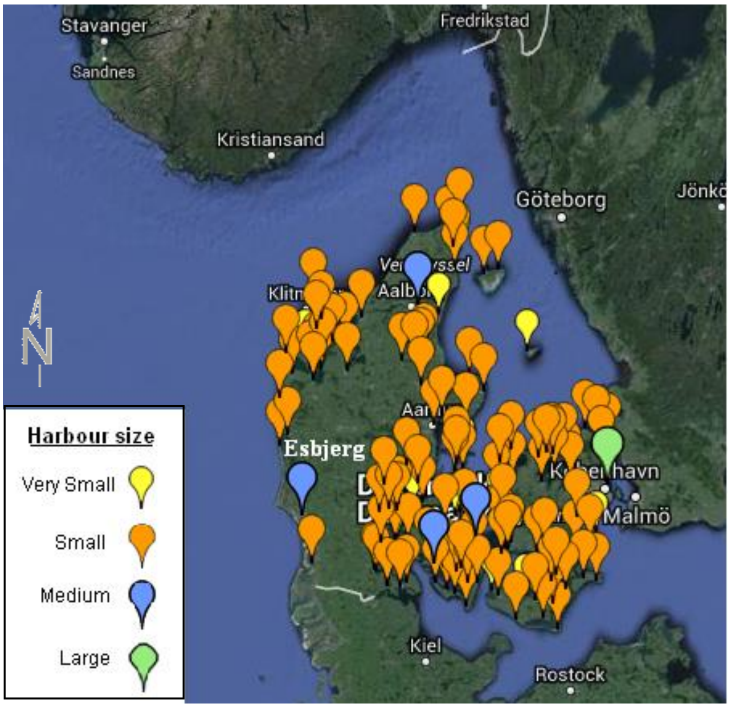

Figure 13. Danish ports and their relative size.

Although both locations showed numerous favourable characteristics for installing a co-location farm, the proximity to shore and offshore cables makes site no. 10 stand out as the best location for a co-located wave and wind farm in the North Sea. It was found that the predominant wave direction (Figure 14) in this location during the study period was 315º, which also corresponded to the predominant wave production (Figure 14). The east side is sheltered by the Danish coast itself so the potential decreases clearly from this direction. The mean significant wave height was between 1 and 2 m. The analysis of the wind direction (Figure 15) is also important to planning wind turbine installations. The predominant wind direction, as well as the directions with higher contribution to the wind power, corresponded with northern winds.

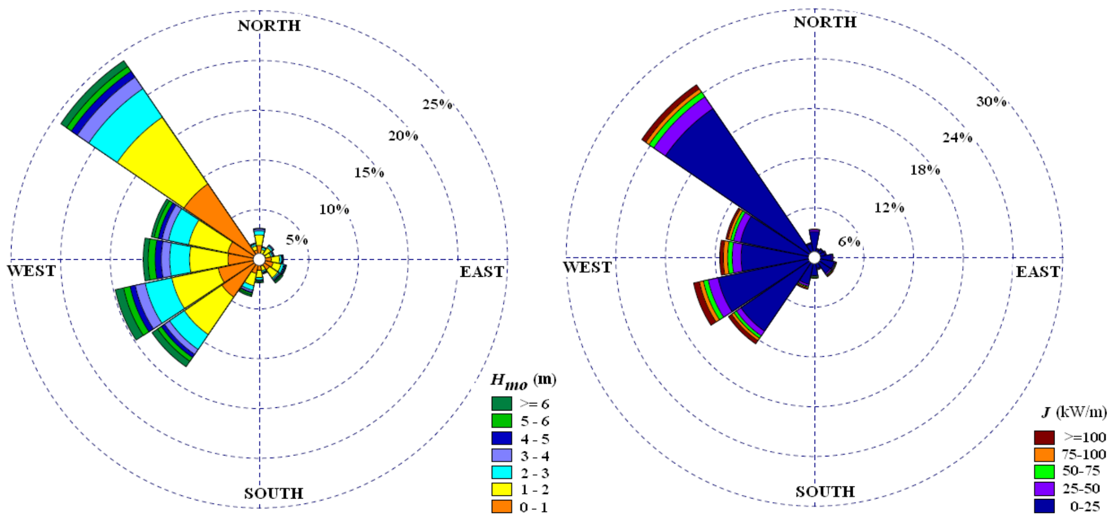

Figure 14. Wave rose (left) and wave power rose (right) for site no. 10 for the total study period (from February 2005 to January 2015).

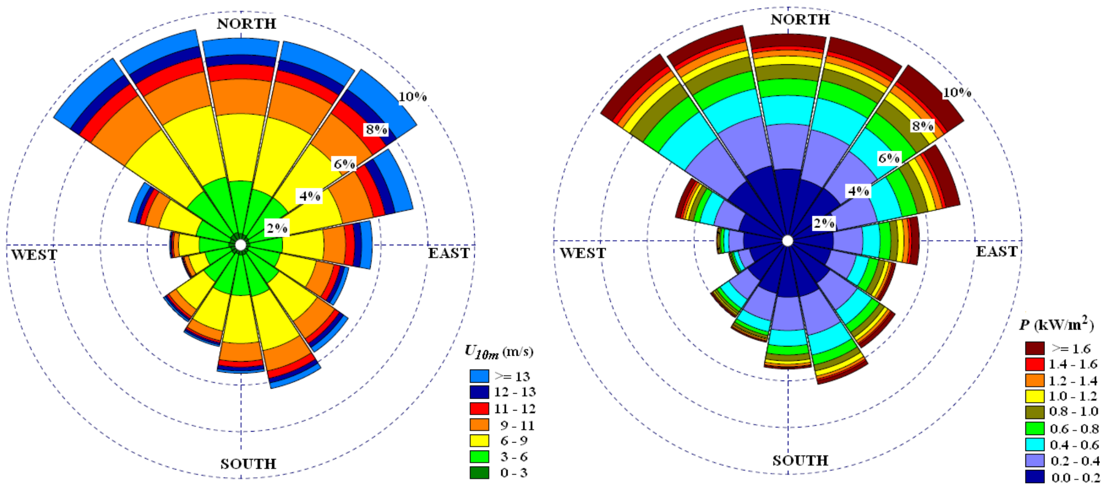

Figure 15. Wind rose (left) and wind power rose (right) for site no. 10 for the total study period (from February 2005 to January 2015).

The average raw wave and wind power during the study period were 15.4 kW/m and 0.44 kW/m^2, respectively. Both the inter- and intra-annual power variability are shown in Figures 16 and 17. The inter-annual variability was low both for wave and wind power. However, the intra-annual variability shows that the soft climate during spring and summer caused a clear decrease in the available power, which would translate into low power output.

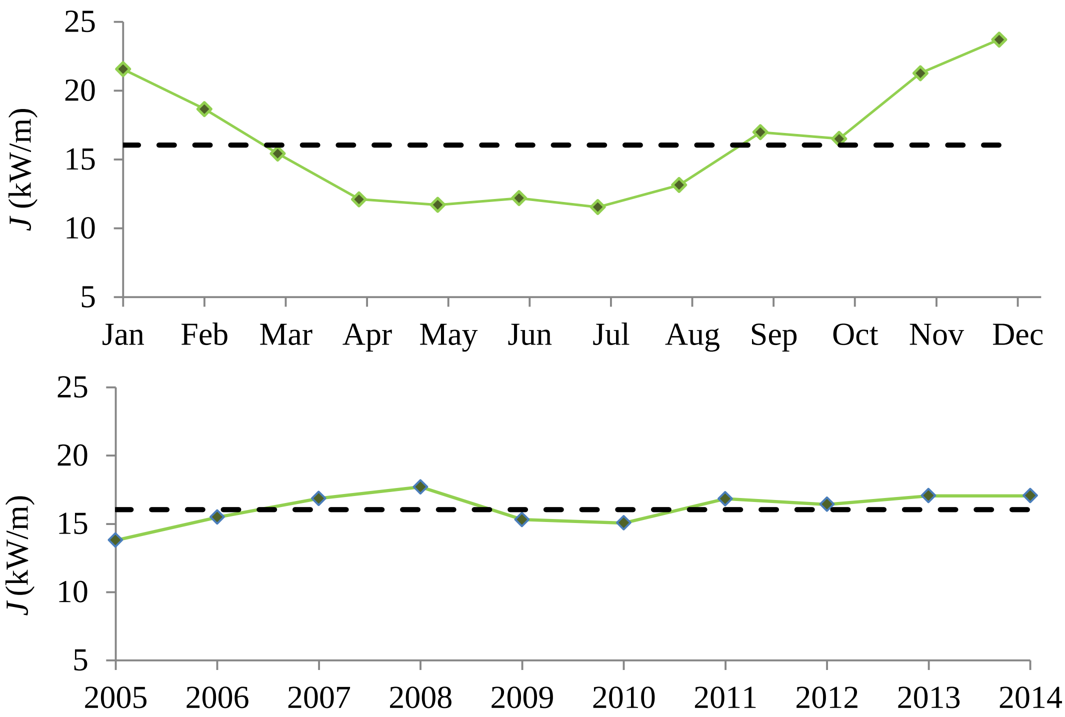

Figure 16. Variability of the mean wave power on inter- and intra-annual time scales for the study period.

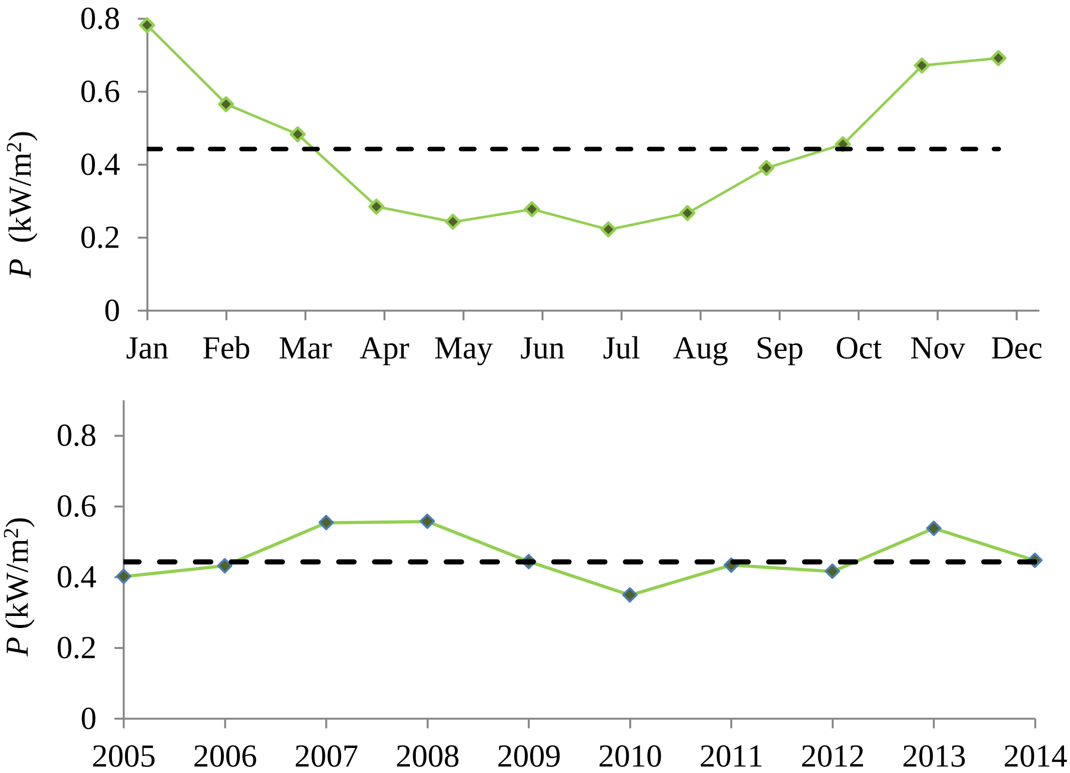

Figure 17. Variability of the mean wind power on inter- and intra-annual time scales for the study period.

The low cross-correlation factor between waves and wind power in this area (Figure 18) presents an opportunity to smooth power output through the co-located farm if compared with independent energy systems. The maximum value of the cross-correlation factor was obtained for a time delay of one hour, which demonstrated the existence of a phase shift between waves and winds that could be used to reduce the power variability and avoid non-operational periods. If wind speeds were outside limits of power production, wave energy could cover the power demand during this period.

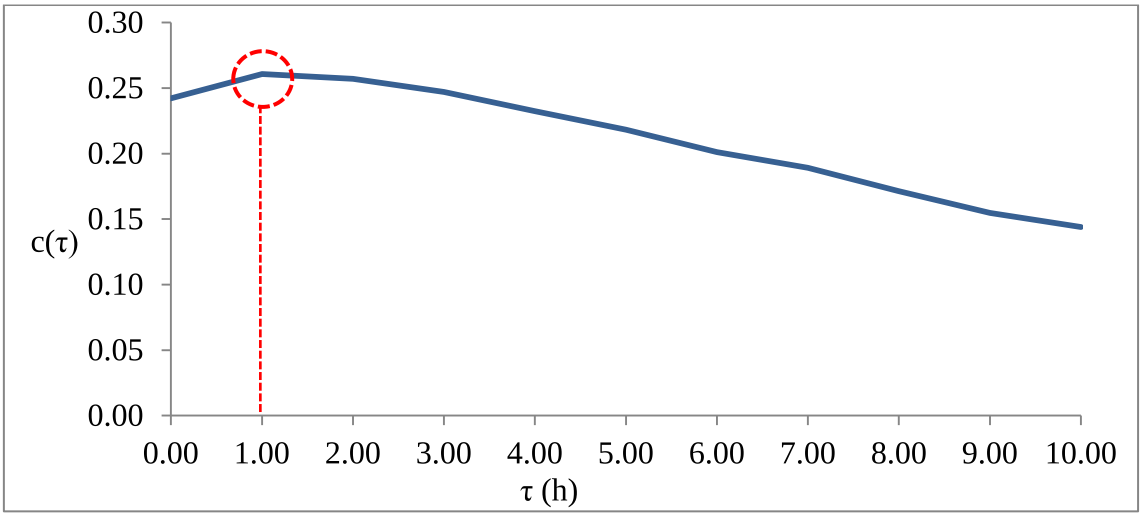

Figure 18. Correlation between wave and wind power in site no.10 for the study period. *c(τ)* is the cross-correlation factor and *τ* the time lag.

4. Conclusions

The aim of this work was to identify the best location to deploy a co-located wave and wind energy farm in the Central and Southern North Sea, based on both the capacity for a combined farm development – influenced by factors such as the wave and wind power, their variability and correlation, and other physical or economic constraints – and the suitability as a function of the overlap with traditional sea uses and nature conservation interests. With regard to the mean wave power, the best results were found in the Danish and Norwegian coasts of the North Sea, with values over 8.8 kW/m. These areas stood out also as the best locations in terms of the mean wind power density together with the northern coast of the UK (values between 0.58 and 0.71 kW/m^2), due to the higher exposure of these locations to the predominant winds coming from the

North. In exchange, these areas presented higher power output variability that those with milder climate. This variability could result in important costs when connecting the farm to the electric grid. However, co-located wave and wind farms may be an opportunity to overcome this challenge thanks to the existing phase shifts between waves and winds. In fact, the lowest correlation (even lower than 25%) between them was found in the areas with the highest power variability. Balancing all the above considerations, 10 of the total 60 points analysed were identified as the most convenient locations for a co-located farm, all of them located in the northern UK coast and the southern Norwegian and northern Danish areas of the North Sea. Some of these points were discarded for being in deep water, exceeding the current technical limitation of 50 m. Moreover, the sites in the UK coast were located in areas that involve high levelised cost for an offshore installation, and were also discarded. The remaining points for the deployment of a co-located farm were off the Danish coast, in water depths between 20-30 m. These points were analysed with regard to the overlap with other activities, and no relevant interferences were found. In addition, they were close to submarine cables that could be used as part of the electric installation of the co-located farm, leading to savings. Moreover, it was noticed that these points were not in natural protected areas. Finally, site no. 10 (56ºN, 8ºE) was chosen as the best location. Apart from having great available resource, with mean values of wave and wind power around 16 kW/m and 0.5 kW/m respectively, this location presented other advantages that made it the best option, such as the low correlation between waves and winds, which could smooth the power output, or its proximity to land.

All in all, the North Sea was demonstrated to be a good area for the deployment of co-located farms due to the available wave and wind resource and the existing shallow waters. Moreover, the bordering countries are at the head of marine energy with plans for an important development of these renewables in the following years, and have the necessary technology and installations to achieve this goal. However, it was found that the North Sea is subject to many demands of use, and an accurate regulatory framework for marine planning would be necessary given that some of the activities concurred are mutually exclusive. Furthermore, promoting deep offshore technology could result in new opportunities for marine energy farms, which could be located in areas farther away from, coast with higher available resource and less interference with other sea uses.

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