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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.

Keywords: Marine renewable energy, combined platforms, geographical information systems, site selection, Europe

## 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

1 space and infrastructure, thus reducing the cost per unit of installed capacity of, for example,  
2 the foundations or electricity network cabling. A further advantage is in the combination of  
3 power outputs from two types of generation. Managing the inherent variability in power  
4 output from wind and wave generators is a prominent issue in renewable energy research. It  
5 was shown in [2] that for sites along the coast of California, co-locating wind and wave  
6 devices would reduce hypothetical power variability and increase the allocated capacity  
7 credit, compared with either technology operating alone.

8 A similar study for Ireland [3] showed that on the south and west coasts, the variability of  
9 wind and wave power is reduced over several time scales when combined, compared to  
10 either type acting alone. In the more fetch-limited Irish Sea, there was little or no advantage  
11 to combinations, as the two individual resources were strongly correlated in time. Analysis  
12 of the particular correlation between the wind and wave resources was demonstrated in [4],  
13 for three Atlantic-facing sites in Europe. The time lags between the peaks and troughs in the  
14 series were identified, and different optimal proportions of wind and wave devices were  
15 found at each site.

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

## 20 **1.2 Using GIS for site selection**

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

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

36 [10] followed a similar approach, considering parameters relevant to wind and solar  
37 developments (individually). The energy resource parameters were given the highest  
38 weighting, followed by transmission line proximity, and then other features such as distance  
39 to roads and cities. The authors analysed the suitability of sites within areas containing  
40 different types of land-cover, indicating the types of land use where future development  
41 could take place.

42 The approaches described so far are mainly focused on individual, mature technologies  
43 (with the exception of [8]) and concern relatively small areas, meaning that a fixed set of  
44 selection criteria and limits can be chosen with confidence. A predecessor to MARINA, the  
45 EU FP7 project, “Offshore Renewable Energy Conversion Platforms – Coordinated Action”

1 (ORECCA), carried out Europe-wide site selection for combined offshore energy platforms  
2 using web-based GIS, looking at a number of contributing factors including resource, water  
3 depth, and port facilities, among others [11]. The project made the first attempt at identifying  
4 the areas in Europe suitable for wind and wave in combination, by allocating ratings to sites  
5 based on their resources.

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

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

## 32 **2. Methodology**

33 In order to consider European-wide site-selection for combined wind-wave energy platform  
34 designs, two significantly different concepts were chosen from the final three considered in  
35 the MARINA Platform project [13], and will be labelled hereafter as ‘Platform 1’ and  
36 ‘Platform 2’. For comparison, a generic floating wind turbine platform which encompasses a  
37 wide range of possible designs (‘Platform 3’) is analysed alongside these. A set of  
38 fundamental physical and resource criteria, dictated by the design of the devices, were  
39 chosen to form the basis for initial site-selection decisions for these concepts, using the  
40 specialised resource data developed for the MARINA project. Following this initial  
41 selection, a secondary analysis was carried out, building upon the analysis techniques from  
42 the ORECCA project, to quantify the sensitivity of the selection to decision criteria where  
43 the limits are not clearly defined, for example, distance to port and environmental  
44 exclusions. Finally, a number of ‘case study’ sites were chosen for further detailed analysis  
45 of their suitability based on parameters that are too complex to consider continent-wide but

1 where the bespoke resource data offers useful insight. Where insufficient design information  
2 was available for the combined platforms, floating wind turbine designs were used under the  
3 assumption that processes for combined platforms would be somewhat similar. Basic GIS  
4 techniques along with bespoke decision tools were applied for each aspect of the selection  
5 process and analysis.

## 6 **2.1 Data**

7 The foremost consideration for site selection for marine renewable energy platforms is, of  
8 course, that of the wind, wave and current energy resources. A bespoke model was created  
9 for the project to produce a 10 year (2001-2010) hindcast of the key wind, wave,  
10 oceanographic and tidal current parameters at an hourly resolution on a co-located  $0.05^\circ \times$   
11  $0.05^\circ$  grid, referred to hereafter as the ‘Wind-wave-current (W2C) atlas’. The models and  
12 processes used to generate this atlas are described further in Appendix 7.1. Statistics based  
13 on the hindcast parameters from the W2C atlas have been calculated and form the resource  
14 map layers in the GIS. The following parameters are available for analysis:

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

22 Other parameters of relevance include bathymetry, environmental restrictions and port  
23 locations, which are described further in Appendix 7.2.

## 24 **2.2 Site selection tools**

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

30 Additional bespoke tools with user-interfaces (GUIs), called ‘plug-ins’, have been  
31 developed within the QGIS framework using the Python programming language. These  
32 interact with the database to facilitate flexible, multi-criteria analysis of the data and more  
33 sophisticated spatial investigation (see Appendix 7.3). Furthermore, the resource database  
34 can be interrogated in greater detail to explore features such as extreme conditions for  
35 individual points and consider weather windows for operations and maintenance activities.

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

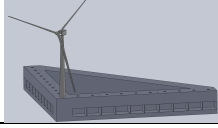
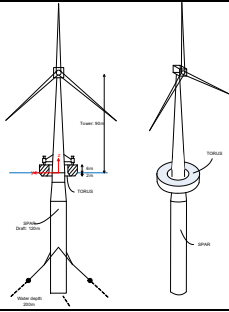
## 39 **2.3 Concept designs**

40 Platform 1 is based on a semi-submersible floating structure which provides the foundation  
41 for an array of twenty 0.5MW oscillating water columns and a single 5MW wind turbine.  
42 Wave power is the dominant technology in this case. Platform 2 is a floating spar structure,  
43 supporting one 5MW wind turbine and one torus-shaped 2MW point-absorbing wave device.

1 The dominant technology in this concept is wind. Platform 3 represents a generic floating  
 2 wind platform suitable for a wide range of depths, e.g. a semisubmersible-type structure. In  
 3 the sections where floating wind turbines have been used as representations of devices  
 4 similar to combined platforms, the assumptions are based on a semisubmersible floating  
 5 platform hosting a single wind turbine.

6  
7

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	1x5MW	20x0.5MW OWC technology	NREL WT characteristics[17]
Platform 2 (led by wind) STC		Spar	1x5MW	1x2MW Point absorber technology	NREL WT characteristics [17]
Platform 3 (wind only) Generic floating technology		Generic float – e.g. semi-submersible	1 x 5MW'	n/a	NREL WT characteristics [17]

8 **2.4 Primary selection criteria**

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

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

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

28 Alongside resources, depth is the main physical parameter to which will impact on a site's  
 29 suitability. Due to the nature of a floating spar structure with a draft of around 120m [18],

1 the minimum depth for Platform 2 is at least 150 m. Given the larger area and much smaller  
 2 draft of Platform 1, its minimum depth is set at 70m. In terms of maximum depths, [19]  
 3 mentions difficulties with cabling layout at water depths of greater than 100m, but present a  
 4 number of upcoming projects that go up to 215m. Currently very few projects exist at depths  
 5 greater than 100m, and those that do (e.g. Hywind [20], or the Goto FOWT [21]) are  
 6 typically in the early stages of development and testing. Solutions for mooring devices at  
 7 great depths and laying both transmission and inter-array cabling have not yet been fully  
 8 implemented and tested, and whilst the industry is keen to explore this frontier, the  
 9 possibility is still considered somewhat tentative. Assuming combined technology platforms  
 10 are some way from commercial development, and can thus be somewhat aspirational, a  
 11 maximum depth of 250m is set for all platforms but with the caveat that 100m might be  
 12 considered the current operable limit.

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

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

Concept	Minimum wind speed @ 10m (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

## 20 Ranking

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

$$29 \text{ Rank} \left\{ \sum_i \text{Rank}(\text{Parameter}_i) \times \text{Importance}(\text{Parameter}_i) \right\}$$

## 30 2.5 Secondary analyses and case studies

31 Criteria for several parameters that could be important in a site-selection process have been  
 32 applied in a secondary phase as there is less confidence in the reasons for specific limits due  
 33 to limited detailed design data. The sensitivity of the selection to these factors is considered  
 34 here by assessing the percentage of points on the 0.05° x 0.05° grid (based on the points in  
 35 the W2C atlas) where development would be prohibited by applying the various restrictions.

## 1 **Electricity networks**

2 The costs of electricity transmission increase with distance, as losses due to reactive power  
3 increase. In terms of site selection for offshore generation, transmission costs will depend –  
4 among other things – on the amount of energy generated and on choices regarding the use of,  
5 for instance, HVDC (High Voltage Direct Current) transmission over more traditional AC  
6 lines. It is suggested in [23] that for a 400MW offshore wind farm in a location with strong  
7 resources, HVAC transmission costs start to look less favourable than some HVDC options  
8 between 50 and 100km from shore. Beyond 150km, HVAC costs increase significantly.  
9 80km is indicated in [24] as the feasible transition point between AC and DC but also point  
10 out that this distance is reducing with time. The effect of selecting only sites within 50, 100  
11 and 150km of the shore are considered here, with the assumption that suitable connections  
12 can be made to the onshore network.

## 13 **Logistics**

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

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

29 [26], [27] suggest maximum travelling distances from construction ports of 250nm and  
30 300nm (460km and 550km) respectively for fixed foundation wind turbines. For floating  
31 foundations, since towing is the only existing method for installation, and given that the  
32 towing speed will be 4-5 times lower than the speed of a typical installation vessel and that  
33 only one foundation will be transported at a time, 200km is perhaps more reasonable; the  
34 effect of applying both 200km and 500km limits are presented here.

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

39 The distances presented here are calculated on the basis of radial distances from site to  
40 ports to enable fast selection in the GIS; the issue of directly calculating port distances is  
41 explored further later using more detailed routing for individual sites.



## 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 1km 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 [28], as a raster containing the number of ship tracks recorded in cells of 1km<sup>2</sup> area during the period October 2004 to 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.

Table 3. Categories for shipping traffic assessment.

Old values (number of ship tracks recorded in a single 1km <sup>2</sup> 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

## 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 [9] used a number of exclusion criteria based on environmental sensitivity, and applied an extra 1000m ‘safe distance’ buffer zone around these areas. A similar approach is taken here, to investigate the impact of excluding development within 1km of the Natura2000 areas.

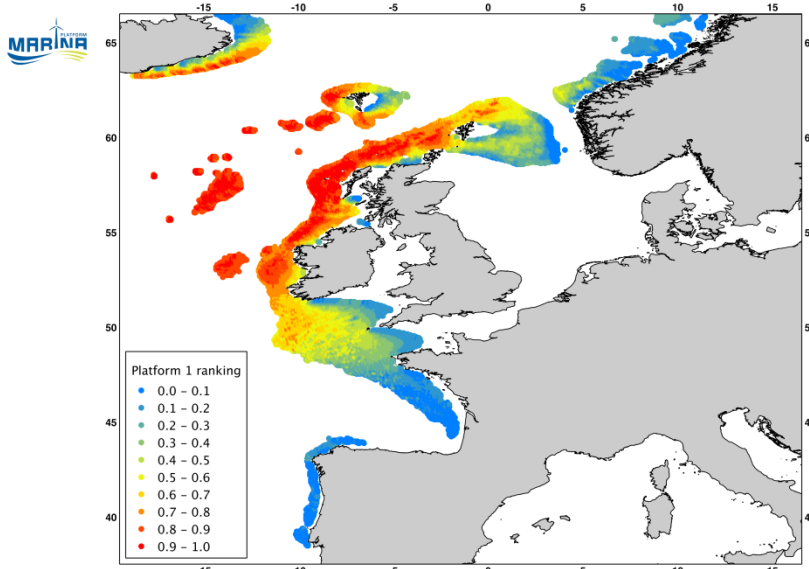
### 2.6 Case studies for particular characteristics

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

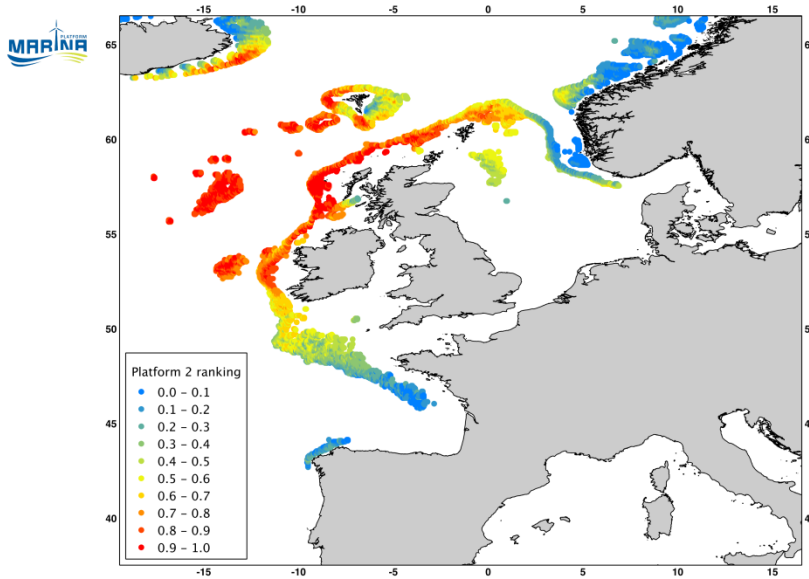
1 used as case studies. The factors analysed for each case study are: power extraction,  
2 transport routes to port, weather windows, extreme conditions and wind-wave correlations.

### 3. Site selection results

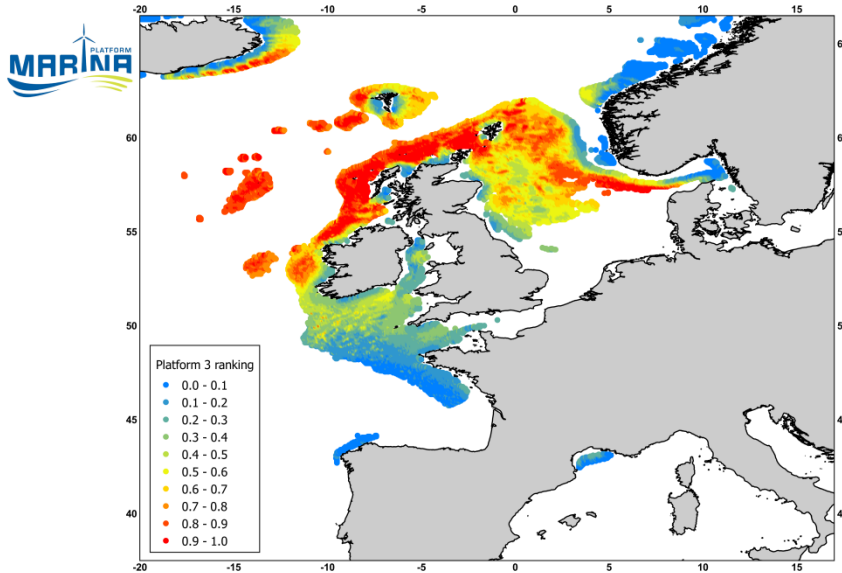
#### 4 3.1 Primary selection



5



6



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

4  
5 Applying first of all the fixed criteria as listed in Table 2, the selection of suitable sites is  
6 presented in Fig. 1. The sites have been ranked from 1-100% according to the resource  
7 parameter of chief importance for each of the concepts, so that out of all the sites indicated,  
8 red highlights the most suitable sites, and blue the least. Wind speeds and wave power  
9 densities are ranked from 1-100% with the highest wind speeds and wave power densities  
10 having the highest rank. Depth is rated from 1-100% where the shallowest water is given the  
11 highest rank – this is indicative of the increasing costs of greater depths. In the case of  
12 Platform 1, wave importance is given a value of 3 and wind 2. For Platform 2, wind and  
13 wave importance is swapped around. For Platform 3, wind is given an importance of 2 and  
14 wave 0. In all three cases, depth is given an importance of 1, to reflect the fact that it is a  
15 critical consideration, but having set limits for each platform, the variation within that range  
16 may not be as important as resources.

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

27 It is interesting to note the specific distribution of points by country. Using the maritime  
28 boundaries as specified in [30], the percentage of the total for each platform design is  
29 specified in Table 4. As indicated by the ranking, the selection strongly favours northern  
30 European countries, where the resource is strong but the change in depth with distance from  
31 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.

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%

### 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.

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

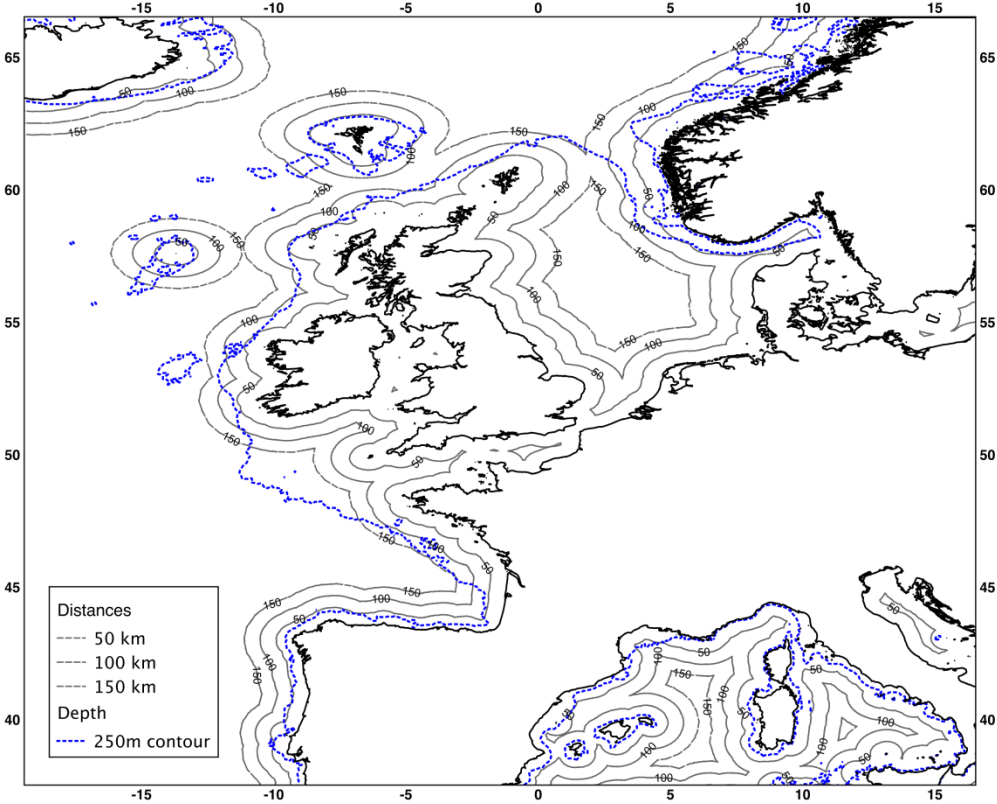
	Exclusion criteria	Platform 1 – percentage of sites excluded	Platform 2 – percentage of sites excluded	Platform 3 – percentage of sites excluded
Electrical networks	Maximum 50km to shore	65.35%	70.21%	66.45%
	Maximum 100km to shore	30.31%	33.47%	34.69%
	Maximum 150km to shore	12.60%	17.82%	17.39%
Logistics	Maximum 50km to O&M port	97.08%	96.36%	95.69%
	Maximum 100km to O&M port	74.95%	77.61%	74.48%
	Maximum 200km to O&M port	22.92%	35.92%	39.25%
	Maximum 200km to Construction port	69.17%	87.17%	71.50%
	Maximum 500km to Construction port	26.39%	40.78%	21.23%
	Maximum 100km O&M port AND Maximum 500km 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 1km buffer zone	1.45%	1.38%	1.11%

The impact of limiting distance to shore is interesting. Eliminating all sites beyond 50km from shore excludes 65-70% of the potential sites. This implies that, based on the limits suggested in [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

1 technologies considered lie beyond the 150km boundary, where HVDC clearly becomes a  
2 cheaper solution for transmission. Despite the increased resources far offshore, there aren't  
3 many selected sites beyond this distance, due to the selected maximum depth limit of 250m.  
4 Fig. 2 shows the 250m depth contour, i.e. the limit for the two technologies selected, along  
5 with the 50, 100 and 150km, distance contours. The costs associated with the increased  
6 depth alongside higher transmission costs would likely prohibit development beyond 150km  
7 in the near future.

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

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

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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 100km eliminates 75-78%. Only 23-36% lie more than 200km from a

1 suitable O&M port. Requiring a construction port with a draft of 9.4m and a large shipyard  
2 within 200km – as was mooted for floating platforms – leads to the elimination of 70-90% of  
3 sites, but if 500km is a feasible distance, only 26-50% of sites would be counted out.  
4 Combining a construction and O&M requirement leads to the elimination of a very large  
5 proportion of sites for all platform designs.

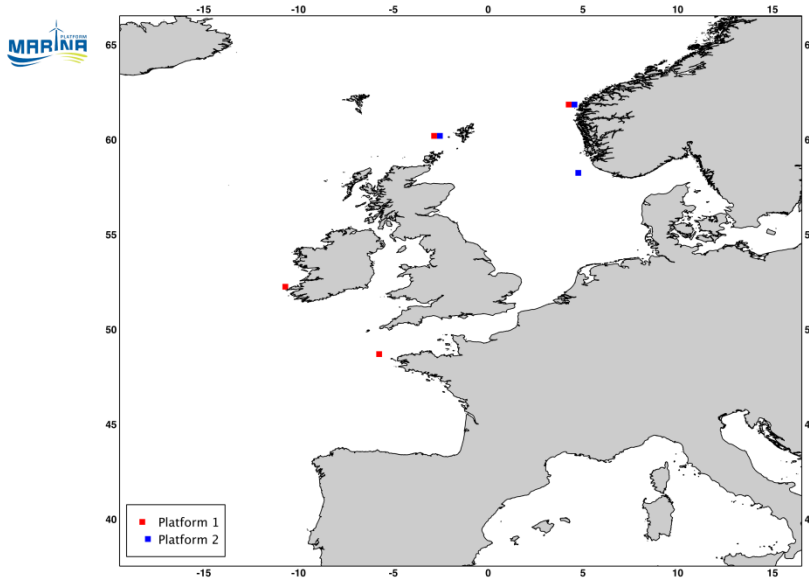
6 It should be noted that the choice of categories in the World Port Index is not definitive,  
7 and it is, by its nature, an over-simplification of information which may not capture an  
8 entirely accurate picture of facilities in every location. As mentioned previously, the  
9 distances have also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

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

19 Applying a no-development policy to Natura2000 sites excludes only 1.3% of sites for  
20 each type of platform. This is reflective of the fact that the majority of the Natura2000 sites  
21 fall within 15km of shore, and have thus been excluded from the selection in the first step.  
22 Applying a 1km buffer zone around Natura2000 zones to further ensure minimal impact on  
23 these areas only eliminates a very small additional percentage of suitable sites for combined  
24 platforms, reflecting that the majority of the Natura2000 restrictions apply in coastal areas,  
25 which do not meet other criteria for these platform designs. It may be the case that in deeper  
26 waters, different environmental concerns apply, and a monitoring plan for these has been  
27 developed (described in [32]). Comparing the three platform options overall, the wind-only  
28 devices offer the largest number of potential sites overall, as the wave resource is sufficiently  
29 strong in fewer locations. Due to its requirement for deeper waters, Platform 2 is most  
30 affected by distance-based exclusions, i.e. a limit on the distance to shore or distance to port  
31 excludes the highest number of potential sites. These designs would have most to gain from  
32 innovations to increase in the feasible distance to shore that a development can take place,  
33 for example HVDC transmission or a cable-laying technique that reduces sea-bed  
34 interference. All three platforms are similarly affected by the exclusion of Natura2000 areas  
35 or areas with high shipping traffic.

### 36 **3.3 Case studies**

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



1  
2 Fig. 3 Map of locations for detailed study

3  
4 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 <sup>2</sup> )	1126	795	1079	1084	946
Mean wave power density (kW/m)	67	50	28	47	71
95% wind speed @ 80m 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>2m, wind speed >10m/s	74	60	48	65	72

### 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.

### 3.3.2 Met-ocean conditions

Table 6 also includes a parameterisation of the relationship between wind and waves at each site (see [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 hours 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 95<sup>th</sup> percentile of significant wave height and 80m 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 95<sup>th</sup> percentile wind speeds, with the two exposed Atlantic sites – Shetland and Sybill Head – experiencing the highest 95<sup>th</sup> 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 3.2 above using a calculation based on a radius from each point. In order to look at the issue with



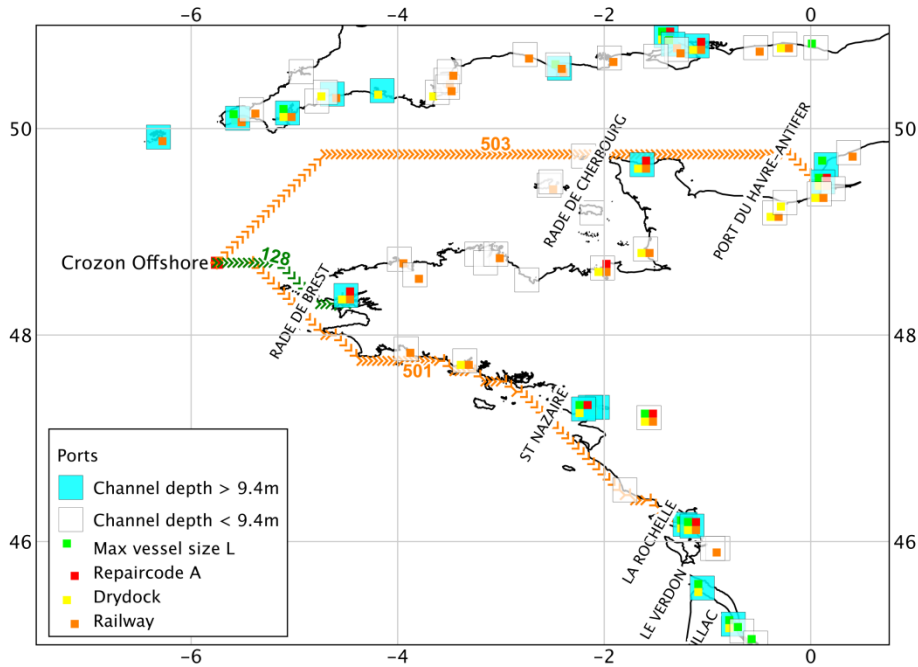
1 more accuracy and detail, the second GIS tool (see Appendix 7.3) has been created to plot  
 2 approximate travel routes between sites and nearby ports that can be selected on the basis of  
 3 their facilities. Similar basic conditions for distance, port draft and facilities are assumed as  
 4 described in section 2.5 with some additional considerations, namely the desirable additions  
 5 of at least a small dry-dock and railway, and the capacity of the port to host a minimum  
 6 vessel size.

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

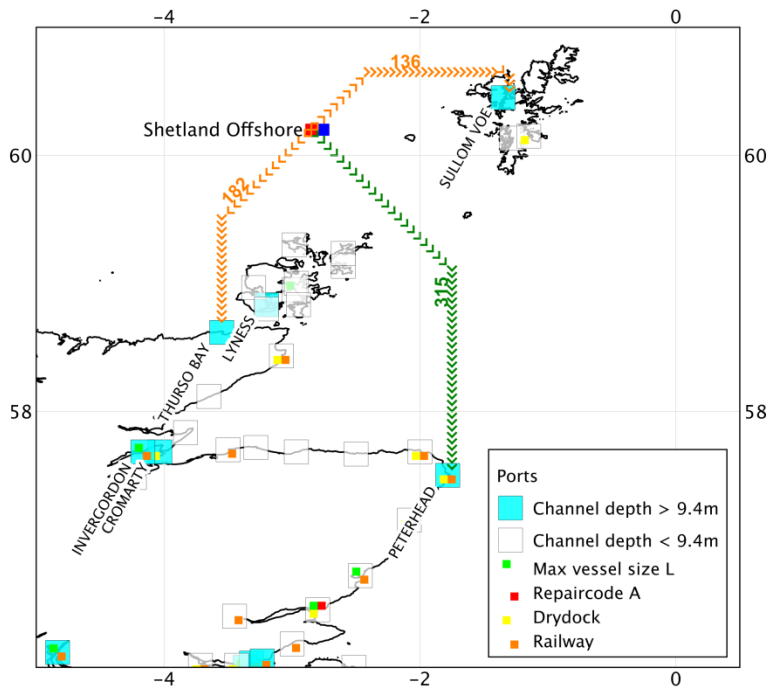
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 18 Table 7 Parameter values selected from the World Port Index

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

19  
 20 Fig. 4 and Fig. 5 show two examples of the output of the Marina Ports tool for two of the  
 21 case study sites. For Crozon (Fig. 4) there is one port allocated within the 200km maximum  
 22 distance that has the draft required for semi-submersible installation – Rade de Brest. There  
 23 is a dry-dock and a railway, but the ‘maximum vessel size’ recorded in [25] for this port is  
 24 M, so it cannot, in theory, host a 150m vessel. Seeking this would require a journey of  
 25 almost 400km to La Rochelle. In the case of Shetland, there are a number of nearby ports but  
 26 none meeting all of the criteria within 500km. The closest, and likely most suitable port is  
 27 Peterhead, which has a dry-dock and a railway, and is of suitable draft, but is listed in the  
 28 World Port Index as Repaircode B, and with a maximum vessel size of M, so could  
 29 potentially need some upgrading. There are two ports within shorter traveling distances that  
 30 may be suitable as staging hubs – Sullom Voe (Shetland) and Thurso Bay (mainland).



1  
2 Fig. 4 Presented routes for suitable ports near Crozon



3  
4 Fig. 5 Presented routes for suitable ports near Shetland

### 5 3.3.4 Weather Windows

6 Weather windows are a major limiting factor in construction and maintenance of offshore  
 7 developments. In terms of the installation process, weather windows along the routes to port  
 8 (as estimated by the Marina Ports tool) have been analysed, and the probability, based on the  
 9 10 year hindcast, of achieving a suitable access window has been calculated. As in the

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

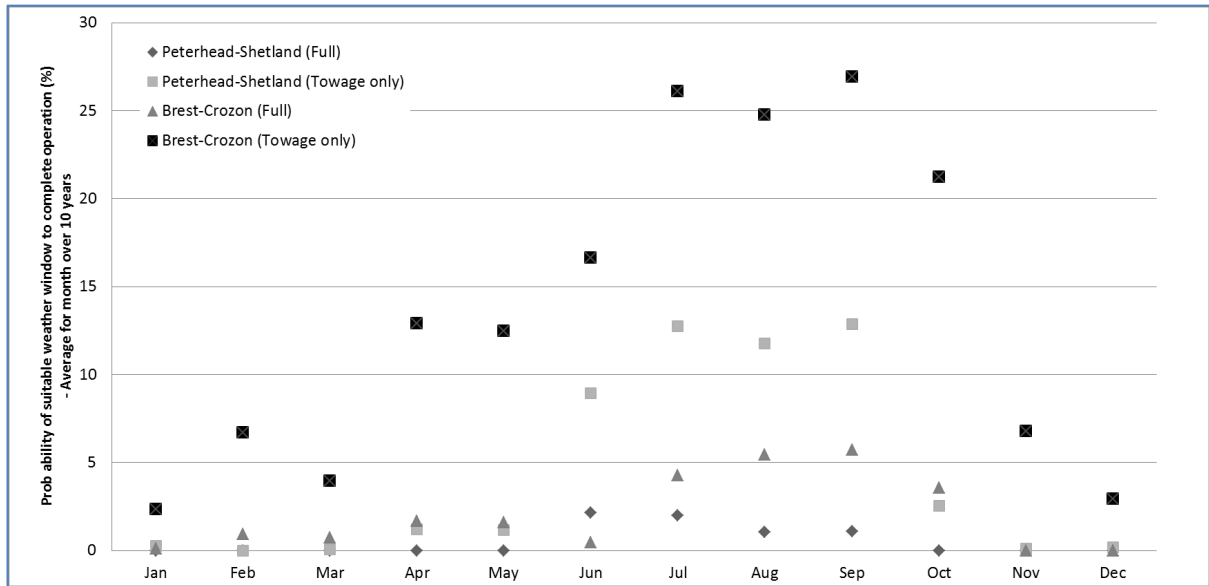
10  
 11 Table 8 Weather windows constraints for the installation of WT semisubmersible platforms.

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

12 Referring to Fig. 6, the significant travelling time (approximately 3 days under the assumed  
 13 speed restrictions), followed by installation procedures of a similar duration give rise to a  
 14 prohibitively low probability of success (less than 5% in summer) for the Peterhead-Shetland  
 15 operation. Based on experience, it is likely that there will be opportunities to pause  
 16 operations due to unacceptable conditions, for example after towing, or approximately every  
 17 16 hours during the mooring line installation. Considering only the towing and assuming  
 18 there can be a break before commencing installation, the probability of a successful and safe  
 19 journey is around 10-15% in summer months. This result emphasises the case for selecting a  
 20 more local staging port to act as a mid-way point. The use of vessels and procedures which  
 21 allow several pauses in operations or vessels which can operate in more severe conditions is  
 22 clearly essential for this site.

23  
 24 The shorter route from Brest to Crozon results in a journey time of around 1.3 days but  
 25 the average probability of successfully completing towing plus installation in one contiguous  
 26 operation is still very low, with a maximum of 5-6% in July-September. Again, assuming  
 27 there can be a pause between towing and installation, the average probability of completing  
 28 towing alone is around 25% in July-September. Whilst better than Peterhead-Shetland, there  
 29 is still clearly a risk in any given summer that these operations cannot be completed and thus  
 30 the need for more tolerant vessels and procedures is highlighted.

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

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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 for the wind industry and DT Ocean 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 10m/s and wave height of less than 2m, 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.

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### 3.3.5 Environmental impacts and conflict with shipping

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None of the case study sites analysed fall within 1km of any of the Natura2000 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 [28], requiring substantial consideration.

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### 3.3.6 Summary of case study sites

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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

1 wind and wave energy at a single site, given its low correlation between wind and wave  
2 resources and the consequently smoother power production patterns, but it does have the  
3 disadvantage of potential conflicts with shipping routes. The wave resources are generally  
4 lower at the Norwegian sites, and Norway 1 is very far from shore, but Norway 3 is still  
5 feasible for both combined platforms, and has a favourable wind-wave correlation. It may  
6 offer the best compromise between resources and the likely problems caused by low  
7 accessibility and extreme conditions. In all cases, innovation in terms of managing weather  
8 windows and distance-related problems will offer more possibility to access strong  
9 resources.

10 The analysis presented uses some basic assumptions about installation and operational  
11 procedures, and relies on simplified parameterisations of complex met-ocean analyses such  
12 as extreme values and the relationship between wind and wave resources. The shipping route  
13 information is a snapshot in time and may not capture all of the existing routes, and whilst  
14 using Natura2000 is a good indicator for environmentally sensitive areas, it is not the  
15 complete picture. Further in-depth analysis of all these features is feasible – and sensible –  
16 only at a smaller scale, perhaps country-by-country.

## 17 **4. Conclusion**

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

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

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

44 A series of subsequent EU FP7 projects, funded under the European Commissions  
45 “Oceans of Tomorrow” initiative, have been investigating the potential for inclusion of other

1 factors in offshore platforms alongside energy production. TROPOS (FP7-288192 2012-  
2 2015), H2Ocean (FP7-288145 2012-2015) and Mermaid (FP7-288710 2012-2016) added  
3 factors such as aquaculture, hydrogen production and transport and leisure facilities to  
4 offshore energy platform designs. The remit of these projects has been to establish if the  
5 European Commission's "Blue Growth" strategy can be assisted by the deployment of multi-  
6 use platforms which share costs and ocean space. The design process for a potential hybrid  
7 platform is discussed in [36]. The multi-purpose nature of these designs further opens up the  
8 possibility to exploit synergies and for cost sharing with other types of technology.  
9 Additionally it offers more opportunity to make the most productive use of precious marine  
10 space [37]. The hybrid nature of such platforms means that the assessment of environmental  
11 benefits and consequences need careful consideration [].

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22 duration of the different processes involved in the installation of the semisubmersible  
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- 27

## 28 **7. Appendix**

### 29 **7.1 Data: Energy resources**

#### 30 **7.1.1 Atmospheric Model**

31 Atmospheric circulation has been simulated using the SKIRON model, developed at the  
 32 National Kapodistrian University of Athens (NKUA) by the Atmospheric Modelling and  
 33 Weather Forecasting Group (AM&WFG) in the framework of the national funded project  
 34 SKIRON and the EU funded projects MEDUSE, ADIOS and recently CIRCE ([38], [39]).  
 35 SKIRON is a full physics non-hydrostatic model with sophisticated convective, turbulence  
 36 and surface energy budget scheme. It is based on the ETA/NCEP model, originally  
 37 developed by Mesinger [40] and Janjic [41].

38 The domain is shown in Fig.7, with a spatial resolution of  $0.05^\circ \times 0.05^\circ$ , 45 levels in the  
 39 vertical (from surface to 50 hPa), and a time step of 15 seconds. The initial condition fields  
 40 are from a high-resolution ( $0.15^\circ$ ) regional reanalysis system, prepared with the  
 41 implementation of LAPS assimilation system [42], [43]. The initial guess fields are the  
 42 ECMWF  $0.5^\circ \times 0.5^\circ$  operational analysis fields while the lateral conditions are updated  
 43 every 3 hours. The model utilizes daily SST fields from NCEP with a resolution of  $0.5^\circ$ . The  
 44 model produced raw hourly outputs for a set of variables at chosen vertical levels (10, 40,  
 45 80, 120, 180) including, for example, pressure, air density, wind components, turbulent  
 46 kinetic energy etc.

47

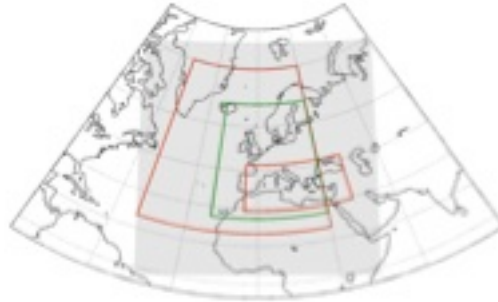


1  
2 Fig.7: The gray-shading indicates the SKIRON model domain. The green frames show the areas over which  
3 SKIRON passes wind data to the WAM model.

#### 4 **7.1.2 Wave model**

5 The ECMWF version of the wave model WAM ([44], [45]) CY33R1([46], [47]) has been  
6 adopted for the simulation of the wave parameters. This version contains updates that  
7 increase the capabilities significantly. In particular, the wave model includes new features  
8 that support the better parameterization of bathymetry and shallow water effects that affect  
9 the time evolution of the wave spectrum ([49], and [50]). Moreover, the option of using  
10 nested domains ensure the utilization of accurate boundary conditions and give the choice of  
11 adopting high resolution domains over the area of interest supporting in this way the  
12 accurate simulation of local effects. On the other hand, the credible simulation by wave  
13 models is critically affected by the quality of the atmospheric forcing as pointed out in  
14 different studies ([46], [51], [53], [58], [63]). Towards this direction, the use of Skiron model  
15 is a critical advantage since the system is designed to use either the hydrostatic  
16 approximation or non-hydrostatic dynamics making it able to run on high resolution mode.  
17 SKIRON is a well-established atmospheric system adopted in a great number of previous  
18 technical and operational studies including wave applications ([54], [63], [67]), oil spill  
19 modelling ([58]), as well as air-quality applications [47], renewable energy ([52], [57], [61],  
20 [65]), photochemical processes ([66]), and desert dust studies ([29], [48], [60], [62]).  
21 Concerning the impact of sea surface currents on the local wave climatology, it has been  
22 proven that they may influence the wave generation mechanism and the wave propagation  
23 resulting in associated alterations in the significant wave height and the mean wave period  
24 due to the Doppler shift ([55], [56], [59], [65], [67]). The wave model adopted in our study  
25 makes possible the use of sea surface currents as a second forcing apart the wind speed and  
26 direction.

27 The wave model is run in two domains (Fig.8): the North Atlantic (20N—75N, 50W—  
28 30E) and the Mediterranean and Black Seas (29N —47N, 6W—42E). The Atlantic domain  
29 extends to the west far beyond the area of interest so as to capture the all-important swell  
30 propagation. A high spatial resolution has been adopted (0.05° x 0.05°). The wave spectrum  
31 is discretized into 25 frequencies (logarithmically spaced in the range: 0.0417—0.5476 Hz)  
32 and 24 equally spaced directions, while the propagation time step is 75 seconds. WAM is  
33 operated in shallow-water mode, driven by 3-hourly wind input (10 m wind speed and  
34 direction) obtained from the SKIRON regional atmospheric model over the areas shown in  
35 Fig.7.



1  
2 Fig.8: The gray-shading indicates the domain covered by LAPS. The red frames show the domains of the  
3 WAM model. The green frame as in Figure 1.  
4



5  
6 Fig.9: Selected locations at which the full wave spectrum is available.

## 7 **7.2 Data: Physical limits and other constraints**

8 The bathymetry dataset used within the wave model was ETOPO 1 [48] at the resolution of  
9 the model ( $0.05^\circ$ ). Two further parameters have been derived from the GEBCO depth data  
10 using QGIS: slope, and ruggedness index (the root-mean-squared difference between the  
11 elevation in the current cell and the elevation of the eight surrounding cells [49]). Distance to  
12 shore can be visualised in the GIS via layers containing boundaries at a range of selected  
13 values between 15 and 200km. This could reflect the minimum distance to, for example,  
14 onshore substations.

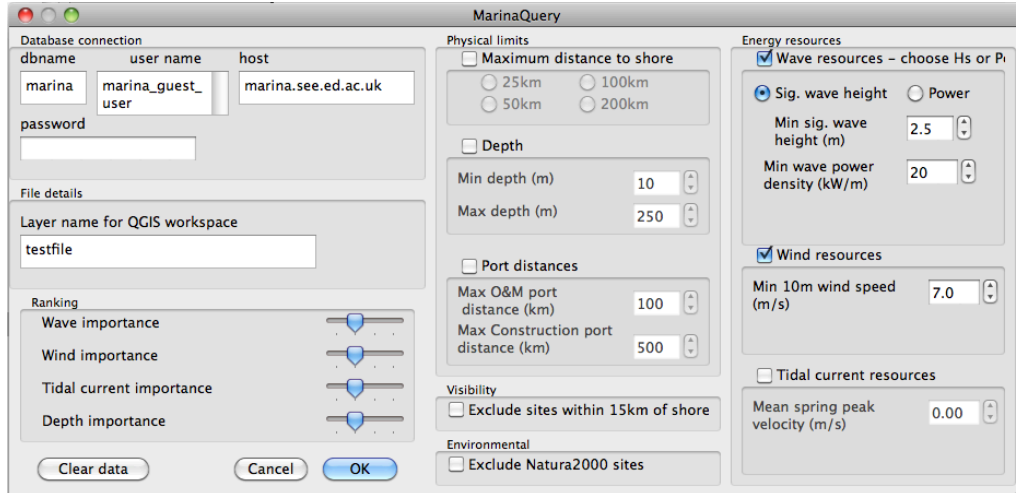
15 Environmental restrictions have been added to the database in the form of the Natura  
16 2000 (2011) areas [29], [50] and ‘Important Bird Areas’, as defined in [51]. These areas do  
17 not absolutely prohibit any development or construction, but suggest areas of particular  
18 environmental sensitivity and where development would be more tightly controlled and  
19 monitored than at other sites.

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

## 28 **7.3 Data: User interaction**

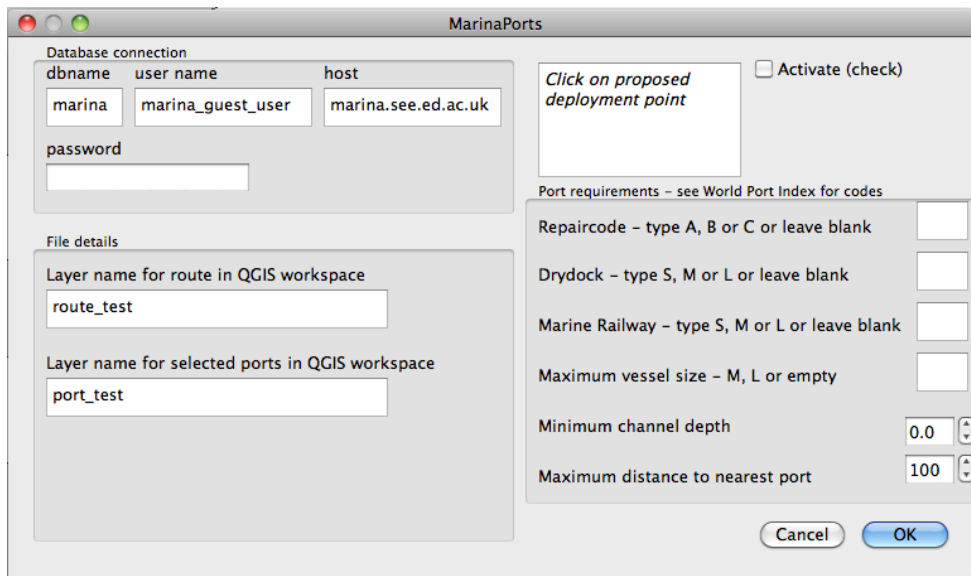
29 Carrying out site selections based on multiple criteria using in-built QGIS functions is time-  
30 consuming and not easily repeatable. A custom tool has been designed (Fig.10), allowing the

1 user to input bespoke criteria limits and weightings. This offers more flexibility to cope with  
 2 different requirements than in previous work, e.g. [11]. Minimum resource characteristics,  
 3 depth ranges and port distances can be specified, and all sites fitting the criteria will be  
 4 highlighted in one step. Options are provided for excluding areas within Natura2000 and  
 5 coastal visibility zones.  
 6



7 Fig.10 The GUI window for the a bespoke query  
 8  
 9

10 For computational speed, the main ‘Marina Query’ tool makes fixed assumptions about  
 11 required port facilities, and calculates their distance on a radial basis, rather than along a  
 12 feasible shipping route. A second QGIS plug-in tool has been developed (Fig.11) to calculate  
 13 travel distance from individual sites to ports with user-defined facilities. It uses the  
 14 pgRouting extension for PostGIS [52], which establishes the shortest travelling distance  
 15 between two points along a network of paths. In this case, the path network was devised  
 16 using a mesh of points spaced at 5km intervals in the offshore areas.  
 17



18 Fig.11 GUI for Port Distance Calculator  
 19