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Multi-criteria site selection for offshore renewable energy platforms

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ABSTRACT

Geographical Information Systems (GIS) are commonly used in renewable energy resource analysis to establish optimal locations for development. Previous work focuses either on a single technology with fixed site-selection criteria, or on small, localised areas. The potential for combining or co-locating different offshore energy technologies, particularly over a large region, has been explored previously but at a relatively low level of detail. Here, bespoke resource data from high resolution co-located, co-temporal wind and wave models are presented in a GIS with a range of additional environmental and physical parameters. Dedicated decision-support tools have been developed to facilitate flexible, multi-criteria site selections specifically for combined wind-wave energy platforms, focusing on the energy resources available. Time-series tools highlight some of the more detailed factors impacting on a site-selection decision. The results show that the main potential for combined technologies in Europe is focused to the north and west due to strong resources and acceptable depth conditions, but that there are still obstacles to be overcome in terms of constructability and accessibility. The most extreme conditions generally coincide with the maximum energy output, and access to these sites is more limited.

1. Introduction

The MARINA Platform EU FP7 project (Grant agreement number 241402) aimed to develop ideas for offshore renewable energy platforms, combining wind, wave and/or tidal current power with shared infrastructure. Over one hundred designs were initially considered, with ten selected for further investigation; a final three designs have been studied in detail. To establish the locations around Europe where such platforms might be constructed, a key outcome of the project is a dedicated geographical information system (GIS). This paper presents the GIS and the bespoke site-selection support tools developed within the project, focusing primarily on the suitability of sites in terms of the available energy resource.

1.1. Combined platforms

A recent review paper [1] presents a wide-ranging overview of many of the possibilities and challenges of developing combined offshore energy platforms. The authors discuss the potential synergies to be exploited, including those relating to legislation for marine spatial planning and technology or project-specific aspects. A key benefit of combining different offshore renewable energy technologies on a single platform relates to potential for sharing space and infrastructure, thus reducing the cost per unit of installed capacity of, for example, the foundations or electricity network cabling. A further advantage is in the combination of power outputs from two types of generation. Managing the inherent variability in power output from wind and wave generators is a prominent issue in renewable energy research. It was shown in Ref. [2] that for sites along the coast of California, co-locating wind and wave devices would reduce hypothetical power variability and increase the allocated capacity credit, compared with either technology operating alone.

A similar study for Ireland [3] showed that on the south and west coasts, the variability of wind and wave power is reduced over several time scales when combined, compared to either type acting alone. In the more fetch-limited Irish Sea, there was little or no advantage to combinations, as the two individual resources were strongly correlated in time. Analysis of the particular correlation between the wind and wave resources was demonstrated in Ref. [4], for three Atlantic-facing sites in Europe. The time lags between

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the peaks and troughs in the series were identified, and different optimal proportions of wind and wave devices were found at each site.

Further studies on combining wind and wave energy at specific sites emphasise the importance of the correlation between wind and wave resources and the desired output characteristics of the platform [5–7]. Clearly the benefit of combination is site-specific and must be carefully considered as part of a site characterisation study.

1.2. Using GIS for site selection

Using GIS to choose locations for renewable energy technology has become relatively common. Developers might typically employ GIS at a number of stages, from screening a whole region to identify suitable sites, down to the point of designing array and detailed cable layouts. On a more general scale, national and regional assessments have been reported in the literature. In Ref. [8], sites around Portugal's coast were classified by their suitability for wave energy installations. Exclusion zones were identified using criteria such as environmental sensitivity and depth. The remaining area was then assessed by measurement and weighting against a second set of criteria. All factors were combined to produce a map highlighting the relative suitability of sites for wave energy development.

An extensive list of criteria was developed for identifying suitable onshore wind power development sites in the UK in Ref. [9], by consultation with a number of public and private organisations. These included basic resource parameters, but the majority were related to proximity to existing features, such as dwellings and historic sites. Sites for a small region in England were rated according to the criteria and their weightings, based on perceived importance.

Ref. [10] followed a similar approach, considering parameters relevant to wind and solar developments (individually). The energy resource parameters were given the highest weighting, followed by transmission line proximity, and then other features such as distance to roads and cities. The authors analysed the suitability of sites within areas containing different types of land-cover, indicating the types of land use where future development could take place.

The approaches described so far are mainly focused on individual, mature technologies (with the exception of [8]) and concern relatively small areas, meaning that a fixed set of selection criteria and limits can be chosen with confidence. A predecessor to MARINA, the EU FP7 project, "Offshore Renewable Energy Conversion Platforms – Coordinated Action" (ORECCA), carried out Europe-wide site selection for combined offshore energy platforms using web-based GIS, looking at a number of contributing factors including resource, water depth, and port facilities, among others [11]. The project made the first attempt at identifying the areas in Europe suitable for wind and wave in combination, by allocating ratings to sites based on their resources.

The ORECCA methodology, described in detail in Ref. [12], split the region into three parts (the North and Baltic Seas, the Atlantic, and the Mediterranean). Wind resource maps for these regions were based on wind conditions derived from scatterometer data measured by the NASA QuickSCAT satellite. The authors state that there is, however, a high degree of inherent uncertainty within this data, and it is particularly problematic close to coasts. The wave resource maps were provided by Fugro-OCEANOR via a product called 'WorldWaves' which combines ECMWF WAM modelling and validation using satellite records. To provide information on the tidal resource, ORECCA used a combination of datasets from different sources but concentrating only on a small subset of points with a resource above a specific threshold. For the purposes of considering site-selection, the ORECCA methodology considered a set of resource classes, based on the annual mean wind speed, annual wave power density, or tidal velocity from the resource databases listed previously. Scenarios of required wind and wave resources for combined offshore energy platforms were evaluated. For the combined platform resource scenarios, the available resource in each of 5 depth and 4 distance classes was evaluated, along with the total available sea area in each of the three regions.

Considering a large climatically diverse continental area, a need was identified for a spatially coherent resource dataset at an appropriately high resolution for continent-wide marine spatial planning. The temporal coherence of such data would also help to identify synergies for combined offshore energy technologies. A tool with the ability to vary different needs and priorities was also required to carry out in-depth analysis and facilitate flexible decision support for designers of combined offshore energy platforms. Where ORECCA considered in Ref. [12] the available resource in depth, distance and regional categories and qualitatively evaluated the impact of factors such as ports and environmental considerations, a quantitative analysis of the sensitivity of the amount of area available for exploitation was not explicitly presented, and thus this idea was developed in MARINA.

2. Methodology

In order to consider European-wide site-selection for combined wind-wave energy platform designs, two significantly different concepts were chosen from the final three considered in the MARINA Platform project [13], and will be labelled hereafter as 'Platform 1' and 'Platform 2'. For comparison, a generic floating wind turbine platform which encompasses a wide range of possible designs ('Platform 3') is analysed alongside these. A set of fundamental physical and resource criteria, dictated by the design of the devices, were chosen to form the basis for initial site-selection decisions for these concepts, using the specialised resource data developed for the MARINA project. Following this initial selection, a secondary analysis was carried out, building upon the analysis techniques from the ORECCA project, to quantify the sensitivity of the selection to decision criteria where the limits are not clearly defined, for example, distance to port and environmental exclusions. Finally, a number of 'case study' sites were chosen for further detailed analysis of their suitability based on parameters that are too complex to consider continent-wide but where the bespoke resource data offers useful insight. Where insufficient design information was available for the combined platforms, floating wind turbine designs were used under the assumption that processes for combined platforms would be somewhat similar. Basic GIS techniques along with bespoke decision tools were applied for each aspect of the selection process and analysis.

2.1. Data

The foremost consideration for site selection for marine renewable energy platforms is, of course, that of the wind, wave and current energy resources. A bespoke model was created for the project to produce a 10 year (2001–2010) hindcast of the key wind, wave, oceanographic and tidal current parameters at an hourly resolution on a co-located $0.05^\circ \times 0.05^\circ$ grid, referred to hereafter as the 'Wind-wave-current (W2C) atlas'. The models and processes used to generate this atlas are described further in Appendix 5.1. Statistics based on the hindcast parameters from the W2C atlas have been calculated and form the resource map layers in the GIS. The following parameters are available for analysis:

- Wave: Mean annual significant wave height, mean period and power density; monthly average significant wave height
- Wind: Mean annual wind speed at 10 m, power density; monthly average wind speed at 10 m
- Tidal current: Mean, maximum, minimum and modal velocities; Mean and maximum spring and neap velocities; elevation range, minimum and maximum elevations; power density

Other parameters of relevance include bathymetry, environmental restrictions and port locations, which are described further in Appendix 5.2.

2.2. Site selection tools

The suite of decision support tools developed within the MARINA Platform project allow the user to interact with relevant data on a number of levels. A GIS has been created using the open-source Quantum GIS (QGIS) software [14], and, by connection with a PostgresSQL database [15] with PostGIS [16] enabled, presents the fundamental data in the form of 'layers', that can be used to produce maps and carry out simple queries.

Additional bespoke tools with user-interfaces (GUIs), called 'plug-ins', have been developed within the QGIS framework using the Python programming language. These interact with the database to facilitate flexible, multi-criteria analysis of the data and more sophisticated spatial investigation (see Appendix 5.3). Furthermore, the resource database can be interrogated in greater detail to explore features such as extreme conditions for individual points and consider weather windows for operations and maintenance activities.

The GIS database along with the plug-in tools for QGIS, is available on request from the University of Edinburgh, and further information regarding obtaining the full suite of resource data can be accessed by contacting the authors at NKUA.

2.3. Concept designs

The concept designs used in the study are described in Table 1. Platform 1 is based on a semi-submersible floating structure which provides the foundation for an array of twenty 0.5 MW oscillating water columns and a single 5 MW wind turbine. Wave power is the dominant technology in this case. Platform 2 is a floating spar structure, supporting one 5 MW wind turbine and one torus-shaped 2 MW point-absorbing wave device. The dominant technology in this concept is wind. Platform 3 represents a generic floating wind platform suitable for a wide range of depths, e.g. a semisubmersible-type structure. In the sections where floating wind turbines have been used as representations of devices similar to combined platforms, the assumptions are based on a semi-submersible floating platform hosting a single wind turbine.

2.4. Primary selection criteria

Table 2 describes the initial set of criteria used to eliminate unsuitable sites for each concept, i.e. limits to resource and physical parameters that render a site completely unusable for the given technology design. Resources are the main consideration in any siting decision in order to provide confidence in a minimum financial return for a site. Due to an emphasis on a different 'leading' technology in each case, the wind and wave resource requirements have been adjusted to reflect this.

A mean annual 10 m wind speed of 5 m/s is often used (see for example, [9]) as the minimum required for selection for onshore wind development. A minimum of 6 m/s was applied in Ref. [12], which may be reflective of the higher costs of offshore wind. Here, for the wave-led Platform 1, a minimum annual average 10 m wind speed of 6 m/s is required but for wind-led Platform 2 and for Platform 3, the level has been increased to a minimum of 7 m/s [12]. also states that a typical minimum wave power requirement would be 20–25 kW/m for existing devices, and thus for wave-dominated Platform 1, a minimum power density of 30 kW/m has been set whilst 20 kW/m is required for Platform 2.

The tool has been developed based on points within a 5 km resolution grid where the resource levels indicate a strong potential for energy generation, given some estimated limits for some machine designs with generic power production characteristics. It is known that different devices can, to a certain extent, be tuned or resized in order to make optimum use of different scales of resources but this has not been considered here.

Alongside resources, depth is the main physical parameter to which will impact on a site's suitability. Due to the nature of a floating spar structure with a draft of around 120 m [18], the minimum depth for Platform 2 is at least 150 m. Given the larger area and much smaller draft of Platform 1, its minimum depth is set at 70 m. In terms of maximum depths [19], mentions difficulties with cabling layout at water depths of greater than 100 m, but present a number of upcoming projects that go up to 215 m. Currently very few projects exist at depths greater than 100 m, and those that do (e.g. Hywind [20], or the Goto FOWT [21]) are typically in the early stages of development and testing. Solutions for mooring devices at great depths and laying both transmission and inter-array cabling have not yet been fully implemented and tested, and whilst the industry is keen to explore this frontier, the possibility is still considered somewhat tentative. Assuming combined technology platforms are some way from commercial development, and can thus be somewhat aspirational, a maximum depth of 250 m is set for all platforms but with the caveat that 100 m might be considered the current operable limit.

A minimum distance of 15 km to shore was chosen to restrict the visibility of developments and the impact on areas of sensitivity [22]. indicates that, for the UK, areas greater than 13 km from shore are considered to be at lower risk of having an impact on visual amenity. Maximum distances to shore are not considered at this stage of the selection but there are many factors to consider as distance to shore increases, including additional cost and the potential environmental impact from cable-laying, which will be discussed.

2.4.1. Ranking

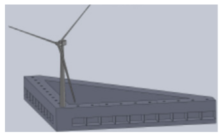
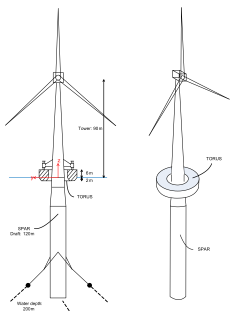
Based on the primary selection, points are given a ranking from 1 to 100. Firstly, the sites are ranked based on each contributing criterion, i.e. wind resource, wave resource and depth. For example, in the case of wind rank, the site with the highest wind speed will be ranked 100, and the lowest, 0. The user, when dictating the terms of the selection, can indicate the importance of the different criteria so, for example, a platform where the dominant technology is wind might give wind speed a higher importance than wave height. The final rank for each site is calculated by ranking the total sum of all ranks multiplied by their importance, as,

$$Rank\left\{\sum_i Rank(Parameter_i) \times Importance(Parameter_i)\right\}$$

2.5. Secondary analyses and case studies

Criteria for several parameters that could be important in a site-selection process have been applied in a secondary phase as there is less confidence in the reasons for specific limits due to limited detailed design data. The sensitivity of the selection to these factors

Table 1
Concepts used within the work.

Concept	Picture	Foundation	Wind turbine	Wave energy converter	Comments
Platform 1 (led by wave) *OWC array*		Barge/semi-submersible	1 × 5 MW	20 × 0.5 MW OWC technology	NREL WT characteristics [17]
Platform 2 (led by wind) *STC*		Spar	1 × 5 MW	1 × 2 MW Point absorber technology	NREL WT characteristics [17]
Platform 3 (wind only) Generic floating technology		Generic float – e.g. semi-submersible	1 × 5 MW	n/a	NREL WT characteristics [17]

is considered here by assessing the percentage of points on the 0.05° × 0.05° grid (based on the points in the W2C atlas) where development would be prohibited by applying the various restrictions.

2.5.1. Electricity networks

The costs of electricity transmission increase with distance, as losses due to reactive power increase. In terms of site selection for offshore generation, transmission costs will depend – among other things – on the amount of energy generated and on choices regarding the use of, for instance, HVDC (High Voltage Direct Current) transmission over more traditional AC lines. It is suggested in Ref. [23] that for a 400 MW offshore wind farm in a location with strong resources, HVAC transmission costs start to look less favourable than some HVDC options between 50 and 100 km from shore. Beyond 150 km, HVAC costs increase significantly. 80 km is indicated in Ref. [24] as the feasible transition point between AC and DC but also point out that this distance is reducing with time. The effect of selecting only sites within 50, 100 and 150 km of the shore are considered here, with the assumption that suitable connections can be made to the onshore network.

2.5.2. Logistics

Constructability and maintainability criteria can be applied in the form of maximum distances to suitable ports. The criteria on which to base suitability of ports for construction or O&M are selected from the World Port Index categories [25]. Construction ports have been set to require a minimum channel depth of 9.4 m. This is greater than that from Ref. [26] as the towing of semi-submersible structures may require this additional draft. A 'Repaircode A' designation (major shipbuilding facilities) is required for construction; whilst only 'Repaircode B' (moderate shipyard facilities) is required for maintenance ports.

Feasible travelling distances to construction ports are based on information from the offshore wind industry. They are heavily dependent on the technology and vessels involved. A mass-production scenario is assumed here – longer distances may be feasible in one-off projects – and that the wind turbine assembly will be performed at the construction yard, and the whole device then towed to the deployment site. The assembly of the wind turbine in-situ would make transport simpler, but increase the weather window requirements for installation, suggesting that this is an area requiring some dedicated research and innovation in the near future.

Refs. [26,27], suggest maximum travelling distances from construction ports of 250 nm and 300 nm (460 km and 550 km) respectively for fixed foundation wind turbines. For floating foundations, since towing is the only existing method for installation, and given that the towing speed will be 4–5 times lower than the speed of a typical installation vessel and that only one foundation will be transported at a time, 200 km is perhaps more reasonable; the effect of applying both 200 km and 500 km limits are presented here.

For operations and maintenance, ideally the travelling distances to the onshore base (port) would be shorter, but again this will be technology specific and related to detailed design regarding maintenance planning, which is not available for the technologies considered here. For that reason, a range of distances from 50 to 200 km are considered.

The distances presented here are calculated on the basis of

Table 2
Case studies for Europe-wide site selection – fixed criteria.

Concept	Minimum wind speed @ 10 m (m/s)	Minimum wave power density (kW/m)	Depth range (m)	Minimum distance to shore (km)
Platform 1 (led by wave) OWC array	6	30	70–250	15
Platform 2 (led by wind) STC	7	20	150–250	15
Platform 3 (wind only) Generic floating technology	7	n/a	70–250	15

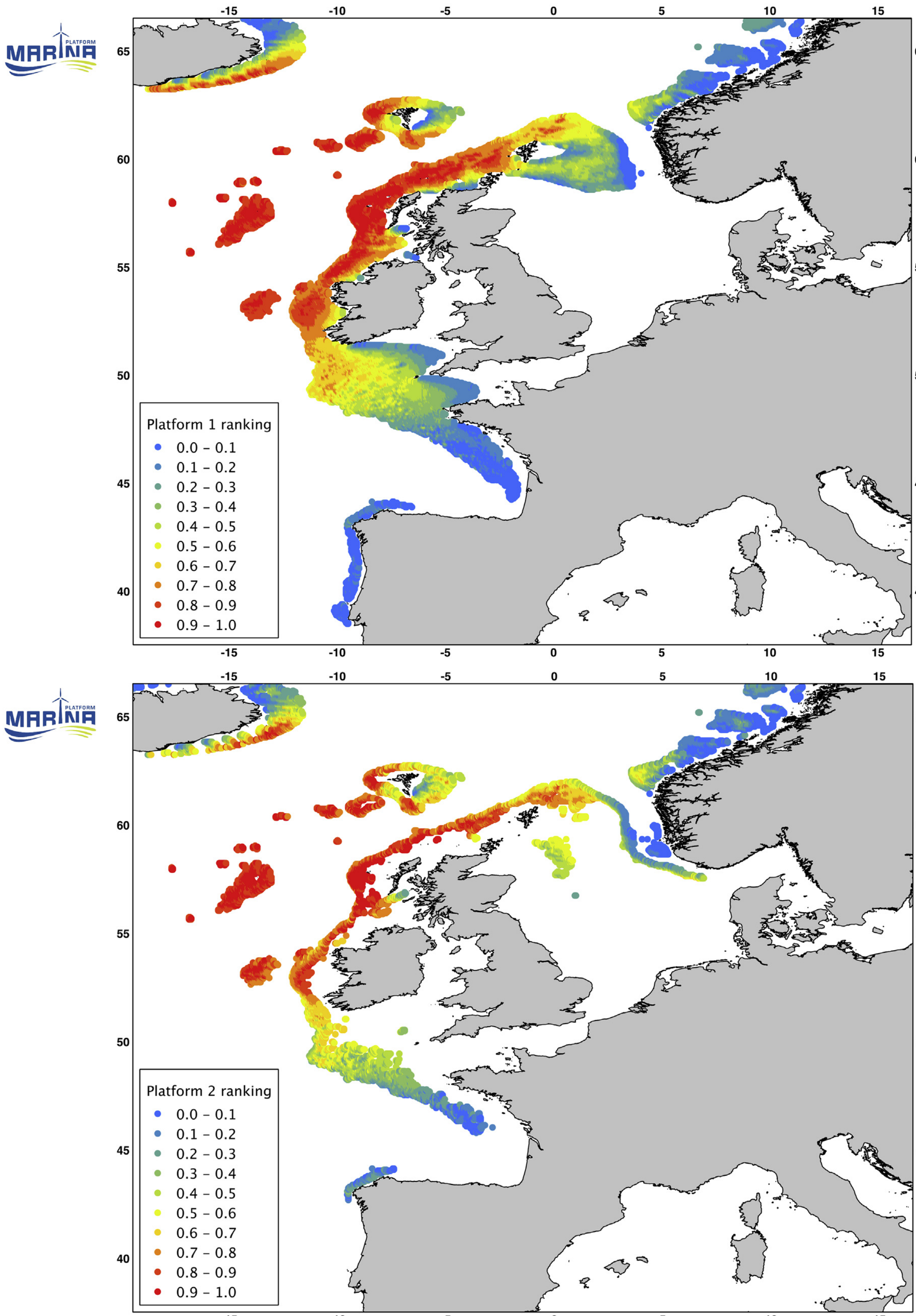


Fig. 1. Selection and ranking of sites for Platform 1 (upper panel), Platform 2 (middle panel) and Platform 3 (lower panel) designs.

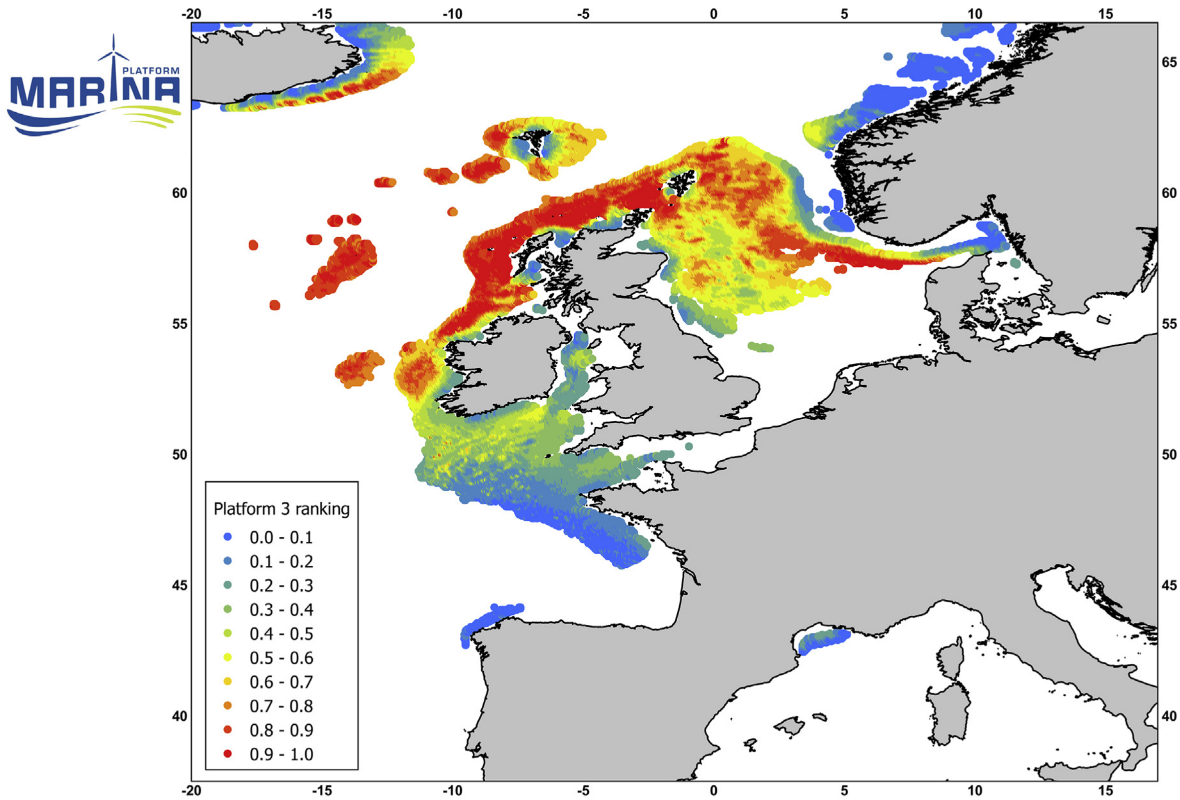


Fig. 1. (*continued*)

radial distances from site to ports to enable fast selection in the GIS; the issue of directly calculating port distances is explored further later using more detailed routing for individual sites.

2.5.3. Shipping traffic

Areas with a high density of shipping traffic would potentially be unsuitable for offshore energy development. Shipping routes are strongly optimised to minimise travel distances, and re-routing existing major channels for a relatively small energy development would be impossible. Whilst arrays of wind turbines can have spacings of up to 1 km between devices, there are additional associated obstacles, such as electricity cables and mooring lines. Here it is assumed that installing such developments could be prohibited in areas with large amounts of traffic, and thus, the impact of setting some different thresholds of maximum shipping traffic density coinciding with selected points is considered.

Global data was obtained from Ref. [28], as a raster containing the number of ship tracks recorded in cells of 1 km^2 area during the period October 2004–October 2005. These numbers are considered by the authors to be an underestimate in high-density areas, but overall appear to capture the main patterns of commercial shipping traffic. The maximum number seen in any single cell was 1,158, in a small area between the north of Germany and the west coast of Denmark, but a typical figure for, for example, cells along the major English Channel route between Southampton and Le Havre, was around 200–300. The raster file was reclassified to 5 categories of density according to the distribution over the whole area and different thresholds applied as shown in Table 3.

2.5.4. Environmental protection

Various areas around the ocean have particular environmental sensitivities that would be a barrier to installing and operating energy devices. Additionally, some environmental issues may require additional monitoring during installation or operation, and this must be fully considered in site-selection. Here, the marine areas designated under Natura2000 [29] are excluded from potential site selections and the effect of this on available sites is considered. The authors in Ref. [9] used a number of exclusion criteria based on environmental sensitivity, and applied an extra 1000 m ‘safe distance’ buffer zone around these areas. A similar approach is taken here, to investigate the impact of excluding development within 1 km of the Natura 2000 areas.

2.6. Case studies for particular characteristics

A number of other important met-ocean related characteristics for combined platform development may be relevant to a site-selection decision. However, the calculations for these using the W2C atlas for the whole European sea area under consideration would be unfeasible. In order to investigate some of these types of characteristics, a small subset of geographically dispersed sites suitable for one or other of the types of platforms have been used as case studies. The factors analysed for each case study are: power extraction, transport routes to port, weather windows, extreme conditions and wind-wave correlations.

3. Site selection results

3.1. Primary selection

Applying first of all the fixed criteria as listed in Table 2, the selection of suitable sites is presented in Fig. 1. The sites have been ranked from 1 to 100% according to the resource parameter of chief importance for each of the concepts, so that out of all the sites indicated, red highlights the most suitable sites, and blue the least. Wind speeds and wave power densities are ranked from 1 to 100% with the highest wind speeds and wave power densities having the highest rank. Depth is rated from 1 to 100% where the shallowest water is given the highest rank – this is indicative of the increasing costs of greater depths. In the case of Platform 1, wave importance is given a value of 3 and wind 2. For Platform 2, wind and wave importance is swapped around. For Platform 3, wind is given an importance of 2 and wave 0. In all three cases, depth is given an importance of 1, to reflect the fact that it is a critical consideration, but having set limits for each platform, the variation within that range may not be as important as resources.

Sites in the north-west, off the coasts of Scotland and Ireland, appear to be the most favourable for the combined platforms, due to the highest importance being given to high wind and wave resources. Deeper waters are more challenging to develop, and given similar levels of resource, this leads to the lower ranking of sites in north-west Spain and along the Norwegian coast. Many sites in these areas that are far enough from shore to meet the resource thresholds are in water that exceeds the 250 m depth limit. For Platform 3, the highest ranked sites are also off the coasts of Scotland and Ireland, but also to the south and west of Norway, indicating that whilst the wave resource, and thus the potential for combined platforms, is less favourable here, the wind resources are still very much exploitable.

It is interesting to note the specific distribution of points by country. Using the maritime boundaries as specified in Ref. [30], the percentage of the total for each platform design is specified in Table 4. As indicated by the ranking, the selection strongly favours northern European countries, where the resource is strong but the change in depth with distance from shore is also more favourable, particularly in the UK, Ireland and north-western France– that is, the depth increases more gradually, giving a greater area along these coastlines with acceptable depths, as shown in Fig. 2.

3.2. Secondary selection

Based on the sites chosen in the primary stage, further analysis has been carried out to examine some additional selection criteria – namely, distance to shore, logistics and environmental issues. It is more difficult to prescribe defined criteria limits for these characteristics as they depend on other factors, such as cost and the availability of different technologies. The proportion of potential development sites that would be excluded, should various constraint factors be applied, is shown in Table 5.

The impact of limiting distance to shore is interesting. Eliminating all sites beyond 50 km from shore excludes 65–70% of the potential sites. This implies that, based on the limits suggested in Refs. [17] and [18], if connections were confined to using AC technology, only 30–35% of sites would be available. Between 12 and 18% of feasible sites for the two technologies considered lie beyond the 150 km boundary, where HVDC clearly becomes a cheaper solution for transmission. Despite the increased resources far offshore, there aren't many selected sites beyond this distance, due to the selected maximum depth limit of 250 m. Fig. 2 shows the 250 m depth contour, i.e. the limit for the two technologies selected, along with the 50, 100 and 150 km, distance contours. The costs associated with the increased depth alongside higher transmission costs would likely prohibit development beyond 150 km in the near future.

The environmental impact of increased distance is worthy of further investigation. The work in Ref. [31] identifies the possible effects of electro-magnetic fields related to power cables on ocean-dwellers, including species that use magnetism for navigation. Clearly, the longer the cable, the more likely it is to cross the normal territory or routes of sensitive species. Selecting routes to avoid particularly susceptible areas would increase the distance, and thus the cost of the development and also the transmission losses. The disturbance of sediment is also likely to be damaging to the seabed environment, and would ideally be minimised. Although the resources often indicate a better performance at a higher distance from shore, the likelihood of having a greater impact on the environment is not trivial.

The issue of logistics appears, under the scenarios presented, to be more significantly limiting than issues surrounding distance. Setting a requirement for a port rated as 'Repaircode B' in the World Port Index, i.e. with moderate shipbuilding facilities (and probable existing local skills), within 50 km eliminates up to 97% of sites, whilst extending the requirement to 100 km eliminates 75–78%. Only 23–36% lie more than 200 km from a suitable O&M port. Requiring a construction port with a draft of 9.4 m and a large shipyard within 200 km – as was mooted for floating platforms – leads to the elimination of 70–90% of sites, but if 500 km is a feasible distance, only 26–50% of sites would be counted out. Combining a construction and O&M requirement leads to the elimination of a very large proportion of sites for all platform designs.

It should be noted that the choice of categories in the World Port Index is not definitive, and it is, by its nature, an over-simplification of information which may not capture an entirely accurate picture of facilities in every location. As mentioned previously, the distances have also been calculated radially for reasons of computational speed. This method will result in some errors, particularly along complex coastline or smaller landmasses where radial distances are not reasonable approximations for actual shipping distances. However, it is considered here as an indicator of the broad picture of the restrictions on development due to ports around Europe.

In terms of applying some blanket exclusion policies for particular areas, the exclusion of all sites that have a shipping density of greater than class 1 only removes 3–6% of sites for both platforms, whilst excluding anything above a class 3 site removes less than 1% of sites in both cases. It is clearly an important consideration but would appear to be sensible to evaluate it on a case-by-case basis.

Applying a no-development policy to Natura 2000 sites excludes only 1.3% of sites for each type of platform. This is reflective of the fact that the majority of the Natura 2000 sites fall within

Table 3
Categories for shipping traffic assessment.

Old values (number of ship tracks recorded in a single 1 km^2 cell)	New values (reclassified into ranked categories)	Classification
0–25	1	Very low
25–50	2	Low
50–75	3	Medium
75–100	4	Quite high
100–1000	5	Very high

Table 4
Distribution of selected sites by country.

Country	Platform 1	Platform 2	Platform 3
Faroe Islands (Denmark)	6%	11%	5%
Iceland	7%	12%	6%
Ireland	21%	18%	17%
Portugal	1%	0%	0%
Spain	1%	1%	0%
France	13%	8%	9%
UK	36%	26%	45%
Norway	13%	22%	15%
International waters	1%	2%	3%

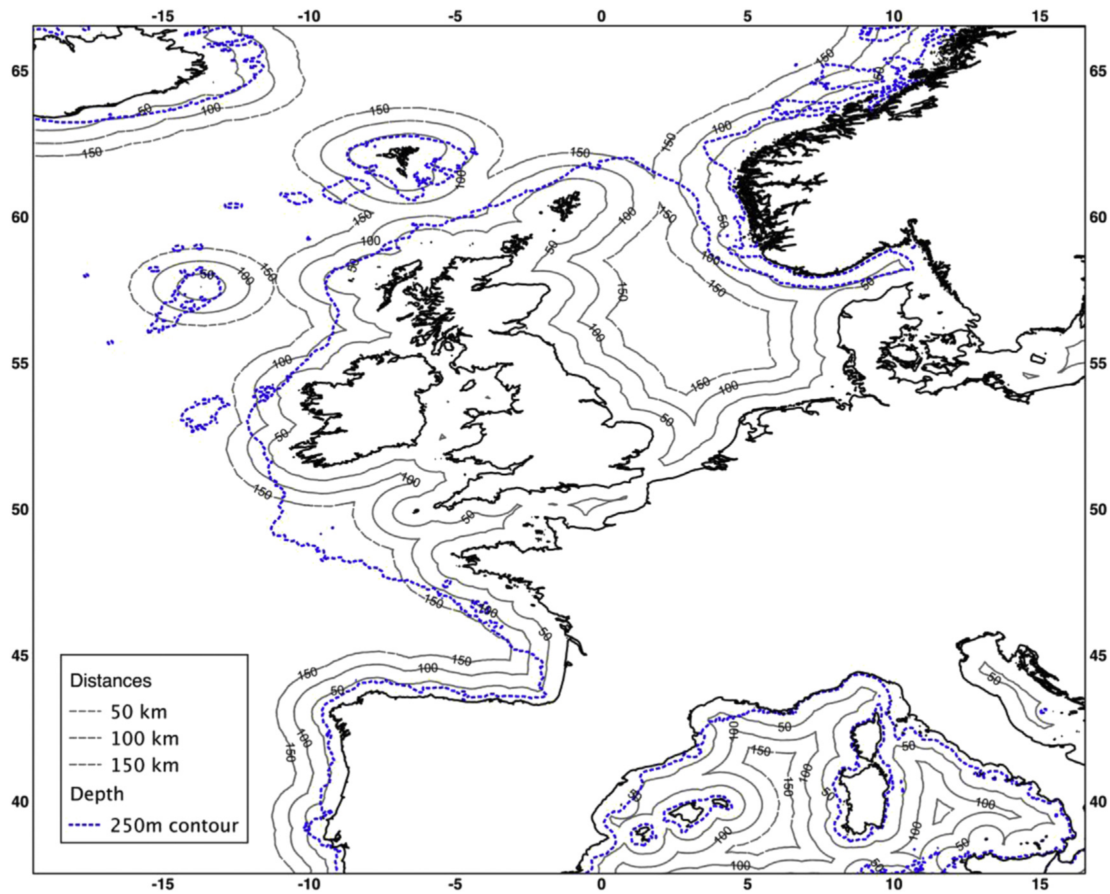


Fig. 2. Distance and depth comparison for the selected area.

15 km of shore, and have thus been excluded from the selection in the first step. Applying a 1 km buffer zone around Natura 2000 zones to further ensure minimal impact on these areas only eliminates a very small additional percentage of suitable sites for combined platforms, reflecting that the majority of the Natura 2000 restrictions apply in coastal areas, which do not meet other criteria for these platform designs. It may be the case that in deeper waters, different environmental concerns apply, and a monitoring plan for these has been developed (described in Ref. [32]). Comparing the three platform options overall, the wind-only devices offer the largest number of potential sites overall, as the wave resource is sufficiently strong in fewer locations. Due to its requirement for deeper waters, Platform 2 is most affected by distance-based exclusions, i.e. a limit on the distance to shore or distance to port excludes the highest number of potential sites. These designs would have most to gain from innovations to increase in the feasible distance to shore that a development can take place, for example HVDC transmission or a cable-laying technique that reduces sea-bed interference. All three platforms are similarly affected by the exclusion of Natura 2000 areas or areas with high shipping traffic.

3.3. Case studies

More detailed calculations based on the 10-year hourly wind, wave and current hindcast in the W2C atlas provide additional information on the characteristics of selected sites as relevant to machine design requirements. A small set of geographically dispersed points have been identified that the previous selections and analyses have indicated would be suitable for combined platforms. These are shown in Fig. 3; the legend indicates their suitability for the two concepts, and all sites are suitable for wind-only platforms. The issues of power extraction, wind-wave correlation, extreme conditions and considerations surrounding ports and weather windows are considered, using data for a semi-submersible WT as a proxy where design information on combined platforms is limited.

3.3.1. Power extraction

For each of the selected sites, the 10-year hourly time series of wind and wave resource parameters have been combined with wind turbine power curves and wave device power matrices to derive annual average capacity factors (i.e. total energy extracted divided by theoretical maximum for the whole device), shown in Table 6. The influence of platform motions on the performance of floating devices has been neglected and no other losses have been taken into consideration. Clearly all of the sites have high capacity factors, with sites on the western seaboard of Europe — as would likely be expected — showing some slight advantage in this regard. The balance of strength of the input resources is evident: for example, Norway 3 has slightly stronger wind than Sybill Head, but Sybill Head has substantially greater wave resources, giving rise to a better performance than Norway 3 in the wave-led platform. At Norway 1, the wave resource is significantly lower than at the other sites, but because the wind resource is very strong, it still gives good output for the wind-led device. In all cases, the addition of wave power reduces the capacity factors overall, as evidenced by the higher capacity factors for the wind-only Platform 3.

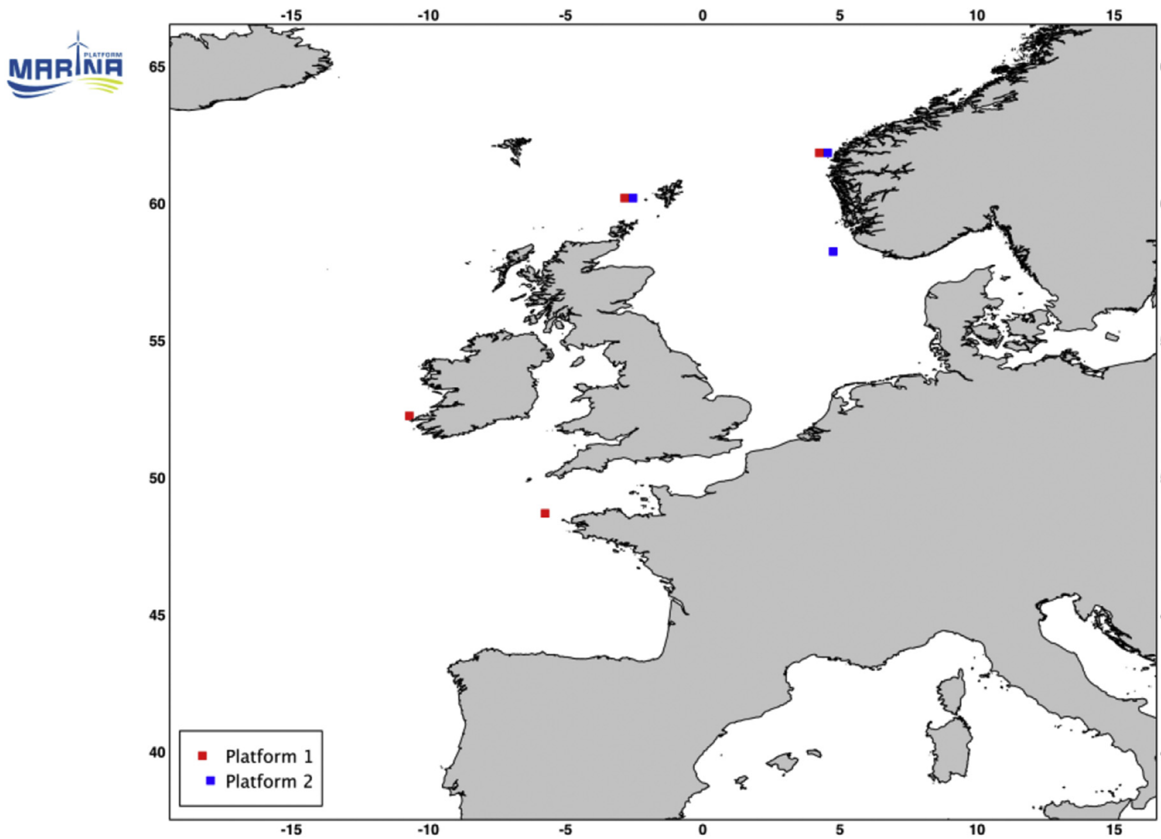


Fig. 3. Map of locations for detailed study.

3.3.2. *Met-ocean conditions*

Table 6 also includes a parameterisation of the relationship between wind and waves at each site (see Ref. [4] for calculation details). To benefit from smoother power, a lower correlation at time zero and a longer time lag for the maximum correlation is preferred, as this would indicate that the wind and wave resources would not 'peak' and 'trough' simultaneously. All the sites have a lag of 3–4 h in the lag between the wind and wave patterns, but Crozon, Norway 3 and Sybill Head have a lower correlation at time zero, indicating a weaker relationship between wind and waves overall, which will likely be beneficial for power smoothing.

Extreme climatological and oceanographic conditions will impact on site suitability and machine design. The 95th percentile of significant wave height and 80 m wind speed are presented in Table 6 as proxies for more sophisticated extreme statistics – return period values would be required for machine design, for example. All the sites experience similarly high 95th percentile wind speeds, with the two exposed Atlantic sites – Shetland and Sybill Head – experiencing the highest 95th percentile significant wave heights. The slightly more sheltered seas around Norway give rise to lower extreme waves but the trade-off with resources is illustrated, with the slightly lower capacity factors of devices here.

3.3.3. *Port logistics*

Port-proximity was considered over the whole European Seas area in Section 3.2 using a calculation based on a radius from each point. In order to look at the issue with more accuracy and detail, the second GIS tool (see Appendix 5.3) has been created to plot approximate travel routes between sites and nearby ports that can be selected on the basis of their facilities. Similar basic

Table 5
Percentage of sites excluded by specific constraint factors with variable thresholds.

	Exclusion criteria	Platform 1 – percentage of sites excluded	Platform 2 – percentage of sites excluded	Platform 3 – percentage of sites excluded
Electrical networks	Maximum 50 km to shore	65.35%	70.21%	66.45%
	Maximum 100 km to shore	30.31%	33.47%	34.69%
	Maximum 150 km to shore	12.60%	17.82%	17.39%
Logistics	Maximum 50 km to O&M port	97.08%	96.36%	95.69%
	Maximum 100 km to O&M port	74.95%	77.61%	74.48%
	Maximum 200 km to O&M port	22.92%	35.92%	39.25%
	Maximum 200 km to Construction port	69.17%	87.17%	71.50%
	Maximum 500 km to Construction port	26.39%	40.78%	21.23%
	Maximum 100 km O&M port AND Maximum 500 km to Construction port	84.08%	92.62%	79.90%
Shipping	Exclude Shipping density category 2,3,4,5	5.48%	3.03%	4.28%
	Exclude Shipping density category 4,5	0.38%	0.15%	0.27%
Environmental	Exclude Natura 2000	1.32%	1.29%	1.01%
	Exclude Natura 2000 plus 1 km buffer zone	1.45%	1.38%	1.11%

Table 6
Physical, met-ocean and production characteristics for the sites.

	Shetland offshore	Crozon offshore	Norway 1	Norway 3	Sybill Head
Latitude (°)	60.2	48.7	58.25	61.85	52.25
Longitude (°)	−2.85	−5.75	4.45	4.25	−10.7
Depth (ETOPO1) (m)	150	114	178	202	103
Distance to shore (km)	65	75	79	30	17
Mean wind power density (W/m^2)	1126	795	1079	1084	946
Mean wave power density (kW/m)	67	50	28	47	71
95% wind speed @ 80 m a.g.l (m/s)	18.83	17.12	18.9	19.06	18.15
95% significant wave height (m)	6.36	5.66	4.85	5.46	6.52
Wind-wave correlation @ time = 0	0.70	0.66	0.78	0.67	0.67
Max wind-wave correlation	0.73	0.69	0.81	0.70	0.70
Time lag to max (hours)	4	4	3	3	4
Platform 1 rank (%)	0.77	0.36	n/a	0.27	0.73
Platform 1 capacity factor (%)	40	32	n/a	33	38
Platform 2 rank (%)	0.87	n/a	0.34	0.32	n/a
Platform 2 capacity factor (%)	46	n/a	42	42	n/a
Platform 3 rank (%)	0.81	0.19	0.41	0.32	0.39
Platform 3 capacity factor (%)	58	50	55	54	53
% of hours inaccessible at Hs > 2 m, wind speed >10 m/s	74	60	48	65	72

conditions for distance, port draft and facilities are assumed as described in Section 2.5 with some additional considerations, namely the desirable additions of at least a small dry-dock and railway, and the capacity of the port to host a minimum vessel size. Table 7 summarises the required characteristics for the selected ports.

Using the "maximum vessel size" category from Ref. [25] as a proxy for minimum quay length, a 'large' size of over 500 feet (approximately 150 m) is desired. Although the maximum dimension of wind turbine components will be approximately 100 m, for the load-out and assembly, larger dimensions are required – in Ref. [24] it is indicated that accommodation for vessels up to 140 m length would be required. Given the early stages of development of combined platforms, the installation method for large devices involve many uncertainties. For this reason the case study has been focused in a semisubmersible WT. It is likely that for larger projects and where it can serve multiple developments, harbours will be willing to upgrade to meet additional needs so this analysis should be considered only as indicative of the current situation.

Fig. 4 and Fig. 5 show two examples of the output of the Marina Ports tool for two of the case study sites. For Crozon (Fig. 4) there is one port allocated within the 200 km maximum distance that has the draft required for semi-submersible installation – Rade de Brest. There is a dry-dock and a railway, but the 'maximum vessel size' recorded in Ref. [25] for this port is M, so it cannot, in theory, host a 150 m vessel. Seeking this would require a journey of almost 400 km to La Rochelle. In the case of Shetland, there are a number of nearby ports but none meeting all of the criteria within 500 km. The closest, and likely most suitable port is Peterhead, which has a dry-dock and a railway, and is of suitable draft, but is listed in the World Port Index as Repaircode B, and with a maximum vessel size of M, so could potentially need some upgrading. There are two ports within shorter traveling distances that may be suitable as staging hubs – Sullom Voe (Shetland) and Thurso Bay (mainland).

3.3.4. Weather windows

Weather windows are a major limiting factor in construction and maintenance of offshore developments. In terms of the installation process, weather windows along the routes to port (as estimated by

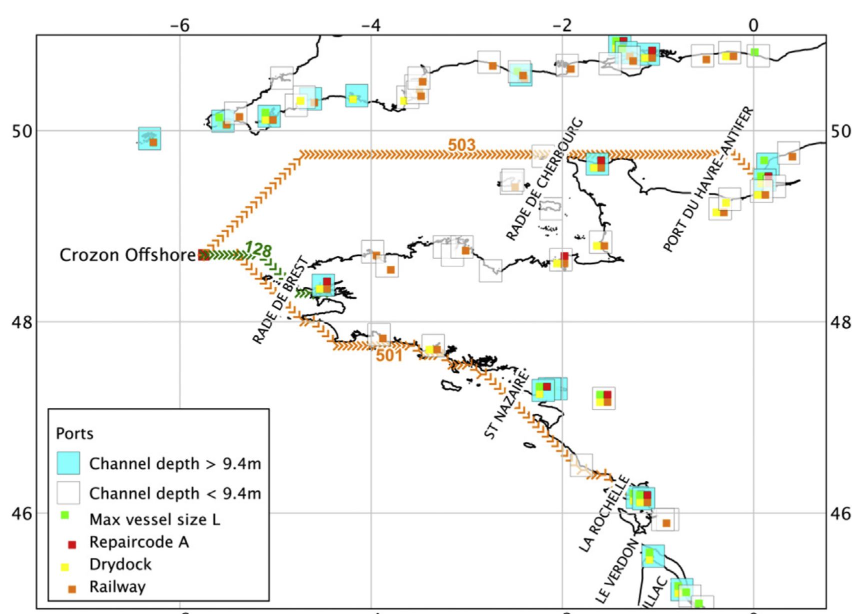


Fig. 4. Presented routes for suitable ports near Crozon.

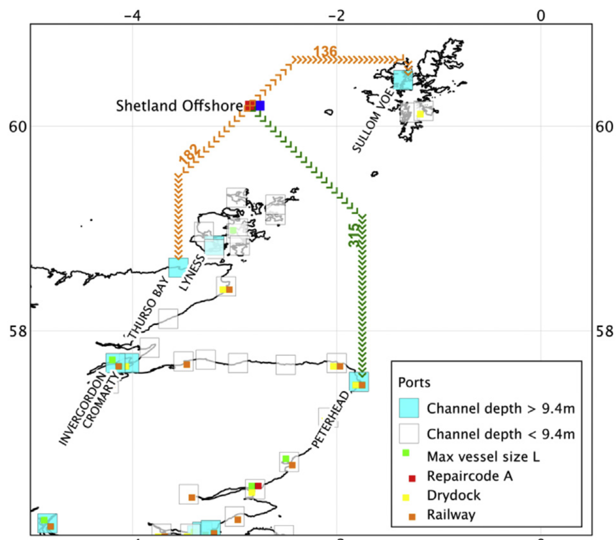


Fig. 5. Presented routes for suitable ports near Shetland.

the Marina Ports tool) have been analysed, and the probability, based on the 10 year hindcast, of achieving a suitable access window has been calculated. As in the previous case, the estimation of weather windows for the installation of large platforms involves many uncertainties. For this reason, and in order to recreate a realistic scenario for the case study, a sequence of typical operations for the installation of a floating semi-submersible wind turbine, described in Table 8, has been proposed based on conservative guidance provided by experienced companies [33,34]. Weather windows for completing the proposed sequence, including travel along the routes to port (as estimated by the Marina Ports tool) have been analysed using the 10 year hourly wind and wave hindcast, and the probability, based on the hindcast, of successfully completing installation has been calculated.

Referring to Fig. 6, the significant travelling time (approximately 3 days under the assumed speed restrictions), followed by installation procedures of a similar duration give rise to a prohibitively low probability of success (less than 5% in summer) for the Peterhead-Shetland operation. Based on experience, it is likely that there will be opportunities to pause operations due to unacceptable conditions, for example after towage, or approximately every 16 h during the mooring line installation. Considering only the towage and assuming there can be a break before commencing installation, the probability of a successful and safe journey is around 10–15% in summer months. This result emphasises the case for selecting a more local staging port to act as a mid-way point. The use of vessels and procedures which allow several pauses in operations or vessels which can operate in more severe conditions is clearly essential for this site.

The shorter route from Brest to Crozon results in a journey time of around 1.3 days but the average probability of successfully completing towage plus installation in one contiguous operation is still very low, with a maximum of 5–6% in July–September. Again, assuming there can be a pause between towage and installation, the average probability of completing towage alone is around 25% in July–September. Whilst better than Peterhead-Shetland, there is still clearly a risk in any given summer that these operations cannot be completed and thus the need for more tolerant vessels and procedures is highlighted.

Due to the stage of the development of the industry, there is a limited amount of knowledge on the precise requirements for accessibility for operations and maintenance. Two current EU FP7 projects are attempting to analyse the detail of the required processes for offshore energy – Leanwind (http://www.leanwind.eu/) for the wind industry and DT Ocean (http://www.dtocean.eu/) for the wave and tidal industries. Here, a basic calculation based on [35] has been carried out to compare the case study sites. Assuming that operations can be carried out safely at a wind speed less than 10 m/s and wave height of less than 2 m, the percentage of hours in the 10 year period of analysis at each site where this is the case is shown in Table 6. The most accessible site according to these simple criteria is Norway 1, due to its much less severe wave conditions, but it is still inaccessible, on average, for around 50% of hours. Crozon is the next most accessible, but operations requiring a threshold such as that proposed here would be impossible on average 60% of the time.

3.3.5. Environmental impacts and conflict with shipping

None of the case study sites analysed fall within 1 km of any of the Natura 2000 sites, but in terms of environmental considerations, the larger distances from shore of Shetland, Crozon and Norway 1 compared to the relatively close Norway 3 and Sybill Head mean that the cable-laying involved will have a greater impact on the sea-bed and associated ecology. Considering existing shipping routes, Shetland and Sybill Head are not likely to cause unwanted interference but Crozon and the two Norwegian sites are located close to some existing shipping routes, as found in Ref. [28], requiring substantial consideration.

3.3.6. Summary of case study sites

The example sites presented here all have strong wind and wave resources but do differ in their overall suitability for development. Shetland and Sybill Head experience the most extreme conditions and both sites are likely to have the lowest levels of accessibility, both for installation and operational purposes. Crozon offers the most likely benefit to combining wind and wave energy at a single site, given its low correlation between wind and wave resources and the consequently smoother power production patterns, but it does have the disadvantage of potential conflicts with shipping routes. The wave resources are generally lower at the Norwegian sites, and Norway 1 is very far from shore, but Norway 3 is still feasible for both combined platforms, and has a favourable wind-wave correlation. It may offer the best compromise between resources and the likely problems caused by low accessibility and extreme conditions. In all cases, innovation in terms of managing weather windows and distance-related problems will offer more possibility to access strong resources.

The analysis presented uses some basic assumptions about installation and operational procedures, and relies on simplified parameterisations of complex met-ocean analyses such as extreme values and the relationship between wind and wave resources. The shipping route information is a snapshot in time and may not capture all of the existing routes, and whilst using Natura 2000 is a

Table 7
Parameter values selected from the World Port Index.

Concept	Means of installation (special transport vessel or towage)	Facilities required	Max distance to the site from the construction port (km)	Min. port draft required (m)	Maximum size vessel
Semisubmersible supporting 5 MW WT	Towage of entire structure	Repaircode A Dry-dock – Small Railway – Small	200	K (9.4 m minimum)	L (150 m)

Table 8
Weather windows constraints for the installation of WT semisubmersible platforms.

	Operation	Maximum Hs (m)	Maximum wind speed (m/s)	Duration
Installation of semi-submersible supporting a 5 MW WT	1. Towage	1.5	15	$\frac{Distance}{Vessel\ Speed}$, speed = 4 km/h (min. required by regulations)
	2. Installation of dynamic cable	1.5	n/a	5 h (only including recovery, since the initial cable laying could be overlapped with the platform towage).
	3. Installation of mooring lines and drag anchors (4 lines and anchors)	1.5	n/a	64 h

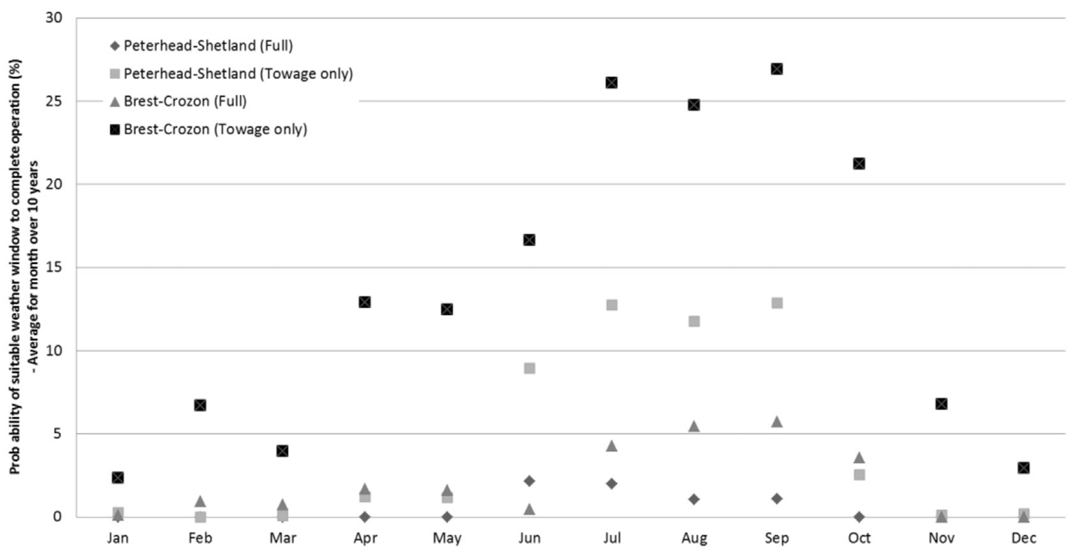


Fig. 6. Probability of suitable weather window for semi-submersible installation including transport from port.

good indicator for environmentally sensitive areas, it is not the complete picture. Further in-depth analysis of all these features is feasible – and sensible – only at a smaller scale, perhaps country-by-country.

4. Conclusion

This paper has examined a wide range of issues surrounding site selection for offshore renewable energy platforms, and in particular, has demonstrated the use of a GIS with bespoke additional tools to help assess multiple sites with multiple selection criteria. It has been shown that some sites may be suitable for combined wind-wave energy platforms along the Atlantic-facing coasts of Europe, with case studies indicating that the machines will produce high capacity factors. There is a potential risk, however, that the sites with the highest power availability also suffer the most extreme conditions and some compromise must be sought between the cost of designing for such conditions and the extra energy extracted. The additional advantage of having a smoother power output from combined technologies is likely to be greater at the sites with lower correlation at time zero and a longer lag to the time of peak correlation.

A potential lack of appropriately-located infrastructure has been highlighted, leading to locations with good resources and suitable physical conditions being under-exploited due to lack of ports with construction facilities. The analysis of weather windows, which considered not just the access conditions at the deployment site but also the conditions along the route taken by the installation vessels, indicate that for many of the suitable locations, there will be a very high risk of not completing operations in a single event given existing vessel and operational weather tolerances, even in calmer summer months.

Legislation governing the installation of offshore renewable energy varies between the countries of Europe – for example, some environmental protection frameworks and the process of planning a development. As such, on a continent-wide basis, some countries will thus present more favourable development opportunities than others and this will clearly form part of a decision-making process for the developer. Conflict with current uses of the sea – including, as discussed, existing shipping lanes – is often also a more localised issue, and as such, site-selection decisions at a smaller scale than evaluated here will necessarily require smaller-scale analysis to incorporate these spatially variable factors.

A series of subsequent EU FP7 projects, funded under the European Commission "Oceans of Tomorrow" initiative have been investigating the potential for inclusion of other factors in offshore platforms alongside energy production. TROPOS (FP7-288192, 2012–2015), H2Ocean (FP7-288145, 2012–2015) and Mermaid (FP7-288710, 2012–2016) added factors such as aquaculture, hydrogen production, transport and leisure facilities to offshore energy platform designs. The remit of these projects has been to establish if the European Commissions's "Blue Growth" strategy can be assisted by the deployment of multi-use platforms which exploit synergies, share costs and ocean space. The design process for a potential hybrid platform is discussed in Ref. [36]. The hybrid nature of the designs offers more opportunity to make the most productive use of precious marine space [37] but also requires that the assessment of environmental benefits and consequences be carefully considered [38].

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5. Appendix

5.1. Data: Energy resources

5.1.1. Atmospheric Model

Atmospheric circulation has been simulated using the SKIRON model, developed at the National Kapodistrian University of Athens (NKUA) by the Atmospheric Modelling and Weather Forecasting Group (AM&WFG) in the framework of the national funded project SKIRON and the EU funded projects MEDUSE, ADIOS and recently CIRCE ([39,40]). SKIRON is a full physics non-hydrostatic model with sophisticated convective, turbulence and surface energy budget scheme. It is based on the ETA/NCEP model, originally developed by Mesinger [41] and Janjic [42].

The domain is shown in Fig. 1, with a spatial resolution of 0.05° × 0.05°, 45 levels in the vertical (from surface to 50 hPa), and a time step of 15 s. The initial condition fields are from a high-resolution (0.15°) regional reanalysis system, prepared with the implementation of LAPS assimilation system ([43,44]). The initial guess fields are the ECMWF 0.5° × 0.5° operational analysis fields while the lateral conditions are updated every 3 h. The model utilizes daily SST fields from NCEP with a resolution of 0.5°. The model produced raw hourly outputs for a set of variables at chosen vertical levels (10, 40, 80, 120, 180) including, for example, pressure, air density, wind components, turbulent kinetic energy etc.

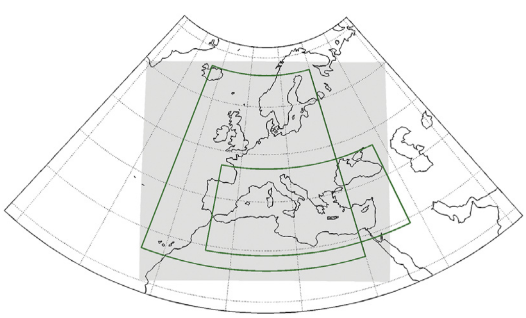

Fig. 1. The gray-shading indicates the SKIRON model domain. The green frames show the areas over which SKIRON passes wind data to the WAM model.

5.1.2. Wave model

The ECMWF version of the wave model WAM ([45,46]) CY33R1([47,48]) has been adopted for the simulation of the wave parameters. This version contains updates that increase the capabilities significantly. In particular, the wave model includes new features that support the better parameterization of bathymetry and shallow water effects that affect the time evolution of the wave spectrum ([49,50]). Moreover, the option of using nested domains ensure the utilization of accurate boundary conditions and give the choice of adopting high resolution domains over the area of interest supporting in this way the accurate simulation of local effects. On the other hand, the credible simulation by wave models is critically affected by the quality of the atmospheric forcing as pointed out in different studies (missing [51–54]). Towards this direction, the use of Skiron model is a critical advantage since the system is designed to use either the hydrostatic approximation or non-hydrostatic dynamics making it able to run on high resolution mode.

SKIRON is a well-established atmospheric system adopted in a great number of previous technical and operational studies including wave applications ([53–56]), oil spill modelling ([58]), as well as air-quality applications [57], renewable energy ([56,58–60]), photochemical processes ([61]), and desert dust studies ([40,62–64]).

Concerning the impact of sea surface currents on the local wave climatology, it has been proven that they may influence the wave generation mechanism and the wave propagation resulting in associated alterations in the significant wave height and the mean wave period due to the Doppler shift ([56,65–68]). The wave model adopted in our study makes possible the use of sea surface currents as a second forcing apart the wind speed and direction.

The wave model is run in two domains (Fig. 4): the North Atlantic (20N–75N, 50W–30E) and the Mediterranean and Black Seas (29N—47N, 6W—42E). The Atlantic domain extends to the west far beyond the area of interest so as to capture the all-important swell propagation. A high spatial resolution has been adopted (0.05° × 0.05°). The wave spectrum is discretized into 25 frequencies (logarithmically spaced in the range: 0.0417–0.5476 Hz) and 24 equally spaced directions, while the propagation time step is 75 s. WAM is operated in shallow-water mode, driven by 3-hourly wind input (10 m wind speed and direction) obtained from the SKIRON regional atmospheric model over the areas shown in Fig. 3.

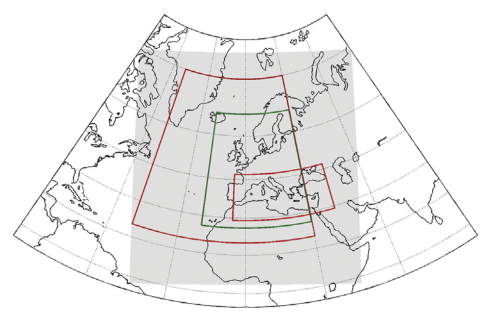

Fig. 2. The gray-shading indicates the domain covered by LAPS. The red frames show the domains of the WAM model. The green frame as in Fig. 1.

Fig. 3. Selected locations at which the full wave spectrum is available.

5.2. Data: physical limits and other constraints

The bathymetry dataset used within the wave model was ETOPO

1 [69] at the resolution of the model (0.05°). Two further parameters have been derived from the GEBCO depth data using QGIS: slope, and ruggedness index (the root-mean-squared difference between the elevation in the current cell and the elevation of the eight surrounding cells [70]). Distance to shore can be visualised in the GIS via layers containing boundaries at a range of selected values between 15 and 200 km. This could reflect the minimum distance to, for example, onshore substations.

Environmental restrictions have been added to the database in the form of the Natura 2000 (2011) areas [29,71], and 'Important Bird Areas', as defined in Ref. [72]. These areas do not absolutely prohibit any development or construction, but suggest areas of particular environmental sensitivity and where development would be more tightly controlled and monitored than at other sites.

Port information from the World Port Index [25] has been added as a layer. A subset of the information has been identified to help with the selection of suitable ports. The categories of '*channel depth*' (classified from A – over 23.2 m, to Q – up to 1.5 m) and '*maximum vessel size*' (M – less than 500 feet, L – over 500 feet) inform as to the limits on vessel length and draft at a given port. 'Repaircode' (classified A – extensive, to D – emergency and N – none) indicates the shipbuilding facilities available, whilst 'Dry-dock' and 'Marine railway' (if present, S – small, M – medium, L – large) are fairly self-explanatory.

5.3. Data: user interaction

Carrying out site selections based on multiple criteria using in-built QGIS functions is time-consuming and not easily repeatable. A custom tool has been designed (Fig. 4), allowing the user to input bespoke criteria limits and weightings. This offers more flexibility to cope with different requirements than in previous work, e.g. Ref. [11]. Minimum resource characteristics, depth ranges and port distances can be specified, and all sites fitting the criteria will be highlighted in one step. Options are provided for excluding areas within Natura 2000 and coastal visibility zones.

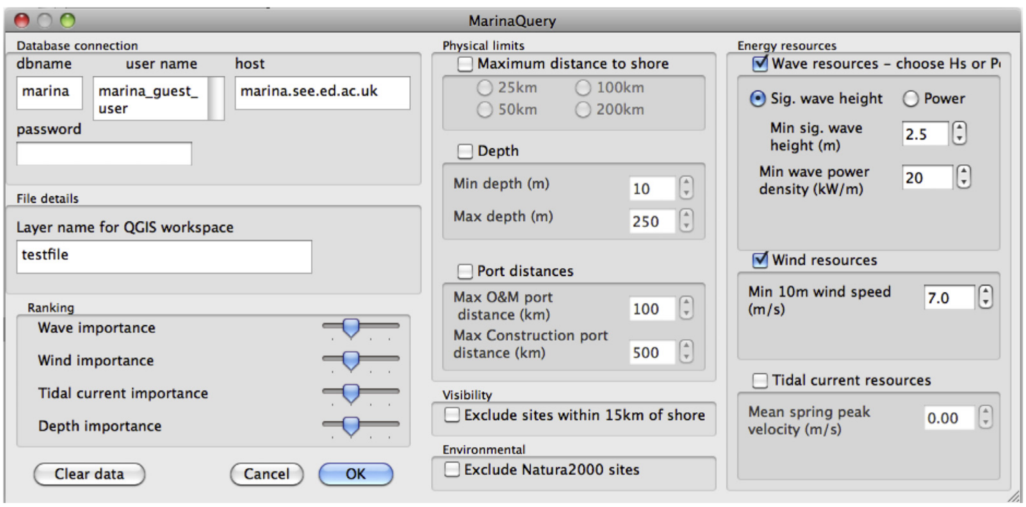

Fig. 4. The GUI window for the a bespoke query

For computational speed, the main 'Marina Query' tool makes fixed assumptions about required port facilities, and calculates their distance on a radial basis, rather than along a feasible shipping route. A second QGIS plug-in tool has been developed (Fig. 5) to calculate travel distance from individual sites to ports with user-defined facilities. It uses the pgRouting extension for PostGIS [73] which establishes the shortest travelling distance between two points along a network of paths. In this case, the path network was devised using a mesh of points spaced at 5 km intervals in the offshore areas.

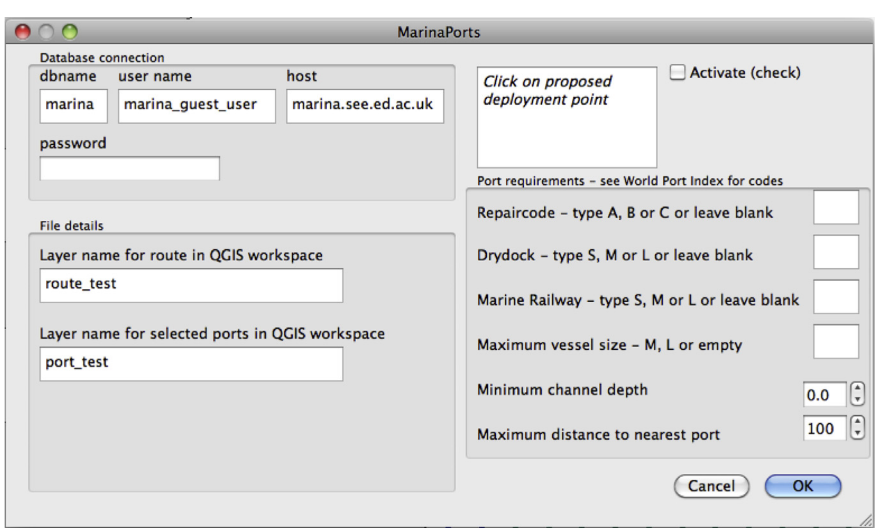

Fig. 5. GUI for Port Distance Calculator

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