


Opportunities for nature recovery within UK offshore wind farms

Blue Marine Foundation

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Submitted by

MRAG

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Executive Summary

This project provides an assessment of the potential scale of opportunity for nature recovery presented by the presence of offshore wind farms (OWFs) in the United Kingdom (UK). Specifically, this work examines the potential synergies between OFWs and marine biodiversity enhancement, examining a range of best practices that could be implemented in support of a new standard in future developments in OWFs. In addition, this project has been developed to provide recommendations to facilitate nature-inclusive design (NID) and marine net gain policy towards OWFs in the UK, as well as support future marine spatial planning to ensure the contribution of OWFs for UK marine conservation objectives.

This work collated and mapped the key benthic and oceanographic variables within the spatial footprint of all identified UK OWFs throughout all life-cycle stages (e.g., construction, current and planning). This showed that such OWFs have been implemented, or have been designated, in areas that have a range of different benthic characteristics, but are dominated by sand, coarse substrates and muddy sand habitats. Importantly, OWFs differed substantially in a range of bathymetric and oceanographic features. Bathymetry of all OWF groupings and regions varied by ~140m, with the shallowest site (Irish Sea) having a maximum depth of -15m and the deepest site (Eastern Atlantic) a maximum depth of -156m. Mean temperatures across all OWF groupings and regions were fairly consistent, ranging from ~9 – 13°C, while salinity ranged from ~34 – 35ppt, mean chlorophyll a concentration ranged between 0.5 – 1.5 mg m3 and mean oxygen concentrations ranged from ~240-340 mmol m3. Mean wave heights across all OWF groupings and regions showed little variance (ranging between 1-3m), turbidity (water transparency) varied between 3-15m, while due to the M2 tide experienced in UK waters, mean current velocities were ~0 ms-1.

Such baseline data to map OWFs was then built on by identifying and compiling a list of 105 species linked to the areas designated as OWFs. This long list of species was then synthesised into a short-list of species of conservation and commercial interest that could be targeted for enhancement with nature-inclusive designs (NIDs). This short list comprised 21 species of conservation and commercial interest.

Building on the understanding of the oceanography, the structure of ecological communities and type of wind farm (e.g., fixed, floating), this work identified the range of NIDs that may be applicable to each of the OWFs. This showed that four different types of NID would be applicable to UK OWFS – those based on the deployment of natural substrates as scour protection (or in addition to scour protection) and cable protection (termed category 1 and 2 respectively), those based predominantly on NID options that could be attached to the main structure of the wind turbine (category 3), and those deployed either on or surrounding the wind turbine, but do not have to be deployed as the wind turbine is deployed (i.e., are not 'attached' to the wind turbine) (termed category 4).

This work then provided a synopsis of the specific biotic, abiotic and/or oceanographic parameters and technical requirements, as well as risks important in determining the success of described NIDs. In this respect, such risks were found to be associated with lack of ecological success of using the NID, the settlement of invasive/non-native species or diseases, enhancement of competition between target species, the complete absence of target species following NID implementation, issues associated with the permanence of the NID habitat as well as the likely stability (or instability) of the NID habitat.

The project then examined the role of OWFs without NIDs (termed 'passive restoration') in structuring marine communities. In this respect, the *in-situ* impact that OWFs have on marine communities, and therefore their potential role in sustaining 'passive restoration' of such communities was examined. Within this, the composition of marine communities that recruit onto structures afforded within OWFs was determined, how such communities develop, as

well as the species that are attracted to such recruitment. This analysis showed that there are a range of benefits for marine communities due to the hard structure provided by OWF development.

This work lastly developed an R-based decision tool for nature-inclusive designs in UK OWF's to support feasibility recommendations for both passive and active (i.e., utilizing NID) species restoration approach combinations. The main aim of the tool was to support the identification of OWFs, species that may be feasible for passive restoration activities, and then additionally NID solution(s) which may be feasible for active restoration activities. The utility of the feasibility tool was then assessed within two stakeholder engagement workshops (at the time of reporting, the first workshop has been completed, the second planned for mid-April 2023). The first workshop was designed to introduce UK wind farm experts to the feasibility decision tool, discuss how it had been developed, the assumptions and limitations of the feasibility tool and provide a relatively detailed explanation of how best to use the tool. The outcomes of this process, including high interest in further understanding how to use the tool, has led to the planning of a 1:1 stakeholder session (to be held 19 April, 2023) which have been designed to provide an in-depth tutorial on the use of the feasibility tool. This work has also been developed to create a shortlist of potentially feasible active restoration activities by site, with the goal of the sessions to peer-review the shortlisting process and to create a firm list of potential case studies and restoration type combinations to take forward.

1 Introduction

The UK government intends to reach up to 50GW of installed offshore wind capacity by 2030, as part of an effort to reach net zero by 2050. The Government's target is to harness the power of offshore wind to help power the economy and decarbonise the future production of electricity in the UK. Offshore wind is therefore expected to be a major contributor to the UK's clean energy mix as the Government moves towards net zero emissions. This commitment will inevitably lead to increased spatial competition and displacement for fisheries and aquaculture but will also create opportunities. For instance, such an expansion of marine renewable energy will lead to increased coexistence and the potential for multiple use of the marine space.

While discussions on the efficient allocation of the marine space to the different use activities is gaining momentum, there are still issues to address regarding the promotion of conservation efforts and goals relating to sustainable use of species and habitats that occur naturally in the areas the OWFs are sited. These issues require an understanding on how ecological functioning can be stimulated during the development of offshore wind projects. Currently, offshore marine policy does not inherently support or facilitate nature-inclusive design and marine net gain policy hasn't been defined for these developments. There is need to develop frameworks that incorporate nature-inclusive design in wind farm site decisions and related permitting. Such a framework could be used to inform regulations such as requiring wind farm developers to make demonstrable efforts to design and build the wind farm in such a way that it actively enhances the marine ecosystem.

Literature shows that the establishment of offshore wind structures may lead to a diverse set of changes on the seafloor ecosystem (Gill et al., 2018). These changes vary based on the implementation stage of the OWF i.e. during construction, operation or decommissioning. During construction, the marine ecosystems are temporally negatively disturbed through sediment displacement that alters the biodiversity, and high impulsive sounds from piling. During the operational phase, introduced structures and/or turbine foundations change the local habitat characteristics, leading to mixed effects. Some can be considered as positive, as they provide a surface for colonization by fouling species and by attracting various organisms (e.g. crabs, lobster) through the provision of artificial reef (Degraer et al., 2020). Several studies have documented the presence of suspension feeder species such as mussels, anemones and amphipods due to scour protection (e.g., Krone et al., 2013; Mavraki, 2020). Further, the structures and their colonizing fouling communities are attractive to mobile organisms. Mobile benthic and demersal species, like cod, lobster and crab as well as pelagic fish like mackerel, seabirds like sandwich tern, and marine mammals such as harbour and grey seals have been observed in high densities in the proximity of these structures (e.g. Krone et al., 2013; Reubens et al., 2014). These species tend to take advantage of the locally enriched areas for feeding and shelter around the structures.

Offshore wind farms also act as 'de facto' closed areas (Ashley et al., 2014). As such, an OWF area can be seen as a passive refuge and recovery area for benthic species and fish, potentially resulting in higher densities and larger animals. They could therefore be used as a tool to conserve fish stocks, for instance, by limiting access for commercial and/or recreational fisheries using a permit system (Fayram et al., 2007). Roach et al., (2018) showed that the Westermost Rough OWF could be delineated as an area for rotational closures of lobster fisheries, and therefore help prevent overfishing. Hooper and Austen (2014) show that the potential of OWFs to increase lobster populations depends on the design of the OWFs; that potential being related to not having scour protection on certain parts of the turbines or installing additional rock armouring.

Depending on the characteristics of the area, and primarily the hydrodynamics, the water column could influence seafloor communities directly and indirectly. Hydrodynamics could directly influence the benthos via the transport and dispersal of larvae, juveniles and adults, with repercussions for population dynamics (Levin, 2006). Hydrodynamics could directly influence the primary and secondary production in the water column and the transport pathways of these food sources to the benthic system (Rosenberg, 1995). Offshore structures and construction activities will create local changes in hydrodynamics and sediment transport, affecting turbidity, fine-grained sediment dynamics and bed shear stress (Whitehouse et al., 2011).

This calls for a review to understand the synergies between wind farm construction and biodiversity enhancement, to assess the opportunities for biodiversity recovery within offshore wind farms, and to identify best practices that can be implemented in future development of OWFs. Enhancement of ecological functioning can be achieved by using measures that can be integrated or added to the design of an offshore structure to kick-start recovery of degraded habitats. By smartly integrating these measures, additional value may be created for some of the key species while at the same time complying with or contributing to conservation objectives.

This project addresses the following research questions

- What is the scale of opportunity for nature recovery within offshore wind farms around the UK and how environmentally and financially feasible are efforts for active restoration?
- Do wind farms provide significant opportunities for the passive restoration of marine life in the UK?
- What are the wider benefits of active and passive restoration of marine species within the footprints of offshore wind farms?
- What are the ecological risks of active and passive restoration of marine species within the footprints of offshore wind farms?
- How can restoration efforts be successfully and feasibly monitored?
- How can UK policy develop and evolve to consider nature-inclusive design, biodiversity net-gain and nature recovery for offshore wind farms?

1.1 Aims and Objectives

The main objective of this project has been to explore the scale of opportunity for nature recovery presented by the presence of OWFs in the UK. Specifically, this project has considered whether there are synergies between OFWs and biodiversity enhancement, and whether there are best practices in both domains that could be implemented for discussion as a new standard in future developments in OWFs. This is with a view to provide recommendations to support or facilitate nature-inclusive design (NID) and marine net gain policy towards OWFs in the UK, as well as support future marine spatial planning to ensure the contribution of OWFs for UK marine conservation objectives.

The specific aim of this project has been to conduct a review of the designated OWF locations in the UK and identify the likely outcomes of the presence of the OWF in enhancing marine biodiversity (termed ‘passive restoration’), as well as the measures that could be integrated with the design of the OWF, or added alongside/adjacent to the design of the offshore wind infrastructure to increase suitable habitat for native species (termed ‘active restoration’). This was structured to be delivered through the implementation of ten tasks:

- Task 1 Assessment and gap analysis of Blue Marine matrix
- Task 2 Mapping benthic and oceanographic variables within UK OWFs
- Task 3 Species identification
- Task 4 Nature-inclusive design species selection

- Task 5 Identification of nature-inclusive designs
- Task 6 Risks of nature-inclusive designs
- Task 7 Feasibility decision tool for nature-inclusive designs in UK OWFs
- Task 8 1st Stakeholder engagement workshop (providing an overview of the tool developed in Task 7)
- Task 9 2nd Stakeholder engagement workshop (providing tutorial on how best to use the tool developed in Task 7)

This Final Report provides the final outcomes of the project, building on the previous Progress Report (which summarised the output from tasks 1 -7), to summarise the output from the Task 8 (1st stakeholder workshop) and the structure of the Task 9, 1:1 stakeholder engagement.

2 Methodology

2.1 Task 1 Assessment and gap analysis of Blue Marine matrix

An assessment and gap analysis of the previously conducted Blue Marine matrix. This previous matrix was developed to assess suitability of UK OWFs for restoration and / or habitat enhancement of UK native marine species (further discussed in detail in Section 3.1.1). The assessment of this matrix within the present project was undertaken to both identify and supplement missing data gaps identified to be important for decision making regarding active and passive restoration at OWFs in the UK.

2.2 Task 2 Mapping benthic and oceanographic variables within UK OWF

One of the key requirements for many marine species is the availability of suitable habitats for larval settlement, foraging, shelter and other key ecological processes. The aim of Task 2 was to map the key benthic and oceanographic variables within the spatial footprint of identified UK OWF within all life-cycle stages (e.g., constriction, current and planning), with a view to inform feasibility of the adoption of nature-inclusive designs in latter tasks.

2.2.1 Benthic

In order to substantially map the benthic habitat present at each OWF site, the detailed data layer called 'EU_SeaMap_2021_Arctic_Atlantic' provided by EMODnet Seabed Habitats[1] was utilised by the contractors (Table 1). This data layer covers the extent of European waters and contains polygon features classified by broad-scale seabed habitat following European Nature Information System (EUNIS) and Marine Strategy Framework Directive (MSFD) benthic broad habitat classification. Substrate types include abiotic (fine mud, sand, rocks etc) and biotic substrate (bivalve reef, worm reefs) classification.

Table 1. Data layer obtained to may key benthic habitats

Variable	Source	Year	Period	Resolution
Substrate	EMODnet Seabed Habitats	2021	n/a	250m

The 'EU_SeaMap_2021_Arctic_Atlantic' data layer was clipped to the spatial extent of each of identified UK OWF using the QGIS geoprocessing tool 'Intersection'. The 'Intersection' tool uses two data layers, the input and overlay layer. In this instance, the input layer was benthic substrate and the overlay layer was a shapefile identifying the spatial extent of all UK OWF. The new data layer detailing the benthic substrate composition of each OWF site was saved as a new shapefile. The spatial area (km^2) of each substrate type within each UK OWF was then calculated using 'Field Calculator', where the '$area' function was applied. The resultant attribute table was then exported and saved as .csv file in Microsoft Excel. A pivot table was created to sum the total area coverage contribution of each substrate type within each UK OWF site.

2.2.2 Oceanographic

In order to understand the oceanographic characteristics of each OWF, data on nine oceanographic variables (Table 2) were sourced in line with the following considerations;

- A minimum of one year of data to capture potential patterns in seasonality;

[1] https://www.emodnet-seabedhabitats.eu/access-data/download-data/

- The highest spatial resolution available;
- The greatest temporal resolution available;
- All data freely available.

Table 2. Data layers obtained for key benthic habitats

Variable	Source	Year	Period	Resolution
Bathymetry	General Bathymetric Chart of the Oceans (GEBCO)	2021	Jan-Dec	15 arc-s
Temperature	Ocean Biology Processing Group (NASA/GSFC/OBPG)	2021	Jan-Dec	4 km
Salinity	Atlantic- European North West Shelf- Ocean Physics Reanalysis	2021	Jan-Dec	0.111° × 0.067°
Currents	Atlantic - European North West Shelf - Ocean Physics Analysis and Forecast	2021	Jan-Dec	0.111° × 0.067°
Waves	Atlantic - European North West Shelf - Ocean Wave Analysis and Forecast	2021	Jan-Dec	0.014° × 0.03°
Secchi	OCEANCOLOUR_GLO_BGC_L4_MY_009_104	2021	Jan-Dec	4 km
Suspended matter	OCEANCOLOUR_GLO_BGC_L3_MY_009_103	2021	Jan-Dec	4 km
Chlorophyl-a	Global Ocean Biogeochemistry Analysis and Forecast	2021	Jan-Dec	1/4°
Oxygen	GLOBAL_ANALYSIS_FORECAST_BIO_001_028	2021	Jan-Dec	1/4°

Data were extracted in MATLAB® software according to the spatial extent of all identified UK OWF and classified into 46 individual groups (A – AM) based on the understanding that variation would not significantly differ within the spatial scale of classified groups. The coordinate extents and mapped distribution of OWF groupings are given in Annex 1 and 2 respectively.

2.3 Task 3 Species identification

The aim of Task 3 was to identify and compile a list of species linked to areas designated as OWF and of conservation and commercial importance, in addition to the 21 already considered by Blue Marine. In order to complete this, priority species of primary conservation concern were extracted and tabulated from the United Kingdom Biodiversity Action Plan (UK BAP) and the relevant devolved nations' priority species lists (e.g., Nature Scot, Natural Resources Wales and Department of Agriculture, Environment and Rural Affairs (DEARA)).

2.4 Task 4 Nature-based solution species selection

The aim of Task 4 was to select species of conservation and commercial interest that could be targeted by nature-inclusive designs and understand their distributional range in relation to UK OWFs. In order to do this, five selection criteria were applied to the species identified under Task 3. Data and information used to support the application of selection criteria were sourced from FishBase, SeaLifeBase Biological Traits Information Catalogue (BIOTIC)[2], the National Biodiversity Atlas (NBNAtlas)[3], Ocean Biodiversity Information System[4] (OBIS) or the Marine

[2] MarLIN, 2006. BIOTIC - Biological Traits Information Catalogue. Marine Life Information Network. Plymouth: Marine Biological Association of the United Kingdom. Available from www.marlin.ac.uk/biotic

[3] National Biodiversity Atlas (NBN) Atlas at http://www.nbnatlas.org.

[4] Ocean Biodiversity Information System. Intergovernmental Oceanographic Commission of UNESCO. www.obis.org.

Life Information Network (MarLIN). Distribution maps for shortlisted species, where available, were sourced from AquaMaps providing predicted distributions of species at a 0.5-degree resolution based on habitat-supporting and environmental preferential data made available through FishBase and SeaLife Base.

1. Depth – species with a depth range that did not intersect 20 - 100m were excluded. This criterion was applied on the basis that one of the limitations to OWF development is depth, with the majority of UK OWF (fixed and floating) located within this depth range (Díaz and Guedes Soares, 2020). This reduced the likelihood of including species that are more likely found within the intertidal, but did not exclude species that are able to move between habitats (i.e., species that will utilise habitat encompassing ~1m to below 20m depth).

2. Benthic association – species that are not associated with the benthos (e.g., pelagic only) were excluded. This criterion was applied on the basis that species with no benthic association are unlikely to benefit from the range of currently identified nature-based solutions which involve the addition of additional hard substrate to the benthos.

Importantly, although benthic communities were the main type of community used in this project to assess the likelihood of OWFs being areas for marine restoration, OWFs may also provide structure for a range of pelagic species. Therefore, although pelagic species were not part of the formal assessment of OWFs (including not being utilised within the decision matrix of Task 7), we do provide a synopsis of the likely effects of OWFs on whole marine communities, and how just by being within the water may support the further development of marine biodiversity.

3. Highly mobile or migratory – species that are highly mobile or exhibit migratory patterns were excluded. This criterion was applied on the basis that highly mobile or migratory species are unlikely to benefit from the range of currently identified nature-based solutions which are stationary therefore limiting synergies with highly mobile species.

4. Substrate preference – species not associated with hard substrates were excluded. This criterion was applied on the basis that species with a preference for soft substrate (e.g., sand or mud) are less likely to benefit from the range of currently identified nature-based solutions which predominantly involve the addition of hard substrate.

Importantly, although the species not associated with hard substrates were excluded from the formal analysis, we do discuss the likely impacts on such species due to the beneficial effects of OWFs described as 'passive restoration'.

5. Commercial relevance – species excluded by the above-mentioned selection criteria that were of commercial relevance were re-included. This criterion was applied on the basis that species of particular commercial interest that may have been excluded by previous criteria may limit the value added in future tasks involving industry.

Figure 1 depicts the application of the above-mentioned selection criterion as a PRISMA flow diagram.

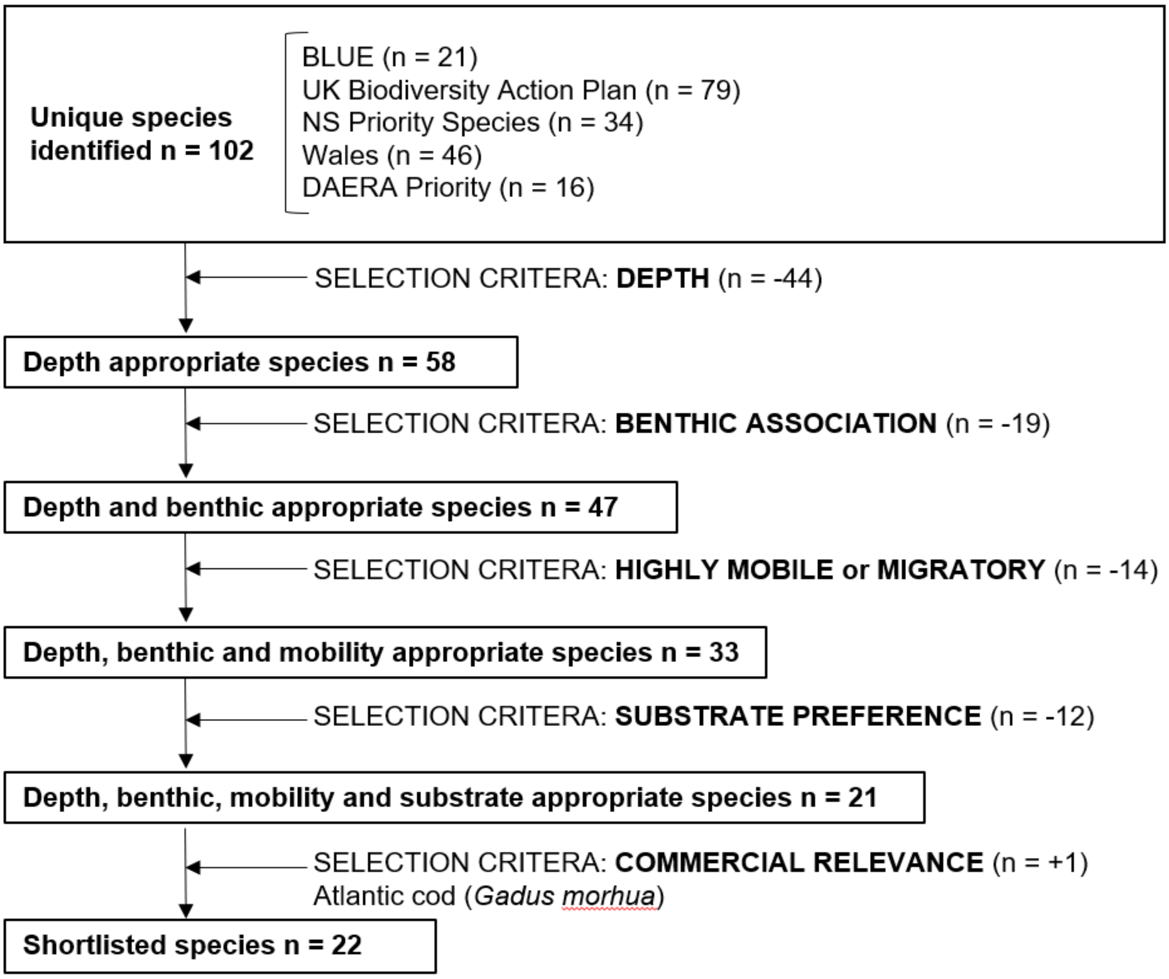


Figure 1. Species selection process

Upon application of the depth selection criterion, 44 species were excluded (e.g., blue whiting, *Micromesistius poutassou*, which has a depth range of 300 – 440m (FishBase, 2022) resulting in 58 depth suitable species. Nineteen species were identified as not having a benthic association (e.g., mackerel, *Scomber scombrus*, a strictly pelagic species (FishBase, 2022) resulting in 47 depth and benthic appropriate species. Application of the highly mobile or migratory criterion excluded 14 species (e.g., European eel, *Anguilla anguilla*) and substrate preference a further 12. Atlantic cod (*Gadus morhua*), although previously excluded by the highly mobile or migratory criterion, was re-included into the shortlisted species due to the perceived commercial relevance to industry.

2.5 Task 5 Identification of Nature Inclusive Designs

Within this Task we have undertaken an extensive literature review to identify the range of nature-inclusive designs that are applicable to the OWFs within the UK, based on the range of substrate (Task 2), species (Task 3/Task 4), and habitat requirements (Task 4), including taking into consideration species that are native to the areas designated as OWFs.

We used Google Scholar to search for both peer-reviewed and 'grey' literature, using compound search terms designed to capture relevant literature. The review has investigated information on a global scale in order to capture relevant nature-inclusive design options from around the UK (e.g., fishing trials in Hywind FLOW in Scotland), as well as other leading OWF countries (e.g., Germany, Denmark, Netherlands).

2.6 Task 6 Assessment of the risks associated with Nature Inclusive Design

Within this section we utilise an extensive literature review to identify the range of potential risks associated with the use of OWFs, using literature from within the UK, as well as the EU and globally. We provide a synopsis of such risks, including a matrix of how best to alleviate/reduce such risks.

2.7 Task 7 Feasibility decision tool for nature-inclusive designs in UK OWF

Under this Task, we have developed an R-based decision tool to allow Blue Marine to make feasibility recommendations for both passive and active (i.e., utilizing nature inclusive design (NID)) species restoration approach combinations, according to biotic and oceanographic constraints. This decision tool has been developed within R, an integrated environment for statistical computing and graphics.

The tool draws on biotic and oceanographic data collected under Tasks 1-6, saved as three .csv files which encapsulate:

- (i) Characterization of the biotic and oceanographic environment of offshore wind farms;
- (ii) Description of the biotic and oceanographic tolerance of selected species; and
- (iii) Description species and OWF affinity to selected nature inclusive design (NID) solutions.

Importantly the biotic and oceanographic variables across the two tables are identical and include, but are not limited to depth, substrate type, temperature, suspended particulate matter, oxygen concentration.

2.8 Task 8 1st Stakeholder engagement workshop

Within this Task a stakeholder engagement workshop was organised and conducted by Blue Marine to provide stakeholders an introduction to the outcomes of Task 7. This workshop was developed to seek expert opinion on the range of nature-inclusive design options versus feasible OWFs identified in Task 7, and provide a platform for all key stakeholders to discuss the technical and ecological viability of the options identified by MRAG and Blue Marine.

2.9 Task 9 1:1 stakeholder engagement session

Following the 1st stakeholder engagement work, a 1:1 stakeholder engagement session has been organised by Blue Marine to occur (19 April, 2023) to provide an in-depth discussion and tutorial session utilising the feasibility decision tool for nature-inclusive designs in UK OWF (developed in Task 7). Engagement will bring together key stakeholders such as OWF developers, relevant members of other closely linked marine sectors (such as fisheries, tourism etc.), local government (e.g., Inshore Fishing Authorities), and other local stakeholders (e.g., NGOs operating in the area, representatives of local residents/local businesses).

3 Task 1 Assessment and gap analysis of the Blue Marine matrix

Under Task 1, an assessment and gap analysis of the previously conducted Blue Marine matrix was undertaken to both identify and supplement missing data gaps identified to be important for decision making regarding active and passive restoration at OWFs in the UK.

3.1.1 Summary of the Blue Marine matrix

In order to assess the suitability of UK offshore wind farms (OWF) as sites for the restoration and / or habitat enhancement for UK native marine species, Blue Marine developed a preliminary, high-level site selection matrix based on the environmental and geographical characteristics of each OWF site for 22 species. This was done with a view to inform discussions with wind farm operators on potentially viable restoration and enhancement opportunities.

The OWFs encompassed within the Blue Marine matrix included OWFs that are either in the pre-planning, planning, consented, under construction or operation phase of development. The matrix encompassed a mixture of threatened, commercially valuable and protected species all of which could benefit from either population restoration (e.g., native oysters) or habitat enhancement (e.g., artificial reef structures, fish ‘hotels’) (Table 3). The matrix calculated suitability of an OWF on 20 identified environmental and logistical variables, relevant to each species and their biological thresholds (e.g., depth) and ecological preferences (e.g., habitat substrate type).

Table 3. Species (scientific name) included in the Blue Marine matrix

Species (Scientific name)	
Atlantic cod (*Gadus morhua*)	Lemon Sole (*Microstomus kitt*)
Bass (*Dicentrarchus labrax*)	Lesser sand eel (*Ammodytes tobianus*)
Blue mussels (*Mytilus edulis*)	Native oysters (*Ostrea edulis*)
Brown crab (*Cancer pagarus*)	Oarweed kelp (*Laminaria digitata*)
Curie kelp	Plaice (*Pleuronectes platessa*)
Dabberlocks (*Alaria esculenta*)	Ross worm (*Sabellaria spinulosa*)
European lobster (*Homarus gammarus*)	Sea bream (*Spondyliosoma cantharus*)
General surface kelp (Laminaria spp.)	Sole (*Solea solea*)
Greater sand eel (*Hyperoplus lanceolatus*)	Sugar kelp (*Saccharina latissima*)
Herring (*Clupea harengus*)	Thornback Ray (*Raja clavata*)
Honeycomb worm (*Sabellaria alveolata*)	Undulate Ray (*Leucoraja circularis*)

For each species and wind farm combination, selected variables were assigned a relative suitability score between one and five (where; one = least suitable and five = most suitable), based upon the raw quantitative or qualitative value of each variable, using identified GIS data layers and supporting literature. The overall suitability of each species and wind farm combination was calculated by an unweighted summation of all relative suitability scores, where the greater the summed suitability score the more suitable that OWF site was for restoration and / or enhancement. The outputs of the site selection matrix were documented in an excel based matrix.

3.1.2 Assessment of the Blue Marine matrix

The matrix provides a reasonable framework for assessment; however, through assessment and critical review of data needs the following areas were identified for development:

Additional variables are required to be built into the assessment. As a minimum in order to provide a balanced and informed output, the matrix should include oceanographic, biotic and abiotic variables. Currently, the Blue Marine matrix does not include any oceanographic variables. Bathymetry (depth); Temperature; Salinity; Currents; Waves; Chlorophll-a; Suspended Matter; Oxygen and Tidal are oceanographic variables identified by MRAG as being important for the purpose of this work.

The data used to describe variables, in some cases, is not suitable. For example, the 1883 georeferenced map used to describe historic native oyster distribution, is debatably beyond a reasonable temporal scale for inclusion within the matrix – no longer representing an appropriate contemporary baseline for potential oyster distribution. Further, the data layer used to describe wave energy provides qualitative data only (i.e., high, medium, low), with no quantitative description of what is meant by 'high', 'medium' or 'low', which presents subjectivity challenges when assessing suitability. There is an identified need to ensure that, where possible, all data layers are within an appropriate spatial and temporal scale, provide an adequate level of granularity and are the most up to date version. Annex 3 provides in-depth comment on the variables and data layers utilised within the Blue Marine matrix.

The adopted approach assumes equal weighting of each variable. The Blue Marine matrix has assigned a relative suitability score to every variable for every species – wind farm combination. This approach assumes the equal weighting of each variable in terms of the importance of that variable for successful restoration or habitat enhancement, and is also heavily time resource dependent. In reality, some variables will be more important than others. Indeed, some variables (available habitat, current strength) may rule out certain species and/or restoration approaches irrelevant of all other parameters. It is therefore suggested that a decision tree approach may be more favourable for the purpose of this work.

The assignment of relative suitability scores requires evidencing. In order to conduct a scientifically robust and well-informed assessment, there is a requirement to evidence decision-making with data / information from literature. Currently the assignment of relative suitability scores appears largely subjective, which could present challenges in future discussions with industry stakeholders.

3.1.3 Gap analysis and data supplementation

Annex 4 provides a list of the biotic, abiotic and oceanographic variables (and data sources) identified as important for the purpose of this work. Examples of variables identified by MRAG that were not encompassed within the Blue Marine matrix include;

Fish spawning and fish nursery sites (biotic); gleaning an evidenced-based understanding of the distribution of fish spawning and nursery sites is required to allow for appropriate selection of restoration / habitat enhancement methods within areas of the seabed considered important or potentially important to key life-history stages of species.

Wind farm cable agreement / Wave site agreements / Tidal stream site agreements / Tidal stream cable agreements and Scotland Energy Infrastructure agreements (abiotic); identifying current and future offshore energy infrastructure developments will be important to understanding potential cumulative impacts, which could affect species restoration / habitat enhancement methods positively (e.g., de facto MPA) or negatively (e.g., anthropogenic noise and disturbance).

Fishing effort (abiotic); the inclusion of fishing effort will enable us to understand the spatial footprint and intensity of fishing effort over selected spatial and temporal scales in relation to OWF sites.

Interference with MPA conservation objectives (abiotic); several OWFs occur within or in close proximity to MPAs (e.g., Hornsea, Race Bank and Dogger Bank). It will therefore be important to understand the potential interaction of species restoration / habitat enhance methods with conservation objectives of an MPA.

Currents (oceanographic); describing the vertical and horizontal components of ocean currents within OWF sites will be critical to understanding the nutrient and food availability to the site, especially for sessile species restoration. Further, high current systems may be unsuitable for some species and/or some restoration technologies.

Suspended matter (oceanographic); the inclusion of suspended matter will enable us to characterise the optical properties of an OWF, which will be important to assessing the viability of a site for certain species (e.g., light penetration for algal species).

Although not considered within this project, inshore fishing effort; sheer bed stress; larval dispersal; sewage outfall and additional offshore infrastructure were identified as potentially important variables to consider should this work be developed further.

4 Task 2 Mapping benthic and oceanographic variables within UK OWF

One of the key requirements for many marine species is the availability of suitable habitats for larval settlement, foraging, shelter and other key ecological processes. Under Task 2 key benthic and oceanographic variables within the spatial footprint of identified UK OWF within all life-cycle stages (e.g., constriction, current and planning) were mapped.

4.1.1 Benthic

Across the total aggregated area of all UK OWF sites (64,983 km^2), sand was the most extensively occurring substrate type totalling at 41,095km^2, representing 63% of the total OWF site footprint (Table 4). The second most extensive substrate type was coarse substrate, totalling an area of 20,067km^2, representing 31% of the total OWF site footprint. Together sand and coarse substrate represent 94% of the total OWF site footprint. Figure 2 provides an example of five OWF sites in the North Sea where sand and coarse sediment dominate the substrate.

Table 4. Total area (km2) and % proportion of substrate types within UK OWF sites.

Row Labels	Sum of Area (km^2)	% Proportion
Sabellaria spinulosa reefs	146.42	0.23%
Coarse substrate	20067.41	30.88%
Mixed sediment	646.27	0.99%
Muddy sand	2107.15	3.24%
Mussel beds	0.00009	0.00000014%
Rock or other hard substrata	484.92	0.75%
Sand	41094.86	63.24%
Sandy mud	50.14	0.077%
Sandy mud or muddy sand	0.41	0.001%
Seabed	106.25	0.16%
Sediment	265.20	0.41%
Worm reefs	13.92	0.021%
Grand Total	64982.96	100%

All other sediment types occupy less than 1% each of the total OWF site footprint, with the exception of muddy sand which covers 3.2% (2,107km^2). Although these values are proportionally small, some of these substrate types cover extensive areas. For example, Sabellaria spinulosa reefs occupy 146km^2 of seabed space. These Sabellaria spinulosa reefs are only located on the east coast of England, mainly around areas of The Wash and Norfolk coastline, spread across a number of OWF sites. Similarly, worm reefs cover a total spatial area of 14km^2 (0.021%), also only occurring on the east coast of England. Sabellaria spinulosa reefs, worm reefs, and mussel beds are the only biogenic substrate occurring in OWF sites. Mussel beds occur across 13km^2 but only at one site, Minestos' Strangford Lough testing site, Northern Ireland. Other substrate types such as sediment, rock or other hard substrate, seabed and mixed sediment, are distributed in a mosaic pattern, the majority of which is surrounded by sand and coarse sediment.

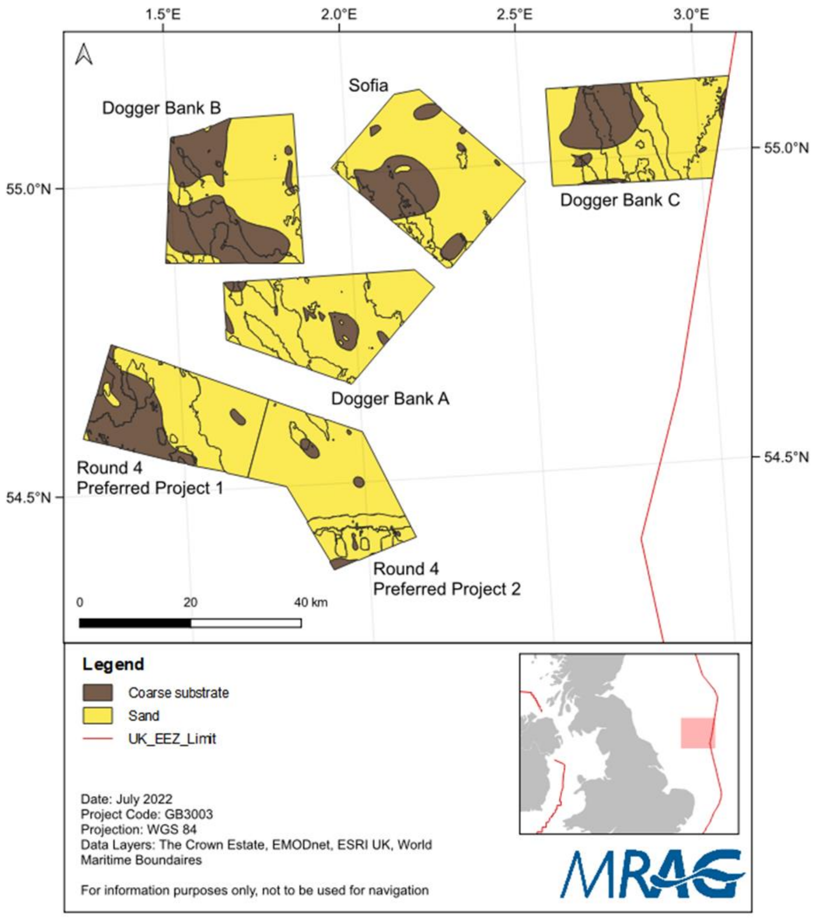


Figure 2. Examples of UK OWF sites where sand and coarse substrate dominate the benthic habitat substrate

4.1.2 Oceanographic

The following sub-sections provide a summary of the oceanographic variables per OWF grouping and region, specifically describing the mean values across a 12-month period and maximum and minimum values to understand the extremities of conditions under each variable.

Depth

Bathymetry of all OWF groupings and regions varied by ~140m, with the shallowest site (Irish Sea) having a maximum depth of -15m and the deepest site (Eastern Atlantic) a maximum depth of -156m. Across all OWF groupings and regions, mean depth of all sites averaged at 22m.

Temperature

Mean temperatures across all OWF groupings and regions were fairly consistent, ranging from ~9 – 13°C (Figure 3). Understandability so, temperature maxima and minima vary more substantially between geographic region. The highest temperature maxima, ~22°C, was recorded in The Irish Sea at OWF grouping Z, reflective of a selection of the T4 OWF sites south of the Isle of Man. The lowest temperature minima, ~2°C, was also recorded in The Irish Sea at OWF grouping AB, reflective of Robin Rigg East OWF near Dumfries and Galloway. The smallest temperature ranges (i.e., difference between minima and maxima) were recorded in the Eastern Atlantic, off the west coast of Scotland.

Salinity

Salinity across all OWF groupings and regions generally ranged from ~34 – 35ppt (Figure 3) In areas where there is greater influence of freshwater salinity minima are much lower between 27 – 29ppt. These areas include OWF grouping V, situated in the Bristol Channel reflective of North Devon Demo Zone OWF, grouping T in the Thames Estuary reflective of London Array, Kentish Flats and Thanet OWFs and grouping AB near the Solway reflective of Robin Rigg East OWF.

Chlorophyll a

Mean chlorophyll a concentration across all OWF groupings and regions generally ranged between 0.5 – 1.5 mg m3 (Figure 3). The highest concentrations of chlorophyll were recorded within the Celtic Sea (i.e., Bristol Channel) and Thames Estuary, where a ~2mg m3 mean concentration was reported and a maximum of >4 mg m3.

Wave height

Mean wave heights across all OWF groupings and regions generally ranged between 1-3m. (Figure 3). The largest wave heights (>9m) were reported in the eastern Atlantic region (i.e., northern Scotland), reflective of the N1 – N4 ScotWind OWFs. The English Channel and the Thames Estuary reported the smallest maximum wave heights (3-4m).

Secchi depth

Secchi depth is a measure of water transparency (turbidity), where transparency increases with increasing depth. Mean secchi depth across all OWF groupings and regions generally ranged between 3-15m (Figure 4). On average, OWF groupings found in the northern North Sea and eastern Atlantic had the greatest secchi depth (least turbid). In contrast, those OWF groupings found in closer proximity to shore with (e.g., the Thames Estuary) were more turbid with average secchi depths ~4m.

Suspended particulate matter

Suspended particulate matter (SPM) is also used as an indicator for turbidity. The highest SPM concentrations were found in coastal regions with high riverine input e.g., the Thames estuary and The Wash where maximum concentrations of ~100 g m3 were recorded (Figure 4). In OWF regions located further offshore, or adjacent to larger bodies of water (e.g., northern North Sea and eastern Atlantic), SPM concentration ranges were considerably lower at 0-5 g m3.

Current velocity (x and y)

Current velocity is a vector (it has magnitude and direction) and therefore has two directional components; horizontal (x) and vertical (y), which are represented in meters per second. Due to the M2 tide experienced in UK waters, mean current velocities are ~0 ms-1 (Figure 4). The highest current velocity (both x and y) was recorded at OWF grouping AC, reflective of Mull of Kintyre OWF off the coast of the Isle of Islay in Scotland.

Oxygen

Mean oxygen concentrations across all OWF groupings and regions ranged from ~240-340 mmol m3 (Figure 5). The highest oxygen concentration was recorded in the northern North Sea (>340 mmol m3), reflective of OWF grouping G off the coast of Aberdeen where Kincardine OWF is located. The lowest oxygen concentration minima, ~240 mmol m3 was recorded in The Wash at OWF grouping P, reflective of Dudgeon and Sheringham Shoal OWF off the coast of Norfolk.

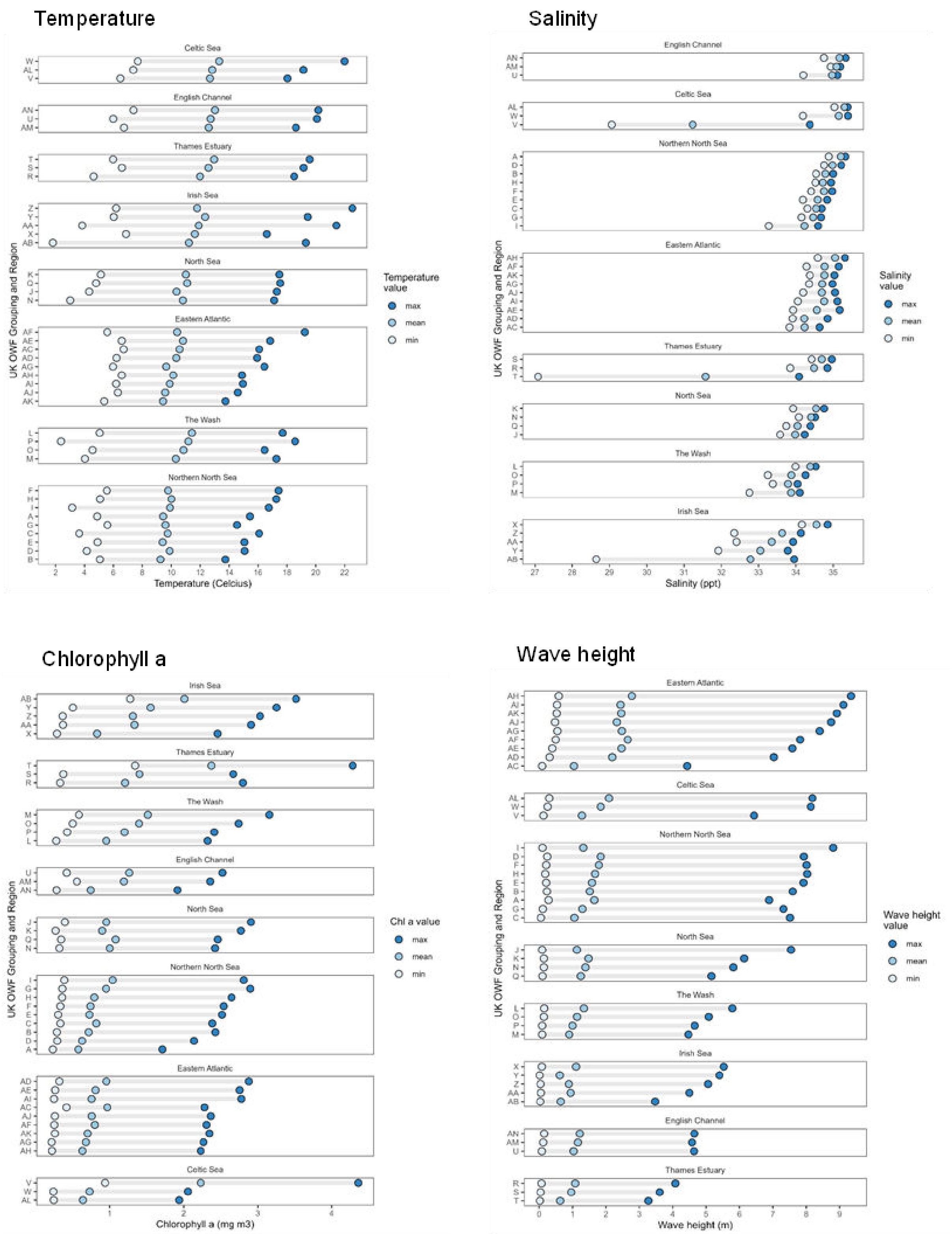


Figure 3. Mean, maximum and minimum values of oceanographic variables across UK OWF regions; temperature (°C), salinity (ppt), chlorophyll a (mg m3) and wave height (m).

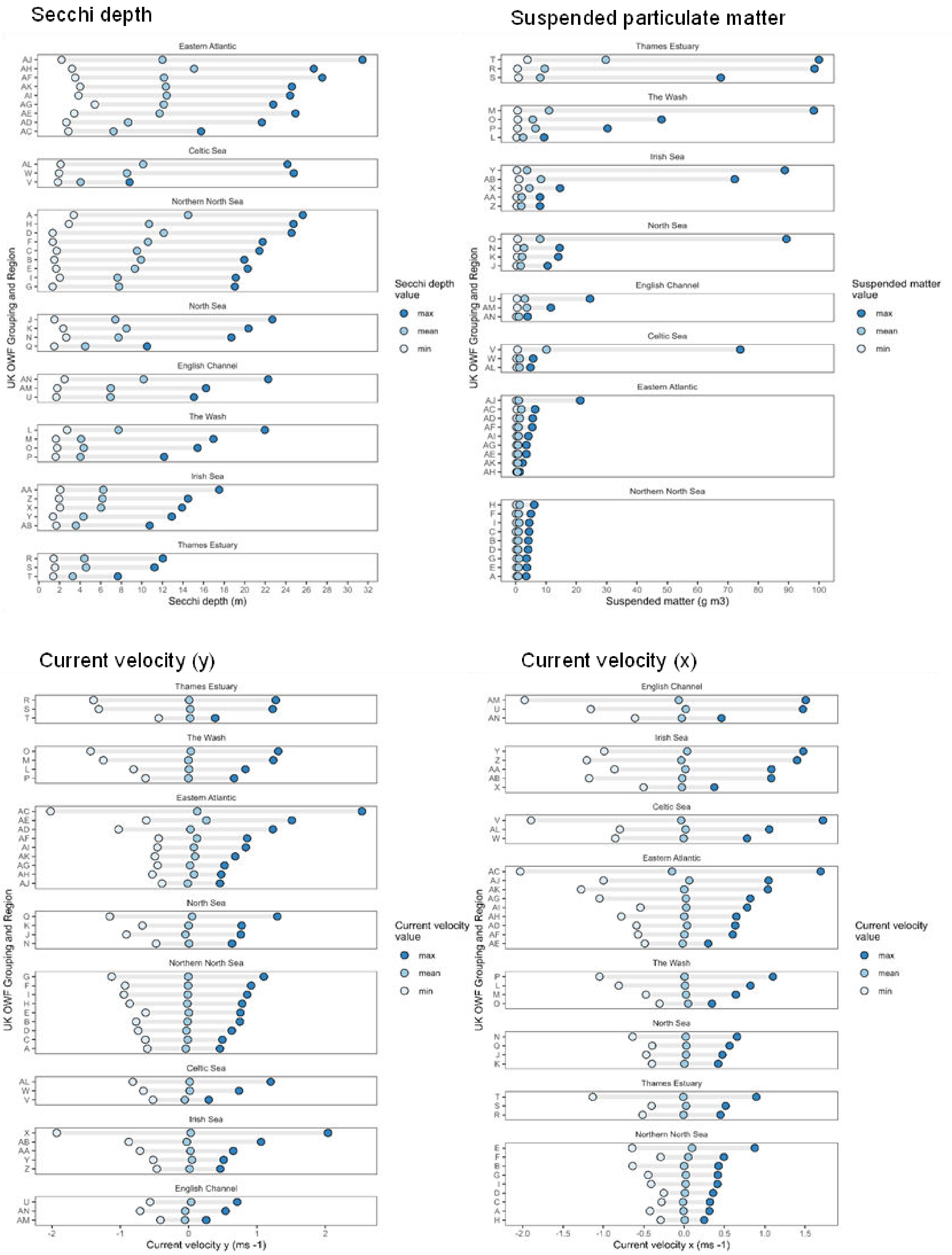


Figure 4. Mean, maximum and minimum values of oceanographic variables across UK OWF regions; secchi depth (m), suspended particulate matter (g m3), current velocity (x and y) (ms-1).

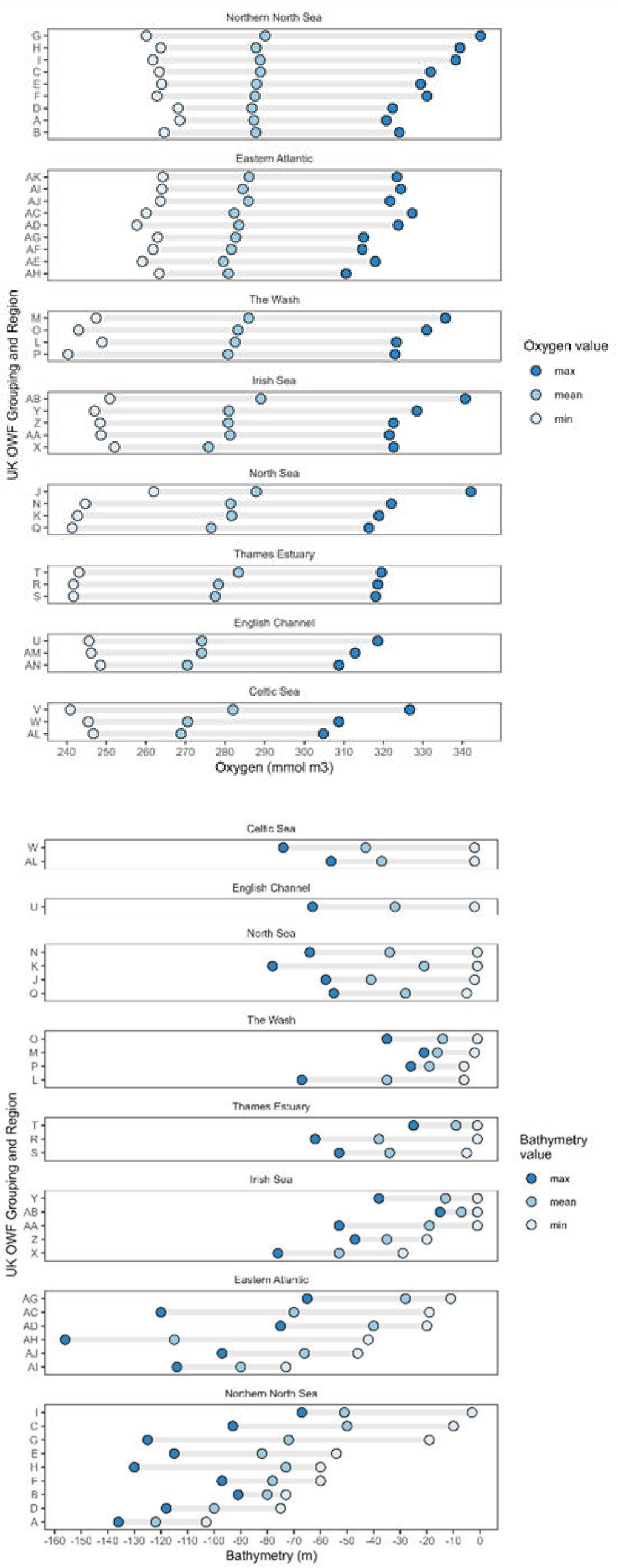


Figure 5. Mean, maximum and minimum values of bathymetry and oxygen across UK OWF regions

5 Task 3. Species identification

Under Task 3 a list of 105 species linked to areas designated as OWF and of conservation and commercial importance were tabulated and have been provided in Annex 5. In addition to the 22 already identified by Blue Marine, 79 were identified in the UK Biodiversity Action Plan; 32 by Nature Scot; 45 by Natural Resources Wales and seven by DAERA. Species groups included algae (13), bony fish (39), cartilaginous fish (17), cnidarians (19), crustaceans (6), jawless fish (2), molluscs (5), tunicates (2) and polychaetes (2).

6 Task 4. Select species which can be bolstered by nature-based solutions

Under Task 4, 21 species of conservation and commercial interest were identified as being able to be targeted by nature-inclusive designs according to the five criteria applied (Table 5).

Predicted distributional ranges for shortlisted species, where available, were plotted in relation to the spatial footprint of UK OWF sites, based on habitat-supporting and environmental preferential data made available through FishBase and SeaLife Base (Figure 6). *Microstromus kitt, Spondyliosoma cantharus, Eunicella verrucosa, Homarus gammarus, Merlangius merlangus* and *Palinurus elephas* had the widest spatial predicted distribution; with the potential to occur across all OWF sites.

Hippocampus hippocampus and *Rostroraja alba* are predicted to have a distribution limited by latitudinal extents, potentially only occurring south of 53 °N and 55 °N respectively. *Ostrea edulis* has a comparatively patchy predicted distribution limited to generally the northern and western coastlines of the UK and little to probability of occurrence in the North Sea.

Table 5. Final species list within indication of species suitability for NBS

Common name	Species name	Depth (m)	Benthic association	Highly mobile or migratory	Substrate preference	NBS Suitable
Sugar kelp	*Laminaria saccharina*	0-30	Y	N	Hard	Y
Oarweed kelp	*Laminaria digitata*	0-20	Y	N	Hard	Y
Peacock's tail	*Padina pavonica*	0-20	Y	N	Hard	Y
Pink sea-fan	*Eunicella verrucosa*	4-50+	Y	N	Hard	Y
European lobster	*Homarus gammarus*	0-50	Y	N	Hard	Y
Brown crab	*Cancer pagurus*	6-40	Y	N	Hard and soft	Y
Gooseneck barnacle	(Mitella) *Pollicipes pollicipes*	0-200	Y	N	Hard	Y
Crayfish, Crawfish or Spiny lobster	*Palinurus elephas*	10-70	Y	N	Hard	Y
Blue mussel	*Mytilus edulis*	0-60	Y	N	Hard	Y
Native oyster	*Ostrea edulis*	0-80	Y	N	Hard and soft	Y
Lagoon sea slug	*Tenellia adspersa*	1-34	Y	N	Hard and soft	Y
Ross worm	*Sabellaria spinulosa*	10-30	Y	N	Hard	Y
Honeycomb worm	*Sabellaria alveolata*	0-26	Y	N	Hard	Y
Lemon sole	*Microstomus kitt*	10-150	Y	N	Hard	Y
European bass	*Dicentrarchus labrax*	10-100	Y	N	Hard and soft	Y
Black sea bream	*Spondyliosoma cantharus*	5-300	Y	N	Hard and soft	Y
Long-snouted seahorse	*Hippocampus guttulatus*	1-20	Y	N	Complex habitat	Y
Short-snouted seahorse	*Hippocampus hippocampus*	0-60	Y	N	Complex habitat	Y
Whiting	*Merlangius merlangus*	10-200	Y	N	Hard and soft	Y
White or Bottlenosed skate	*Rostroraja alba*	50-500	Y	N	Hard and soft	Y
Atlantic cod	*Gadus morhua*	0-600	Y	Y	Hard and soft	Y

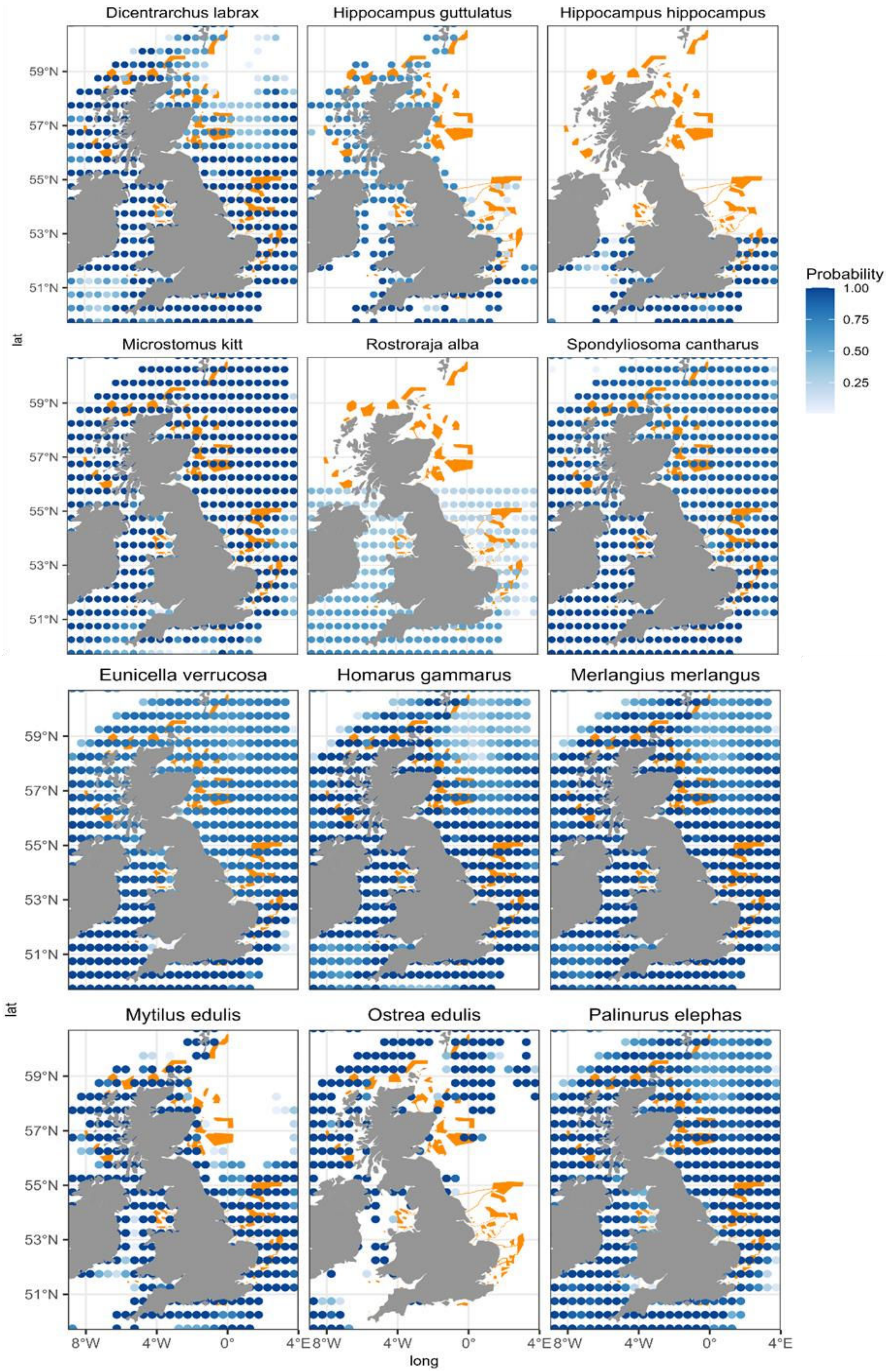


Figure 6. Predicted distributional ranges for shortlisted species

7 Task 5 Nature-Inclusive Designs

There is a need to understand the range of nature-inclusive design (NID) options for active or passive restoration/enhancement. Although these have been identified in earlier Blue Marine projects, further work is needed to ensure such design options are proven, but also would potentially work within a UK setting. Within this section we have focused and completed three subtasks, the first to establish the range of NID options that are available, the second to assess how best these would be in enhancing biodiversity associated with OWFs within the UK, and then third in mapping NIDs to specific UK OWFs.

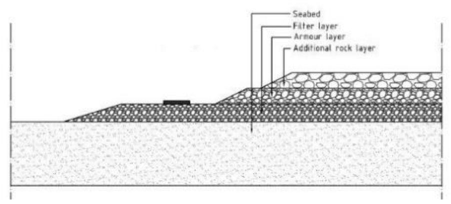
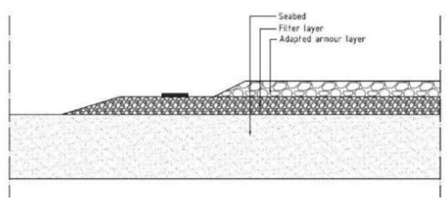
What we find with the available literature on NIDs, is despite a range of different engineered solutions having been proposed to enhance certain types of biodiversity (i.e., benthic habitats, specific fish species), the majority of such solutions are predominantly theoretical, or have only been tested at very small scales. In this respect, of the nature-based solutions discussed in the literature, the majority are in the planning phase, with on-going field trials still being undertaken to determine their success.

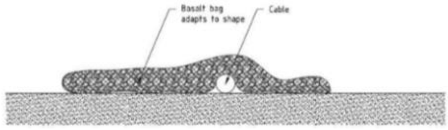
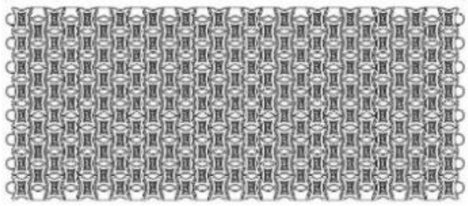
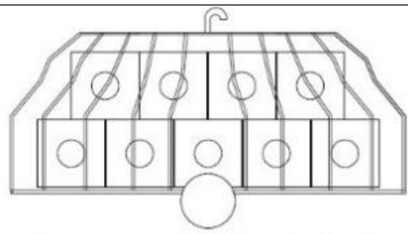
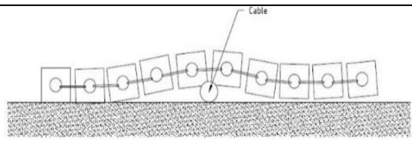
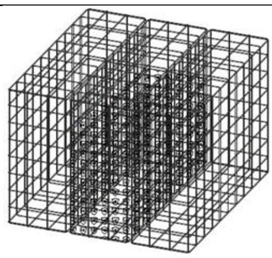
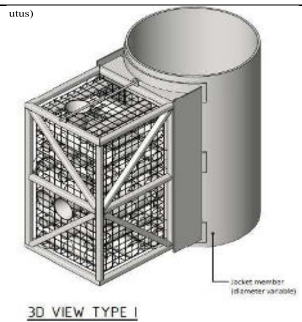
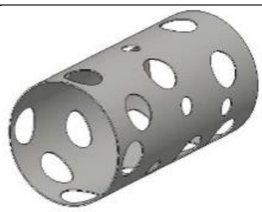
7.1 Review of Nature-Inclusive Designs

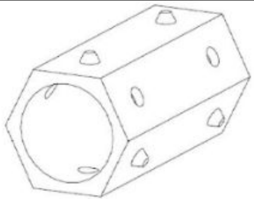
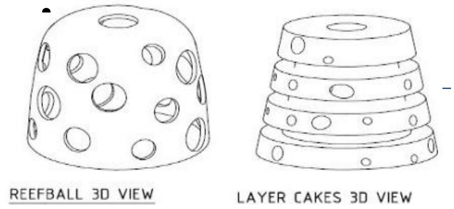
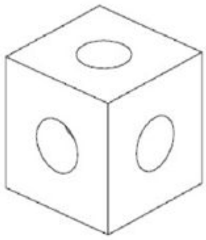
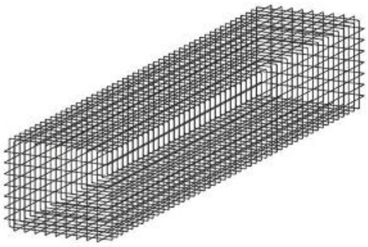
Within this section we provide the full range of different NID structures that can be developed within OWFs. Such NIDs range from relatively passive methods (e.g., scour protection which can act as a pseudo artificial reef, attracting and enhancing local biodiversity) to substantial and specific engineering solutions to 'attract' and enhance specific species or range of species to the OWF (i.e., NIDs).

The most recent information on how best to utilise NID options is organised into four categories based on the aspect of the offshore infrastructure they apply to (summarised in Prusina et al., 2020). The first two categories are those that are associated with enhancing the coverings of the wind turbine – focusing on the scour protection and the cable protection (Table 6). The second two categories are those that can be thought of as more akin to specific NIDs – these are structures that can be attached to the wind turbine, or be placed around the turbine – both are developed to enhance the biodiversity associated with the wind turbine (Table 6). Within each of these four categories, there are a range of different measures that can be utilised. Below we provide a summary of these measures, and where possible the environmental benefits of such measures.

Table 6. List of categories with listed Nature-Inclusive Design (NID) options

NID Category	Description	NID Measure	Schematic Diagram
Category 1: Optimized scour protection layer.	Optimization of a standard scour protection design for a monopile or a substation	Additional rock layer	
		Adapted grading armour layer	
		Seeding the scour protection layer	

Category 2: Optimized cable protection layer.	Optimization of a standard cable protection design for a subsea power cables or cable crossings	Filter Unit® (Rockbags)	
		Basalt bags	
		ECO Mats®	
		Reef cube® filter bag™	
		Reef cube® mattresses™	
Category 3: Add on units	Structural additions in a design of an offshore substation (or a monopile), thus making NID its integral part	Biohut®	
		Cotel; Eotel; Sqotel	
Category 4: Standalone units.	Artificial structures placed around the asset	Habitat pipes	

		Fish hotel	
		Reefball® and Layer cakes	
		Reefcube®	
		3D printed units	
		ECO armour block®	
		Oyster gabions	
		Biohut®	See above
		Cod hotel (Cotel); Eotel; Sqotel	See above

7.1.1 Category 1: Optimized scour protection layer

This category is predominantly based on the deployment of natural substrates (i.e., boulders and gravel) as scour protection (or in addition to scour protection). In this respect, this category is not developed to enhance specific species abundance, but is to provide a hard substratum that will enhance the overall diversity of species settling around the OWF. In utilising both large and small natural rock and stones, this provides an array of habitat that may facilitate a range of different species, including large mobile species (e.g., large elasmobranch), and small habitat-associated reef fishes and invertebrates.

Additional rock layer This involves adding an additional non-moving layer of rocks to the scour protection surrounding an asset, with such extra rocks covering at least 20% of the total scour protection layer. Such rocks would be of different size grades, e.g., 40 - 200 kg, with minimum crevices sizes of 10 – 30 cm in diameter, and 20 – 50 cm in depth. Importantly, this potential NID will add a much larger array of small-scale structures than conventional scour protection, creating more small holes and crevices, as well as attachment and settlement substrate; i.e., creating more habitat complexity on a small scale. The ecological benefits of such a rock layer are expected to be an increase in the number, and therefore biomass, of species that use such crevice habitat (i.e., invertebrates, a range of fish species), including habitat of egg-, larvae- or juvenile stages of many species.

Adapted grading armour layer This involves utilising an optimised layer of graded rocks, which can replace the typical armour layer. Such a layer should be covering a minimum surface of 20% of the total scour protection layer. When this optimised layer is added, grading can be adapted to provide habitat for a much more diverse array of fauna (e.g., crab, lobster, juvenile cod).

Seeding the scour protection layer To further enhance the use of such natural substances, there is evidence that providing or mimicking natural (biogenic) chemical substrate properties may also facilitate species settlement into the habitat. An example is to provide chalk-rich substrate such as concrete with added chalk, or even natural substrate such as shell material. In this respect, such treatment may then facilitate the settlement of specific target species that seek chemical cues that are normally associated with their natural settlement substrate. Larvae of the European flat oyster, for instance, are known to settle better on chalk-rich substrates such as empty shells of oysters or mussels.

To further the use of natural substrates in enhancing biodiversity surrounding OWFs, the introduction and enhancement of species can be undertaken within the habitat (i.e., oyster larvae added to the habitat) to enhance the establishment of new populations. Such mechanisms may then facilitate recruitment at locations where reproduction by naturally occurring adults is absent or too scarce. For example, this has been undertaken within North Sea waters, where a small population of adult European flat oysters of different sizes have been added to the scour protection around OWFs to provide a larvae source that is absent in the current situation.

7.1.2 Category 2: Optimized cable protection layer

This category is based on adding NIDs which provide the utility of protecting cables, but also enhances the availability of habitat for both sessile and mobile fauna. In this respect, the NIDs proposed are predominantly comprised of either adding bagged rocks, or in providing large concrete structures with 3-dimensional shapes.

Filter Unit® (Rockbags) These are polyester mesh nets/bags filled with quarry rocks/aggregate, which can be installed for a scour and/or cable protection or at cable crossings. The rocks are well sorted, with a grading of between 40 and 200 kg. Such filter units are usually placed for a structural function, but the design of such units could be optimized, including utilising larger rocks, to enhance habitat for juvenile fish and invertebrates.

Basalt bags These are similar to polyester mesh nets/bags, but the outer casing of the net/bag is comprised of basalt fibre. As in filter units, these are filled with quarry rock that are graded between 40 to 200 kg. These bags are slightly flexible in their structure and are expected to create crevices of varying sizes, which can provide substantial shelter for a diverse array of fauna.

ECO Mats® These are large mats comprising of interlocking concrete units, resulting in a flexible structure which can be placed on top of cables. Each concrete unit also contains 10% ECOncrete®, which strengthens the concrete's compression forces and reduces the CO2 footprint. These mats can also provide recruitment substrates and shelter for a wide range of species.

Reef cube® filter bag™/ Reef cube® matt™ These comprise reef cubes (see details for reef cubes below) which are placed in either cage-like structure or are constructed as a mat. These structures can provide a more homogenous structure compared to the filter unit and basalt bags, including providing shelter for juvenile Atlantic cod, crab and lobster, while also substrate for sessile species.

7.1.3 Category 3: Add-on options

This third category is based predominantly on describing NID options that can be attached to the main structure of the wind turbine, and can be deployed as the wind turbine structure is placed in the seabed. In this respect, these NID options will need to be manufactured and attached in situ with the manufacturing of the wind turbine.

Biohut This is a system of 2-3 cages in succession, which can be modified and adjusted for placement on a jacket/or as a stand-alone unit. The middle cage should be filled with quarry. When used on offshore jackets, biohuts may enhance the available habitat for a range of fishes, acting as a shelter and nursery area.

Cod hotels (including for a range for a fish species) This consists of 3 main parts: (i) the saddle which connects the frame of the cod hotel to the jacket structure; (ii) the steel frame forms the structural casing; and (iii) the ecological unit consists of a steel gabion basket filled with perforated steel tubes and monitoring funnels. The structural steel of the fish hotel (frame, saddles and double plates) is coated like the jacket structure. The ecological benefits of this NID are to accommodate primarily Atlantic cod by providing shelter and foraging area.

7.1.4 Category 4: Standalone units

This last category of NID options is those that can be deployed either on or surrounding the wind turbine, but do not have to be deployed as the wind turbine is deployed (i.e., are not 'attached' to the wind turbine). In this respect, these NID options are able to encompass a number of different shapes and geometries. However, as they are not physically attached to the benthos or the wind turbine, they must be of suitable structure to ensure stability and permanence in the habitat. Importantly, this category of NIDs can be deployed on a range of habitats, including sand, mud and silt.

Habitat pipes These are steel pipes, of which one end is accessible with at least four holes between 15 - 30 cm in diameter. To enhance the stability and interface of these units with the interface of the armour layer, pipes are placed in 'T' or 'X' shapes. These structures are expected to allow for the movement of species in and out of the pipes, while the steel material allows for the settlement of sessile species.

Fish hotel These concrete tubes can be interlocked and stacked, enhancing their stability, as well as the likelihood of fauna recruiting to them. In this respect, these are purposely designed structures to enhance fish and invertebrate biomass on assets. They are expected to provide shelter for a range of commercial species, but will also provide refuge for relatively large adults.

Reefball® and Layer cakes These, either in a Goliath or Layered cake design, are reinforced concrete units. They are placed on the scour protection layer and have interconnecting holes and an aggregated exposed outside surface texture. Importantly, the design geometry, most substantially hole size, can be modified to accommodate specific site conditions and specific species. A layer cake design, with a domed shaped structure, provides a large surface area in a relatively compact space. This horizontal surface area can provide shelter for large invertebrates, as well as settlement habitat for oysters and other molluscs

Reef cube® These are concrete structures that can be placed individually or stacked in groups. The geometry of the hole structure can also differ between individual units, with such size varying to provide shelter for different sized individuals. Although reef cubes are expected to attract a range of mobile species, the material is also designed to enhance the settlement of sessile invertebrates (e.g., oysters and mussels).

3D printed units These structures are like reef balls, with the added benefit that they can be designed in a great variety of shapes, though designs with a complex texture with randomly allocated holes are suggested. These structures can create a range of habitats for a diversity of species, including creating horizontal surface area for sessile vertebrates to settle, as well as shelter for species such as lobsters and crabs.

ECO Armour Block® These are concrete blocks with 10% ECO admix, which strengthens the concrete's compression forces, while also reducing the CO2 footprint associated with the production of such bricks. As with other concrete structures, these provide shelter, though are more suited for small individuals, while also allowing for settlement of sessile vertebrates - the concreted mixture is adapted to enhance settlement by being developed with bio-enhancing additives, as well as having an outer surface texture which enhances the surface area for settlement of biota.

Oyster gabions A mesh net cage placed directly on the armour layer of the scour protection, filled with oyster shells. Mesh size not smaller than 5 cm x 5 cm to prevent shell from falling out. The structure is to be lowered with the crane and placed on the outer size of the armour layer of the scour protection. The ecological benefits of the oyster gabions is to create additional hard substrate suitable for oyster growth. However, it also creates shelter for small cod, crabs and lobsters. The function of the oyster gabions is to create additional hard substrate suitable for oyster growth. The species which will inhabit the gabions will provide nutrients to the target species.

7.2 Utility of Nature-Inclusive Designs (facilitating active restoration)

The aim of this section is to examine the range of NID options known to exist (detailed above), and provide an assessment of those that could be applied to UK OWFs. Within this section we also discuss the feasibility of such NIDs in terms of both ecological and technical aspects. Importantly, NIDs for the UK OWF market must be ready-to-use with clear design guidelines and associated risks.

There are a number of specific factors which may enhance or reduce the effectiveness of the majority of NID options for UK OWFs. These firstly encompass a range of environmental and oceanographic parameters. Most predominant is depth, whereby NIDs which are deployed in deep habitats (e.g., deeper than ~ 40 to 50m) are unlikely to develop substantial and diverse communities. This is predominantly associated with increasing light attenuation with depth, thereby reducing potential photosynthetic activity and development of a complex and biodiverse benthic sessile community (and therefore an associated invertebrate and fish community). Secondly, the level of sedimentation, predominantly associated with levels of turbidity within the water column, will have a substantial impact on the success of marine community development. In this respect, a substantial level of turbidity (i.e., suspended matter) within the water column will be potentially associated with high levels of sediment settling onto the NID. If water movement does not move such sediment, then the chances of any benthic communities associated with the NID being smothered by high levels of sediment are high. This is likely to cause high mortality of the benthic communities and therefore reduction in the success of such NIDs in developing communities. Water movement (which will include tidal movement, waves and currents) is also likely to be associated with success of enhancement of NIDs. This will firstly be associated with high water movement reducing successful recruitment of, and movement of, larvae, juveniles and adults into the habitat. High water movement will also likely reduce the efficacy of NIDs as habitats, especially if there is movement of the habitat. Conversely, low water movement will likely impact the success of NIDs associated with reduced movement of sediment off NIDs, leading to smothering of benthic communities. Other oceanographic factors likely to impact NIDs will be high or low variance in salinity levels, water temperature (which will be impacted by the latitude at which the OWF is situated around the UK), as well as low levels of chlorophyll-a and oxygen.

The type of OWF is also likely to have a substantial effect on the potential use of different NID options, predominantly associated with different operational parameters. Firstly, of the types of wind farm structures, monopile, jacket, and twisted jacket structures will all be conducive to the use of all four categories of NID. Category 1 will be associated with the scour protection inherently utilised around the base of these three types of structure, while Category 2 and Category 4 NIDs can be utilised once such structures have been deployed. Lastly, Category 3 options may be suitable for monopile, jacket, and twisted jacket structures, but these will need to be associated with the construction of the structure (i.e., before deployment). This is due to the fact that Category 3 NIDs need to be physically attached to the wind farm structure, with the most suitable time being while such a structure is being manufactured.

There is now further use globally of wind farm structures that are built as floating structures (e.g., tension-leg floating platforms, semi-submersible platforms, spar-buoys). For these types of wind turbine structure, there are likely much fewer NIDs that could feasibly be deployed. For these, Category 2 NIDs may be the predominant structure that can be used to enhance marine biodiversity associated with the wind turbine structures. In addition, there is also the likelihood that Category 3 NIDs may be utilised for such structures. However, such NIDs will need to be associated with the wind turbine structure during its construction. Lastly, there is the possibility of Category 3 NIDs being utilised within the footprint of floating wind turbines. However, the depth at which the anchors of such platforms are deployed may reduce the utility of such NIDs.

7.2.1 Specific ecological literature associated with different NID options

There is a growing realisation that biodiversity may be enhanced with the use of different NID options associated with OWFs. Despite this, there is still little primary or secondary literature providing quantitative evidence for the type of community that may recruit and remain within different NID options, when associated with OWFs, as well as the time it will take for such communities to develop. Despite this, and to provide Blue Marine with the most up to date information on what is known about different NID options utilised in conjunction within OWFs, below we summarise this literature. In addition to OWFs, there has been some recent work looking at different NID options associated with artificial structures – these have also been provided here, Importantly, there is only quantitative information on community development associated with a small percentage of the available NID options: these are reef cubes, biohuts and eco-blocks. Overall, the majority of work have focused on the type of communities that may be associated with such NID options, but do not provide detail on the ecological parameters which may meter such success; we provide a synopsis of such parameters where this has been reported.

Reef cubes

Hickling et al., (2022) examined macrofaunal communities recruiting and growing on reef cubes made from either Portland cement (normal cement) and alkali-activated materials (AAM) (lower alkaline materials). This work was focused on understanding the types of macrofaunal communities, including barnacles, tube worms, saddle oysters (*A. ephippium*) and tunicates that would recruit to such habitats. The biological outcome was that macrofaunal communities were relatively similar between different types of Reef Cubes, with the only ecological parameters stated to lead to success being the availability of hard substratum for such communities.

Kardinaal (2021) have examined the outcomes of a reef cube deployment in the North Sea, in which deployment was undertaken to enhance reef associated fishes and benthic communities within the area of deployment. The biological outcome of the deployment was enhanced abundance of Ross worm (*Sabellaria spinulosa*), the sand mason worm (*Lanice conchilega*), common mussel (*Mytilus edulis*), oysters (*Ostrea edulis* and *Crassostrea gigas*), crustaceans, including the brown crab (Cancer pagurus) and European lobster (Homarus gammarus), pouting, common dab, red mullet, gobies, common dragonet, starfish, serpent stars and velvet crabs.

Biohuts

There have been several recent publications focused on understanding the role of biohuts in structuring marine fish communities (Bouchoucha et al., 2016; Mercader et al., 2017; Selfati et al., 2018), including the environmental parameters which may impact success of such recruitment. In all this work biohuts, which are artificial experimental units provided by the Ecocean®company (dock Biohut®) have been utilised. These are composed of a pair of stainless steel alloy cages (50 cm × 80 cm × 25 cm). The inner cage has a 2.5 cm mesh and is filled with a biogenic com-ponent (oyster shells) to promote colonization by benthic fauna and flora, as well as to increase the structure complexity, while the outer cage has a 5 cm mesh and is left empty. The use of a larger mesh enables juvenile fish to move between cages, and reduce the likelihood of predators moving into the cage. The work using such an NID has found that a range of fish species will utilise such NIDs, including Atherinopsidae, Blenniidae, Gobiidea, Labridae, Mugilidae, Sparidae, Tripterygiidae (i.e., mainly reef associated, small bodied fishes). Although in all of the work using biohuts, there are a range of ecological parameters collected, there were no outcomes as to which were most important for the success of the NID. Where analysis was undertaken this showed that enhanced habitat diversity was most important.

Ecoblocks

The use of ecoblocks has been examined for their use as structural support associated with OWFs (albeit this work was not directly associated with an OWF) (Sella et al., 2020). This work examined ecoblocks that had been wired to each other to form an Ecological Articulated Concrete Block Mattresses (ECO ACBMs). The biological outcome associated with the deployment of the ecoblocks was the recruitment of barnacles and bivalves in the intertidal, oysters and sponges in the subtidal, and the attraction of a large range of small reef-associated fishes. No ecological parameters were collected.

Epifouling communities directly recruiting to windfarm structures

Coolen et al., (2019, 2020) have recently examined the epifouling communities that settle on the base, collar and scour protection surrounding wind farm structures. In this respect, this such work is more examining the potential passive restoration that may occur within OWF deployment. The outcome of this work was that a range of macrofaunal species will recruit to the three types of substrates, including annelids, arthropoda, anemones and molluscs. This work found that ecological parameters for success were predominantly associated with depth, which has a substantial impact on the types of species recruiting and settling into each habitat.

7.2.2 How each of the four NID options may be utilised to enhance UK marine communities

Category 1: Scour protection optimisation and the use of natural substrates

The first category of NID that could be utilised within UK OWFs is the use of substrates as scour protection. This is predominantly introduced to enhance habitat availability for natural benthic communities (i.e., native oyster, blue mussel) to settle into the OWF, but also in more mobile species to use such habitat as shelter. Implementation options include different types of shell material, stones or multiple shells/stones glued together with concrete or biodegradable substances.

Importantly, this category can not only provide more hard structure for settlement of marine communities, but also a much more diverse array of habitats. In this respect, the optimisation of scour protection can include rock/boulder of different sizes, which will provide an array of holes in the habitat, and therefore a diverse range of habitats. Such diversity will be vital in providing habitat for new settlers and juveniles of a range of species (i.e., small holes/crevices), but also in providing space to ensure that a range of larger bodied species may utilise the habitat (i.e., through movement of individuals into the habitat). By ensuring larger individuals are able to use the habitat there is then the possibility of supporting reproductively active communities within the structure, enhancing the likelihood of such communities becoming viable.

Importantly, if larvae cannot naturally reach the desired location, or if the settlement success of the larvae is largely dependent on the presence of an existing population close by, the target species can be also be introduced to the natural substrate. For example, within the Dutch North Sea translocation experiments of oysters into OWFs have taken place. These are within the Voordelta, the Borkum Reef Grounds, Wind farm Luchterduinen and Wind Farm Gemini. A small number of adult oysters were deployed in racks, with thousands placed on the sea floor and empty shells were added as substrate. Survival in the Borkum Reef Grounds has been high with larvae observed in the water column (Didderen et al., 2019).

In understanding the likelihood of success, the deployment of natural structures, especially in using an array of different sized substrates is a proven technology. There are a large number of cases supporting the development of benthic communities associated with the deployment of natural substrates (with and without supplementation of larvae/adult of the targeted species), as well as supporting more mobile species.

Category 2: Optimized cable protection layer

Within this category, all four of the NID options are expected to be suitable for UK OFWs. Two of these options are based around the deployment of substrate-filled bags (either comprised of polyester or basalt), while the other two are based on utilising pre-fabricated concrete habitats, that are formed into specific structures (i.e., cages or mats). All four NIDs will inherently lead to an increase in the diversity of habitats (or at least an increase in the abundance of such habitats) surrounding the wind turbine. However, the use of prefabricated concrete habitats is likely to provide a much more diverse array of suitable habitats, due to the manufacturers of such structures being able to ensure such habitats are pre-constructed within the NID. Ensuring that there is a diverse array of habitats provided in the NID (i.e., a selection of both small and large holes, with varying diameters) is much less likely to be found if using pre-filled bags of substrate.

The use of prefabricated habitat modules, either in cages or mat formation, is also likely to be much more ecologically feasible. This is as such structures have a well-documented history of use in both temperate and tropical marine regions, and are well known to substantially enhance marine communities when deployed as artificial reef structures. Such success is likely due to their stability in a range of benthic habitats and their high surface area (i.e., facilitating development of benthic communities on their surface). Success will also be associated with the range of holes that can be placed within the structures, facilitating habitat for a range of small and large invertebrate and vertebrates.

Category 3: Add-on units

NIDs that are attached to the wind turbine, and are inherently part of the structure of the jacket of the piles are the most under-examined category of NIDs, and may also be the most difficult to utilise within the UK OWF setting. This category is based on two major designs (named Biohuts and Cod hotels), but that can be utilised to enhance the diversity of a range of different fish and invertebrate species within wind turbines. These act predominantly by providing fine-scale habitat for the larvae and juvenile forms of a range of species, with the inherent likelihood that once species have settled into these habitats they will remain within the confines of wind turbine, and grow into adult populations.

There are a number of reasons why such structures would be ecologically viable, due in part to the utility of providing a stable and highly structured habitat for the larvae and juvenile forms of a range of species. In this respect, such structured habitats have been used in a range of marine settings to enhance the biodiversity of associated communities, predominantly fish communities (Bouchoucha et al., 2016; Mercader et al., 2017; Selfati et al., 2018).

The technical requirements for the use of add-on units means that such structures need to be placed on the wind turbine before its deployment, therefore any use of these structures need to be part of the manufacture of the turbine. Such technical requirements mean that add-on units are only feasible for wind turbines that have not been deployed (i.e., still being developed). This is discussed in further detail (Section 7.4), but is expected to have a substantial impact on the likelihood of manufacturers utilising such technologies, but also the costs associated with their manufacture and deployment on UK OWFs.

The use of add-on units in enhancing the diversity and biomass of marine communities associated with OWFs has still not been substantially examined. Although there are now a range of studies that have examined the role of such structures, as well as the mechanisms by which the ecological viability of the structures can be enhanced, these are still at the pilot stage. Inherently, there is the likelihood that such structures will lead to increases in the abundance and diversity of marine communities on wind turbines, but the degree to which they will be successful is still unknown.

Category 4: Stand-alone units

Stand-alone structures are likely to be the most viable option for introducing diverse manufactured NID options to UK OWFs. This category comprises a range of prefabricated structures designed to enhance the diversity and abundance of the marine communities in the areas they are deployed. This can be due to their providing a substantial amount of hard substratum (if that is lacking in the area), but also a diversity of potential habitats (i.e., flat surfaces as well as holes) that can enhance and/or promote the settlement and recruitment of invertebrate and vertebrate larvae and juvenile marine fauna, but also the movement of adult forms into the habitat. In this respect, there is a broad awareness of the ecological viability of a range of such structures, which have already been deployed in a diverse array of habitats within both temperate and tropical settings. There are many examples of artificial substrates with nature-inclusive design, amongst others: Reefballs, Reef Cubes, 3D-printed reefs, ECOncrete, 'Fish hotels' (Lengkeek et al., 2017).

Stand-alone structures can be deployed in a range of benthic habitats, but are likely most suitable for areas of flat sand or soft sediment, reducing the need for providing further rock material as a base for the structure. However, these structures predominantly cannot cope with strong currents, and high sedimentation rates decrease the chance of successful reef development. Additionally, for deploying artificial substrate on soft sediment, it is necessary to consider the possibility of erosion around the structure and the occurrence of sand waves.

Deployment of stand-alone structures can be undertaken in conjunction, but also following, turbine deployment, reducing any technical issues associated with NIDs being physically attached to the wind turbine. In this respect, there are likely to be a number of different feasibility issues associated with add-on units that stand-alone units do not have to deal with.

Most projects using stand-alone NIDs on OWFS have utilised small-scale pilots (e.g., Sas et al., 2016, 2018; Didderen et al., 2018, 2019). Extrapolation to a larger scale is not yet feasible.

7.3 Identified Nature-Inclusive Designs Based on Their Similarities in Ecological Habitat Requirements, Impact on Design, Risk and Installation Method

Below we provide a synopsis of the specific biotic, abiotic and/or oceanographic parameters that will be important in determining the success of the described NIDs. To provide such a synopsis we utilise a three-way system to itemise importance: Dark Blue = High importance for success; Light Blue = Low importance; Blank = No relevance. Where there is a perceived high importance of the parameter in ensuring the success of the NID option, we then provide a summary of what factors may structure such importance (Table 7, Table 8).

Biotic

- For all NID options (Category 1 to Category 4), the presence of target species will likely be an important precursor to successful enhancement of such target populations.
- Where the NID option is associated with attracting fish biomass (larval stage, juveniles and adults), the presence of fish spawning sites (i.e., larvae and adults) and nurseries (juveniles) will likely enhance their success.
- Where the NID option is associated with seeding the substrate (Category 1), the type of seabed already existing will be important (as this will be where the seeding will occur), while the historical presence of the target species (as this option will be wholly associated with the settlement of benthic species) may be an important precursor for success.
- Where the NID option is associated with deploying bags of substrate (filter unit, basalt bags), the historical presence of the target species (as this option will be wholly associated with the settlement of larvae of benthic species) may be an important precursor for success.

Abiotic

- For all NID options there will need to be wind farm site agreements in place, as all options will need to be deployed within the footprint of the offshore infrastructure, and therefore will require appropriate sign off by the OWF operators and owners.
- For all five Category 2 NID options there will need to be wind farm cable agreements in place, as all options will be associated with the cables of the infrastructure, and therefore will require appropriate sign off by the OWF operators and owners.
- The success of all NID options will likely be associated with distance to coastal habitat, associated with high distances leading to low levels of larvae being available to settle into the NID options.

- Commercial fishing will likely have negative impacts on the success of NID options which are designed to enhance fish biomass, as any loss of fish biomass surrounding these NID options reduces the chances of such biomass utilising such NID options.

Oceanographic

- Of the range of oceanographic parameters associated with the OWFs, the depth at which the NID option is placed, as well as the variability in water temperature, the strength of currents, waves and tidal movement, as well as the level of suspended sediments ('secchi' and 'suspended matter') will also strongly determine the success of all NID options.
- In this respect, NID options will need to be deployed in areas that are not substantially deeper than the habitats in which target species are predominantly located. For benthic communities, and the majority of fish communities (especially at settlement) this is in the upper 20 - 50 m of the water column; depths below 50m are usually either too cold, or do not receive enough light for abundant coastal communities to develop.
- The strength of currents (associated with tidal and wave action) will also be an important precursor to NID success. This will be associated with both maximum and minimum water movement values. If currents surrounding NIDS are very weak, high levels of sediments may settle from the water column into NIDs, reducing the amount of, but also the quality of habitats. In comparison, where water currents are strong, larval settlement is reduced, as well as the recruitment and habitat use of a number of mobile species.
- The presence of high levels of chlorophyll-a may be an important precursor the success of seeding, filter units, basalt bags and oyster gabions, due to the filter feeding strategy of benthic communities.

Table 7.Synopsis of the biotic, abiotic and/or oceanographic parameters that may be important in determining the success of Category 1 and Category 2 NID options.

Parameter	Category 1: Scour protection				Category 2: Cable protection			
	Rock layer	Armour	Seeding	Filter Unit	Basalt bags	ECO Mats	Reef cube filter bag	Reef cube mattresses
Biotic								
[Type of] Seabed substrate								
[Presence of] fish spawning site								
[Presence of] fish nursery								
[Presence of] target species								
Historical presence of target species								
Abiotic								
Wind farm site agreement								
Wind farm cable agreement								
Wave energy site agreements								
Tidal stream energy site agreements								
Tidal stream cable agreements								
Scotland Energy Infrastructure agreements								
Distance to coast								
Distance to port								
[Presence of] MPA								
Distance to nearest MPA								
Interference with MPA conservation objectives								

Parameter	Category 1: Scour protection				Category 2: Cable protection			
	Rock layer	Armour	Seeding	Filter Unit	Basalt bags	ECO Mats	Reef cube filter bag	Reef cube mattresses
[Commercial/Recreational finfish] Fishing effort								
[Type of/Distance to] Coastal habitat								
Oceanographic								
Bathymetry (depth)								
Temperature								
Salinity								
Currents								
Waves								
Chlorophyll-a								
Secchi								
Suspended Matter								
Oxygen								
Tidal								

NB: Dark Blue = High importance for success; Light Blue = Low importance; Blank = No relevance

Table 8. Synopsis of the biotic, abiotic and/or oceanographic parameters that may be important in determining the success of Category 3 and Category 4 NID options

Parameter	Category 3: Add on units		Category 4: Standalone units								
	Biohut	Cotel; Eotel; Sqotel	Habitat pipes	Fish hotel	Reefball and Layer cakes	Reefcube	3D printed units	ECO armour block	Oyster gabions	Biohut	Cod hotel; Eotel; Sqotel
Biotic											
[Type of] Seabed substrate											
[Presence of] fish spawning site											
[Presence of] fish nursery											
[Presence of] target species											
Historical presence of target species											
Abiotic											
Wind farm site agreement											
Wind farm cable agreement											
Wave energy site agreements											
Tidal stream energy site agreements											
Tidal stream cable agreements											
Scotland Energy Infrastructure agreements											
Distance to coast											
Distance to port											
[Presence of] MPA											
Distance to nearest MPA											
Interference with MPA conservation objectives											
[Commercial/Recreational finfish] Fishing effort											
[Type of/Distance to] Coastal habitat											

Parameter	Category 3: Add on units		Category 4: Standalone units								
	Biohut	Cotel; Eotel; Sqotel	Habitat pipes	Fish hotel	Reefball and Layer cakes	Reefcube	3D printed units	ECO armour block	Oyster gabions	Biohut	Cod hotel; Eotel; Sqotel
Oceanographic											
Bathymetry (depth)	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue
Temperature	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue
Salinity	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue
Currents	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue
Waves	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue
Chlorophyll-a	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Dark Blue	Light Blue	Light Blue
Secchi	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue
Suspended Matter	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue
Oxygen	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue	Light Blue
Tidal	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue	Dark Blue

NB: Dark Blue = High importance for success; Light Blue = Low importance; Blank = No relevance

7.4 Technical requirements for successful NID deployment

Independent of the category of NID that is used within the wind turbine, there are a range of technical requirements that may enhance the sustainability and success of different NID options. Below we provide a synopsis of these technical requirements, including how best to deploy and maintain, but also the practical methods to ensure the sustainability of any ecological communities that associate with the NID

Table 9.Overview of specific technical requirements for NID options, developed through expert sessions and listed per category

Category	Technical requirement	Description
All	Material choice	Where possible materials used should be biodegradable or autochthonous, e.g., rock, gravel, sand, shell, wood or rope or re-usable materials as steel. When using concrete, mixtures used should have low CO_2 emissions and low potential of chemical leakage.
	Monitoring access	Monitoring will be vital to determine the structural integrity, as well as the ecological success of NIDs. Such monitoring must take into account how best to access the NID (ROV for video surveys) as well as the possibilities to retrieve and replace (elements /the entire unit) the NID for monitoring on-deck (e.g., for oysters' growth rims).
Category 1: Optimized scour protection layer	Boulder size	When adjusting (sections of) the scour protection, the maximum boulder size should be considered to allow pile driving for installation of the monopile.
	Internal stability armour layer	The internal stability of the armour layer, in relation to the larger rock grading used to increase crevices sizes should be considered.
Category 2: Optimized cable protection layer	Cable heating effect	The NID and expected marine growth need to be taken into consideration when calculating the expected temperature range of the cable. The NID should be designed such that it does not insulate the cable.
	Cable maintenance	Possible cable maintenance is required during the life span. This requires space and will disrupt the (formation of) reef growth on the NID. When designing the NID, it should be taken into account that maintenance can be carried out with a minimal amount of disruption to the NID, e.g. the ability to lift a cable mattress and place it adjacent to the cable during repairs, and replacing it after completion.
Category 3: Add-on units	Pile driving forces	Pile driving forces can be severe. When an NID is attached to a structure prior to pile driving, the forces associated should be considered. This force is not only exerted on the NID structure but also, if applicable, on the filling material (shells, rock).
	Transport	Implementing an NID option prior to installation requires a review of the transport process. For example, if a structure would be integrated into a monopile it might influence the stacking method during transport. Add-ons at this current stage

		of the technical development are only feasible for offshore substations.
	Planning	The moment of integration of an NID needs to be considered carefully, e.g., working with live oysters places restrictions on the duration the oysters can be kept out of the water. There are also non-biological considerations as pile driving forces and transport method. Furthermore, offshore ROV operations and submerged welding introduce risks and costs. Importantly, there is also the need to include biosecurity means during transportation of the biological samples (e.g., oysters) to ensure no transportation of invasive species, pathogens or disease.
Category 4: Stand-alone units	Stability and interface	When placing elements (reef balls, oyster gabions etc.) on the scour protection, the stability and interface of these NID units and the interface with the armour layer should be considered. Importantly, as close to the pile currents are generally stronger, it is advised to focus mostly on the outer edge of the scour protection when placing such structures (Lengkeek et al., 2017). Every artificial substrate has its own prerequisites, but in general they cannot cope with strong currents, and high sedimentation rates will decrease the chance of successful reef development. Additionally, for deploying artificial substrate on soft sediment, it is necessary to consider the possibility of erosion around the structure and the occurrence of sand waves.

8 Task 6 Potential issues with Nature Inclusive Designs

Every NID option may encompass a number of technical and ecological risks that have to be considered from an early phase (design) and monitored in the later phase (operational) in order to properly mitigate these risks and prevent negative consequences. Within this section we provide a synopsis of the main risks associated with NID options, and where information is available, any mitigating factors which may reduce such risk.

8.1 Ecological risks

Lack of ecological success

One of the biggest ecological risks is that the NID option does not yield the desired ecological success. Such lack of success may be associated with a lack of operator experience, unforeseen environmental circumstances but also a lack of information on the required ecological factors needed to ensure target species success within the NID. The consequences of the lack of ecological success are wasted resources, both economical and material. Importantly, for the majority of NIDs proposed in this study, there is still little experimental work being undertaken to examine their utility in an offshore wind farm setting. In this respect, this risk can be reduced by undertaking assessment of the utility of all of the NID options.

Settlement of invasive/non-native species or diseases

Introduction of hard substrate, in areas in which a sandy seabed dominates, may attract a range of invasive/non-native species (INNS) other than the targeted species. This is termed the ‘stepping stone’ effect (i.e., the relevant species can colonise the new structures and use these to move in to areas previously outside of their natural boundaries) (Krone et al., 2013; De Mesel et al., 2015). Due to the stepping-stone effect, sequential establishment of INNS may occur rapidly on newly established OWF foundations. The consequences of such settlement by INNS may be no, or a smaller population of, the targeted species. Importantly, there is also the risk of such INNS carrying diseases that are not naturally prevalent in the area, and infecting the local native or endemic species already utilising the OWF (or adjacent to the structures within the OWF).

There are relatively few actions that may mitigate of the introduction of INNS with OWF deployment. Deploying OWFs between the spawning season of INNS may reduce immediate settlement onto the wind farm structure, though is likely to have little long-term effect on the likelihood of the settlement. Monitoring and physical removal of INNS immediately after settlement may also temporarily reduce the population growth of INNS. However, due to the small size of new settlers, and the extent of area on wind farm structures could be settled on, such removal may have little long-term success in reducing INNS diversity and abundance.

Competition between target species

Settlement patterns associated with North Sea OWFs show that an NID is likely to be colonised predominantly by one species - it is difficult to design an NID structure for multiple target species. The causes of such competitive density dependent settlement can be an overlapping use of habitat, with one species dominating either by being the first to colonise or able to more effectively colonise. Local levels of predation may also impact species settlement success, and therefore their population expansion within the OWF. A better understanding of the habitat requirements and functioning of NID options is required to mitigate this risk.

Absence of target species

The NID measure may not be successful due to the lack of (larvae or juvenile) target species. This could occur due to a lack of stock population, especially if the OWF is away from natal habitats of that species, as well as unsuitable environmental factors (i.e., high water movement, high level of sedimentation), while also a lack of settlement cues from the environment. Importantly, this risk can be mitigated by selecting the appropriate NID option which aligns with the need of the species at settlement, as well as ensuring that such NID options are utilised in areas in which larval abundance will be high enough to find such habitat. Further local enhancement of target species may be needed to ensure target species do settle on the OWF habitat, including seeding the habitat with larvae or ensuring that spawning adults are placed within the habitat.

Permanence of the NID habitat

This is especially important where Category 1 and Category 2 NID options are deployed. For example, when small-scale habitat complexity is provided close to the sandy bottom (i.e., through use of bagged substrate), these may trap sand and sediment, filling up and effectively losing the holes and cervices within the habitat. Such reduction in the quality and quantity of crevices can also occur where large substrates (i.e., boulders) are placed on soft substrates, which results in the sinking and loss of such habitat. To reduce the loss of small-scale complexity, deployment should occur in locations where water flow is medium to relatively high, as well as within locations away from the sandy bottom. Larger elements (such as boulders) should be deployed on a specific filter (i.e., rock) layer, to prevent sinking and habitat loss.

Stability of the NID habitat

Habitat stability, defined as the permanent non-movement of the deployed NID is vital for the long-term growth of communities within the deployed NID. For example, the majority of benthic species communities will be damaged or even completely destroyed if associated with moving habitats (i.e., rocks rolled over in a storm). Such stability is also important for species settling into the benthic environment, as well as larger individuals utilising the habitat for shelter or feeding – reduced NID stability will negate the majority of these behaviours, reducing the overall diversity and abundance of communities utilising the habitat. Reducing this risk involves clear methods to ensure non-movement of the NID, with the use of more stable substrates preferred over less stable substrates.

Placement options surrounding the monopile.

Current speed and bed shear stress are affected by the placement of a monopile and the scour protection layers. Close to the monopiles currents are generally stronger, reducing with distance from the structure. Therefore, to reduce the effects of sedimentation into substrates, deployment can be undertaken at the right orientation with respect to the monopile and scour zone (i.e., in the shadow), while large boulders installed closer to the monopile will experience less sedimentation in the pores between the boulders, because of higher flow and turbulence levels in this area. Importantly, where habitats are placed within areas of higher water movement such areas may also have lower levels of successful species settlement – especially for species that settle into areas of medium or low water movement.

8.2 Technical risks

Displacement and/or structural failure of the NID

This will likely be associated predominantly with Category 3 NIDs, where such NIDs are permanently attached to the monopile. This is predominantly due to little understanding of how such NIDs may be impacted by environmental parameters surrounding the offshore infrastructure. High current levels, biological interference, as well as sediment loading may all place undue strain on the NID. Mitigating such risks will involve further in-situ assessment of the use of NIDs, associated with periodical inspections and maintenance. To enhance the longevity of such NIDs, the design should be modular so they can be removed if maintenance efforts are deemed too high or the structure is in danger of failing.

Biofouling

All NIDs will become biofouled with time. This may be a necessary mechanism to enhance settlement of species to the NID (i.e., where such biofouling covers a substrate). However, where such biofouling occurs on NIDs that provide fine-scale habitat, this may then prevent the target species from utilising the structure, reducing the utility of the habitat such species. To reduce the risk of such biofouling, NID structures need to be designed to ensure space between surfaces are sufficient to allow for some growth of non-target species without function loss.

Biofouling may also add to the drag on the NID, increasing the likelihood of displacement and/or structural failure of the NID (see above). The likelihood of this risk is very high and the technical impact can also be high if the additional drag is not included in the drag forces on the NID structure. Such risk can be mitigated by accounting for sufficient drag in the design of the structure, but also in ensuring that periodic inspection, removal of the biofouling, or removal of NID (if biofouling is unable to be cleared) is able to be undertaken.

Incorrect deployment

For Category 1, 2, and 4 NID options, incorrect deployment could reduce the efficacy of the structure. NIDs that are deployed upside down, sideways or in disarray in relation to other NID structures or the offshore infrastructure may be more likely to fail both technically and ecologically. Such outcomes may be associated with unexpected weather conditions or local seabed anomalies, as well as the use of sub-optimal equipment at deployment. This risk can be mitigated by selecting the correct weather window for the placement, ensuring the use of a recent morphological survey with the resolution fitting the size of the NID and using the optimal equipment.

Unforeseen costs

The development, deployment and long-term utility of all NID options may be impacted by a range of unforeseen costs. Such costs are associated with uncertainties in every project phase and range from permitting, rules and regulations (current and future) delays, scope (size and number of NID structures), vessel mobilisation, possibilities to combine placement with other activities etc. Such uncertainties are likely due to the lack of experience with NID implementation, especially in utilising new technology, or in deploying NIDs in areas in which they have not been deployed before. To mitigate such economic risks, close communication with experts from all disciplines as well as regulatory bodies, while also including a buffer within the project budget will all be important.

8.3 Economic risks

Besides the ecological or technical risks associated with different NID options, there is a clear need to provide an estimation of the economic costs associated with the different NID options Such costs will firstly be associated with the costs of the material being utilised to construct the NID, and the number of individual units of the NID being manufactured, with potentially economics of scale reducing such costs with the larger number of units being manufactured. The costs of NID will also be dependent on the logistics needed to support deployment, which may include a range of heavy machinery, specialised equipment and specialised team members. Such costs of implementation will also be impacted by the range of technical uncertainties and risks associated with NID options, which will translate into an increase of the overall project cost. Lastly, there may be the need to maintain such NID options, while decommissioning of the options may also need to be undertaken.

Prusina et al., (2020) have provided detailed costs for all NID options. This is the only publication available at present (report submitted 16 December, 2022) that has endeavoured to list specific costs for different NID options. Such costs were developed in close collaboration with stakeholders within the North Sea (predominantly the Netherlands), and therefore we do not believe that simply replicating this output within the present study will be useful for Blue Marine. However, we feel that providing the overall steps needed to implement each of the 4 NID options, including an estimate of overall costs, will provide to Blue Marine an understanding of the potential economic costs associated with each option. This then allows Blue Marine to have the ability to undertake a more pragmatic assessment of the potential for each NID option to be utilised within the UK, including the funding sources that will be needed to support such implementation.

Using Prusina et al., (2020) an estimate of investment costs has been outlined within the report for each NID option where information is available. Such costs must be taken in the context of when and where the information has been provided, with such costs estimated for Europe (the Netherlands in particular), are in Euros (£ provided in brackets), and published in the year 2020. We can assume that such costs may have changed (likely increased) since publication of Prusina et al., (2020), but also assume that they are a relatively unbiased assumptions of deployment costs. Such cost estimations are based on a reference wind farm comprising of 60 monopiles (i.e., no floating structures).

The cost estimation provided includes onshore and offshore activities, direct (material) and indirect costs (site organisation, mobilisation, facilities, risk), contingency, construction, engineering, permits and insurances, with costs of decommissioning also included. The total life cycle costs are also provided, which are comprised of the initial investment costs and the costs across a 25-year cycle (Table 10). Capital expenditure includes: (i) the costs for the NID option per monopile/single structure in which the NID will be deployed (and based on a total quantity of 60 monopiles/structures in a wind farm); and (ii) two NID options on the scour protection around the monopile (except for scour layer (m^2) and fish hotel (1 pcs).

There are a number of issues associated with the four different NID options, which may impact their final costs. **For optimised scour protection layer**, costs may increase due to additional vessel mobilization and additional rock material, while the costs may also be affected by the depth in which the option is deployed due to navigation and maintenance of the NID (in addition to there will be a limitation as to the workable depth these can be deployed) Any cost estimation for optimising the scour protection should include both material but also mobilization costs. For **optimised cable protection**, additional installation methods may increase the cost for deployment, which may also result in additional vessel mobilization and additional material costs. For standalone NID options, both the material used to manufacture the NID, but also mobilization costs will be needed to examined, while for add-on units. costs will include both material but also mobilization costs. Further increased costs may be due to changes in transportation associated with this option, including stacking of monopiles and increased logistic support needed to ensure the NID option is not damaged during transport to deployment sites.

Once deployed, there may be a need for a monitoring program to be implemented by the industry (or government) to obtain the required scale for robust monitoring results. The costs for such a monitoring programme, although not itemised here, may be supplemented by being part of the regular monitoring undertaken by the company running the wind farm.

Table 10 Summary of Life Cycle Costs for different NID options based on a total quantity of 60 monopiles in a wind farm with two NID options per monopile (total 120 structures) with the exception of the fish hotel (1 pcs), while scour protection layer options are based on an area of 20% of 30 m^2.

	Onshore	Offshore	Decommissioning	Engineering & permitting	Total costs per monopile (25 years)
Add-on					
Biohut®	£ 2,319	£ 0	£ 254	£ 582	£ 3,156
Cotel	£ 2,089	£ 0	£ 140	£ 504	£ 2,733
Optimized scour protection layer, Optimised cable protection					
Protection added during design	£ 0	£ 0	£ 0	£ 0	£ 0
Protection added during turbine placement	£ 0	£ 4,458	£ 8,916	£ 3,025	£ 16,398
Protection added after following turbine placement	£ 0	£ 0	£ 0	£ 0	£ 0
Placing unit on or in scour protection layer:					
Habitat pipes	£ 1,393	£ 418	£ 1,170	£ 674	£ 3,655
Reefball® and Layer cakes	£ 1,393	£ 1,393	£ 1,810	£ 1,039	£ 5,637
Reef cube® 1 m^3/pcs	£ 307	£ 1,393	£ 1,810	£ 794	£ 4,304

9 Passive Restoration - the importance of OWFs

Within this section we examine the role of OWFs, without any specific intervention (i.e., OWFs without NIDs) in structuring marine communities. In this respect, we discuss below the *in-situ* impact that OWFs have on marine communities, and therefore their potential role in sustaining 'passive restoration' of such communities. To provide the full range of measures that the presence of OWFs can have we have discussed the composition of marine communities that recruit the structures afforded within OWFs, how such communities develop, as well as the species that are attracted to such recruitment. We show that there are a range of benefits for marine communities due to the hard structure provided by OWF development.

The structures comprising OWFs can have a localised impact on marine communities (Dannheim et al., 2020), through the provision of hard substrata in areas of low topographical complexity (i.e., sandy benthic habitats) that can be colonized by hard substrate species (Petersen and Malm, 2006). Commonly referred to as the "artificial reef effect", this refers to the addition of anthropogenic hard structures being deliberately deployed at sea to mimic characteristics of natural reefs. In this regard, OWFs generally provide two artificial surfaces: a vertical surface, and an array of horizontal surfaces depending on the foundation type and extent and type of scour protection (Lengkeek et al., 2017). In addition, dependent on the type of wind turbine structure (i.e., monopiles, jacket/twisted jacket and tripod structures) novel surfaces can be present throughout the entire water column.

Colonisation by marine communities of OWF structures (at least those associated with continual submergence) encompasses a variety of fouling organisms, which over time can evolve into a highly biodiverse community composed of many species from a large number of phyla (Coolen et al., 2020). There is substantial zonation where vertical substrata reach the surface (i.e., structures associated with monopiles, jacket/twisted jacket and tripod structures), with different species colonizing the splash, intertidal, shallow, and deeper subtidal zones ((Krone et al., 2013; De Mesel et al., 2015). However, three distinct stages in marine community development on OWFs have been identified. A pioneer stage (within 2 years of the deployment of the structure) is characterised by a rapid covering of the available surfaces by algae and small sessile invertebrates (i.e., mussels, barnacles). This is then followed by an intermediate stage (3 – 5 years following deployment) characterized by an increase in the number and diversity of suspension feeding invertebrates. Following 6 years of deployment (termed a 'climax' community) benthic communities are predominantly composed of anemones and blue mussels (*Mytilus edulis*) (Kerckhof et al., 2019). Mussels mixed with hydrozoans and anemones dominate deeper sections of the structure (~15 – 50 m) (Coolen et al., 2020).

There are a range of benthic, or pelagic associated species that may recruit (or move) to the OWF structure, due in part to the development of a biofouling community. Macrofaunal species, including crabs and lobsters, will utilise structures, predominantly feeding on the biofouling community (Krone et al., 2017). Higher-trophic-level species with mobility appear to be attracted to the OWF structures for shelter and food availability. In this respect, three groups of fishes have been identified on OWFs: one group (e.g., Atlantic cod: *Gadus morhua*; pouting: *Trisopterus luscus*) permanently feed on the benthic community, a second group (e.g., Atlantic mackerel: *Scomber scombrus*) occasionally predate the benthic community, while a third predominantly use the structure for shelter (i.e., not feeding on the benthic communities associated with the structure) (Bergström et al., 2014; Reubens et al., 2014; Mavraki, 2021).

The communities that are attracted to OWF structures may show temporal and spatial changes in structure. For a range of fish species that have been identified associated with OWFs (e.g., Atlantic mackerel) these may show migratory behaviour between spawning and feeding grounds, utilising the OWFs for a limited period of their life cycle. In addition, for many fishes and invertebrate, their larvae move over distances up to tens of kilometres from spawning to nursery grounds (Lacroix et al., 2018). Therefore, for these species OWFs may be used for only limited parts of their lives and/or during very specific periods of their life cycles. For example, within Belgium waters Reubens et al. (2014) has shown that pouting only utilise OWFs during their feeding and growing season (summer and autumn), after which they migrate to their spawning grounds outside Belgian waters. Barbut et al. (2020) further showed a differential overlap between the spatial distribution of the spawning grounds of six southern North Sea flat fish species and the distribution of OWFs, assuming a species-specific effect of OWFs on the larval influx to the nursery grounds along the southern North Sea coasts.

There is evidence to show that OWFs may provide opportunities for non-indigenous species to recruit and develop viable communities. This is due to OWFs providing hard substrate in an environment largely comprised of soft mobile substrates, favouring the spread of hard substrate species through the creation of new dispersal pathways - the “stepping stone effect” (Adams et al., 2014). For example, Pacific oyster (*Crassostrea gigas*) and the marine splash midge (*Telmatogeton japonicus*) have both been found associated with OWFs in the southern North Sea (De Mesel et al., 2015), while a range of nonindigenous species (including the slipper limpet *Crepidula fornicata*) have been reported in subtidal surface within North Sea OWFs (Coolen et al., 2020).

10 Task 7 Feasibility decision tool for nature-inclusive designs in UK OWF

The tool has three tabs which allows Blue Marine to identify offshore wind farm(s), species or NID solution(s), depending on their objective. Under each tab, the tool has three major components (i) a side-panel, which gives the end-user the ability to enter data values for each biotic and oceanographic variable upon which to filter the underlying data; (ii) the output data table, which shows the OWF(s), species or NID solution(s) that aligns with the inputted data variables and (iii) download function, which allows the end user to download the output data table as a .csv file and select which data variables to include within that .csv file (Figure 7).

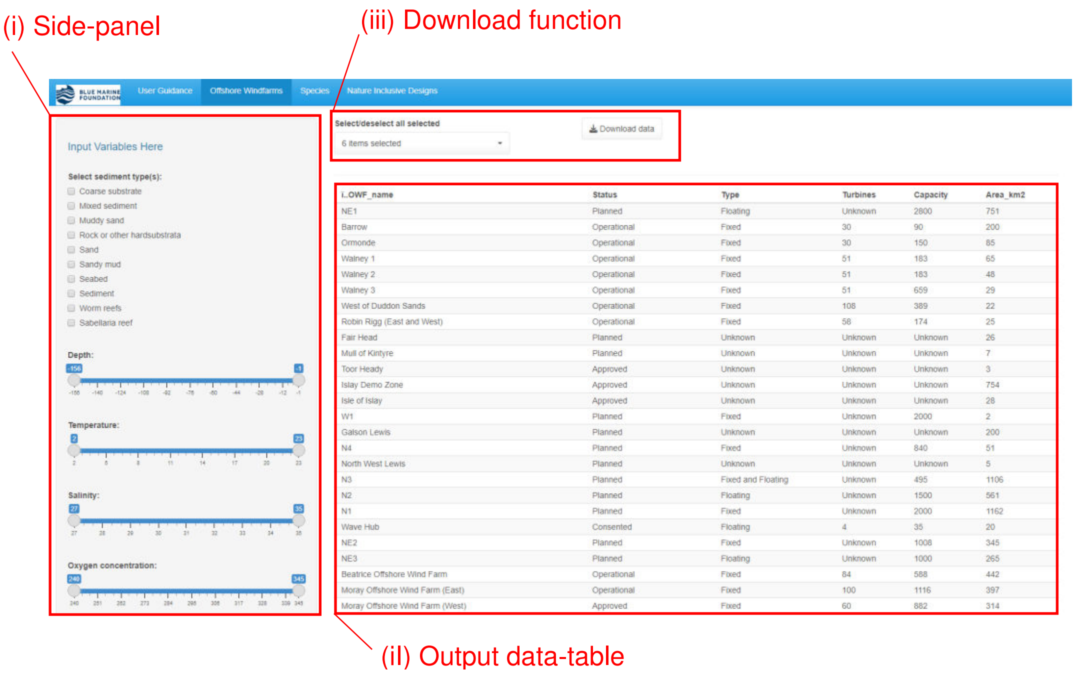


Figure 7. Example of the feasibility decision tool for nature inclusive designs in UK OWFs

For example, Figure 7 shows an example of the 'Offshore Windfarm' tab, where the end-user is in-essence asking the tool which offshore wind farms could be feasible for restoration of a particular species of interest (e.g., oysters). As data is entered under each variable, the tool filters out the offshore wind farms that fall outside the tolerance of that species. The resultant table on the right, will only show offshore wind farms that could be biotically and oceanographically feasible for restoration of that species.

Additional variables characterizing OWFs that have not been used as a selection criterion but may be important to consider (e.g., presence of an MPA, historical presence of a fish spawning site) can be visualized in the output data table by selecting additional columns next to the download function.

Instructions on how best to use the tool have been provided within the tool itself, but are also provided here (Annex 6) to facilitate the use of the tool for all stakeholders.

11 Task 8 and 9

In support of Task 8, MRAG (David Feary) attended a Blue Marine organised workshop and provided support in presenting the feasibility decision tool for nature-inclusive designs in UK OWF. This workshop comprised Blue Marine staff, but was also attended by representatives of Ocean Winds, The Crown Estate, Defra, Van Oord, Natural England, Renewable UK, Pathways to Growth Coordination Group and ARC Marine

In support of Task 9, MRAG staff (Sarah Davie, Pippa Howarth) will undertake a 1:1 stakeholder training session on utilising the feasibility decision tool for nature-inclusive designs in UK OWF.

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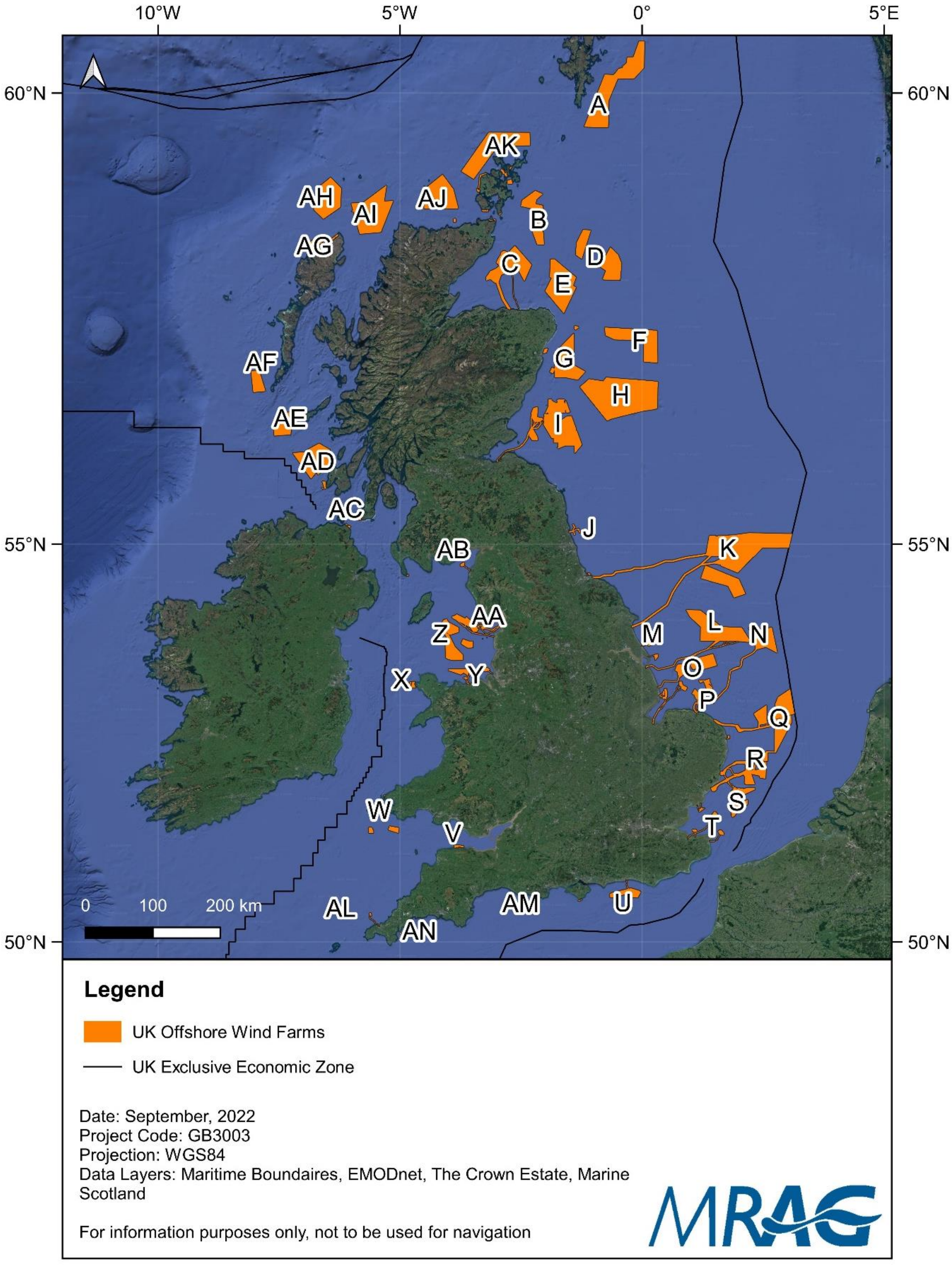
Annex 1 Coordinates for spatial extent of all identified UK OWFs

OWF Grouping	Latitude	Longitude	Bathymetry (m)
A	-0.838	59.997	-114
B	-2.329	58.653	-45
C	-3.025	58.068	-46
D	-0.975	58.299	-109
E	-1.716	57.876	-84
F	-0.270	57.416	-78
G	-1.757	57.068	-103
H	-0.472	56.698	-73
I	-1.843	56.296	-45
J	-1.322	55.151	-50
K	1.525	54.693	-23
L	1.284	53.975	-34
M	0.118	53.725	-16
N	2.501	53.853	-48
O	0.845	53.495	-13
P	1.263	53.109	-23
Q	2.445	52.861	-33
R	2.107	52.199	-33
S	1.794	51.764	-32
T	1.216	51.517	-3
U	-0.493	50.571	-45
V	-3.907	51.265	-31
W	-5.580	51.359	-73
X	-4.911	53.261	-44
Y	-3.636	53.450	-20
Z	-3.826	53.763	-35
AA	-3.804	54.041	-35
AB	-3.741	54.738	-9
AC	-5.983	55.280	-139
AD	-6.809	55.878	-54
AE	-7.429	56.362	-89
AF	-8.000	56.850	-99
AG	-6.886	58.385	-50
AH	-6.617	58.861	-138
AI	-5.749	58.693	-106
AJ	-4.270	58.925	-62
AK	-3.256	59.434	-73
AL	-5.879	50.329	-46
AM	-2.526	50.439	-45
AN	-4.962	50.074	-48

Annex 2 Geographic extent of Offshore Wind Farms throughout the Exclusive Economic Zone of the United Kingdom



Annex 3 Variables and data sources considered within the Blue Marine matrix, with MRAG comment

Variable	Data source	MRAG comment
Maximum depth	Environment statements and ecology reports, Crown Estate Marine Data Exchange	Maximum depth is not considered to be an important variable for the purpose of this work. The maximum depth of an OWF site does not provide adequate information to assess a site in its entirety. For example, the maximum depth of a OWF site may be 100m, but if this only covers 1% of the site and the majority of the site has an average of 20m, then maximum depth isn't particularly informative. It will be important to consider the overall depth profile of a site, from both a biological and/or logistical point of view. To represent this, MRAG proposes to use a raster data layer from General Bathymetric Chart of the Oceans (GEBCO), able to identify depth across an entire site (Table 4).
Distance from shore	ESRI UK	Distance from shore is an important variable to consider when thinking about logistical constraints of restorations methods, specifically more active restoration methods that may have a larger resource requirement. The greater the distance from shore a selected site is, the greater the time resource requirements and fuel costs are to access the site. MRAG proposes to retain this variable; but has identified an alternative data set to represent it from Global Fishing Watch providing, at one kilometre resolution, the distance from shore (km) of every point in the ocean (Table 4). The minimum distance between the coastline and/or other coastal feature (such as port) and the OWF can also be calculated using a “nearest neighbour” tool, available in most GIS software.
Wind farm area	The Crown Estate	Identifying the area of an OWF will be crucial to understanding the area available for restoration or habitat enhancement. The Crown Estate data layer suggested by Blue Marine, provides the most up-to-date picture of OWFs in England, Wales and Northern Ireland; and therefore, will be retained for the purpose of this work. As the scope of the assessment also encompasses Scottish waters, MRAG has sourced an additional data layer identifying OWFs in Scottish waters; ‘EMODnet, EU Offshore Wind Farms’ (Table 4).
Benthic habitat/sediment type including; Coarse sediment area; Coarse sediment % area; Mixed sediment area; Mixed sediment % area; Total area for sites with mixed + coarse sediment; Total % area for mixed + coarse sediment; Score for sites with mixed + coarse sediment; Sand area; Sand % area; Sandy	EMODnet EUSeaMap broad-scale seabed habitat	Understanding the substrate composition of an OWF site is vital to assessing the habitat suitability. Additionally, identifying areas of suitable substrate composition adjacent to OWFs may indicate sites where there is opportunity for possible connectivity with existing features. The EMODnet EUSeaMap broad-scale sea bed habitat data layer adopted by Blue Marine will allow us to understand and visualise the spatial extent, the area and the proportion of each substrate type within all OWF sites. However, within the Blue Marine matrix, it is apparent that the area and the % area contribution of selected substrate types have been scored individually, accounting for 12 out of the total 20 variables scored. In some cases, this could lead to an unbalanced representation of suitability. For example, an OWF site that is characterised by a mosaic of low scoring substrate

Variable	Data source	MRAG comment
mud area; Sandy mud % area; Muddy sand area; Muddy sand % area; Energy level of best substrate		types could on aggregation score higher than an OWF dominated by fewer higher scoring substrate types. MRAG will be retaining this variable as part of the assessment; but has identified an alternative more up-to-date version of the EMODnet EUSeaMap data layer (2021), containing more diverse substrate types including biogenic features (e.g., reef building Sabellaria worms and bivalve reefs) (Table 4).
Depth of wind farm	EIA reports, Crown Estate Marine Data Exchange	As above, MRAG has identified a global terrain model for the ocean from GEBCO as a suitable data source for this variable, providing elevation data on a 15 arc-second interval grid, which is equivalent to ~ 0.5km across the entirety of an OWF site. MRAG further recognises the potential importance and utility of the EIA reports collated by Blue Marine as supplementary material to the GEBCO layer. However, there is variation between EIA reports in how bathymetry of an OWF site is reported (e.g., some have used high precision methods, while others only include general marine charts), which raises inconsistencies when assessing sites. Another advantage of using the GEBCO layer as the primary data source for this variable is that data is provided in a GIS-compatible format (i.e., raster). In comparison to the review of EIA reports, using the GEBCO layer will reduce the demand on time resources and is standardised and comparable across all OWF sites. Additional GIS files describing bathymetry may be available from OWF developers upon request, we cannot rely on unknown data availability at this time.
Within 20km native oyster restoration areas	Environment Agency Native Oyster Bed Potential	An OWF sites' proximity to native oyster restoration area(s) would be important to assess when considering the restoration and / or habitat enhancement of native oysters, specifically. The data layer identified in the Blue Marine matrix, produced by the Environment Agency, acts as an initial aid to identify sites with a potential for oyster restoration. However, the data is derived from the outputs of a large-scale model, and thus may not be precise at the local spatial scales. Whilst this variable may be indicative of potential oyster restoration sites, thinking more broadly, it will be important to consider the current and historical presence / absence of a range of target species and habitats (including oysters) both within an OWF site and within a reasonable buffer distance of an OWF site. In order to do this, Table 4 highlights the use of data repositories such as MARLIN and NBN Atlas. Further, selection of a reasonable buffer distance needs to be evidenced.
Within 20km relevant MCZ	Joint Nature Conservation Committee	Distance to a relevant MCZ, or MPA with a marine component, will be important to consider when thinking about synergies between habitat, benthic or biogenic features and restoration or habitat enhancement opportunities (e.g., connectivity). MRAG has identified and holds shapefile layers containing polygon data for MCZ, SPA, and SACs (Table 4), which will enable the identification of the spatial extent and conservation objectives of MPAs. Consideration will need to be given to any MPA within an OWF site or within a reasonable buffer distance of an OWF site to assess whether selected restoration / habitat enhancement opportunities would interact with conservation objectives of the designated features. The selected restoration or enhancement method would at

Variable	Data source	MRAG comment
		least need to be sympathetic, or ideally enhance, improve or augment. Further, selection of a reasonable buffer distance needs to be evidenced.
Species found at site	Environment statements and ecology reports, Crown Estate Marine Data Exchange	The presence or absence of target species within an OWF may have some influence on the likely success of a selected restoration or habitat enhancement method, albeit depending on the abundance and spatial distribution of the species. It may be important to consider a quantitative threshold or reference point in regards to abundance to inform suitability before this variable can be appropriately be measured. As mentioned above, the use of the repositories MARLIN and NBN Atlas will be important in the identification of species currently and historically found in and around any site. Supplementing this data with information derived from EIA reports could be used to triangulate data.

Annex 4 Biotic, abiotic and oceanographic variables and representative data sources identified by MRAG

Variable	Sub-variable	Metric	Data source	File	Year	Res	Description
Biotic	Seabed substrate	Area of substrate / % area	EMODnet, 'EUSeaMap'	.gdp	2021	Vector	Polygon broad-scale seabed habitat for the European Mediterranean region, following EUNIS and MSFD benthic broad habitat classification. Contains both abiotic (fine mud, sand, rocks etc) but additionally, biotic substrate types (bivalve reef, worm reefs).
	Fish spawning	Relative abundance of ichthyoplankton (n)	Cefas	.shp	2010	Vector	Point data from series of ichthyoplankton surveys reporting the location of surveys and relative abundance of fish eggs for selected fish species. Reported in Ellis et al., 2012 - Occurrence and relative abundance of eggs of the species of interest. Where surveys only identified egg stage for selected species, then the data were aggregated across all egg stages. The exception to this is for horse mackerel and mackerel where broad scale data on the distribution and abundance of early-stage eggs were available, with early stages of eggs more likely to correspond to a close proximity to the spawning ground.
		Spatial area (km2) and intensity of spawning grounds	Cefas	.shp	2010	Vector	Species specific polygon vector data identifying fish spawning grounds, with an 'intensity' metric of 'high' and 'low'. Reported in Ellis et al., 2012 - "spawning ground layer based on half ICES statistical rectangles, with sites of higher importance noted for selected species. This layer was based on the evidence provided by the ichthyoplankton survey data and the layers provided by Coull et al. (1998)".
	Fish nursery	Relative abundance (n) of juveniles and maximum CPUE by survey station location	Cefas	.shp	2010	Vector	Reported in Ellis et al., 2012 - Point data indicating the presence of juveniles in field surveys (within the length range given in Table 2) and whether they were found in at least one haul, 50% of hauls at the station (for fixed station surveys) or 70% of the hauls at the station. The maximum catch per unit effort (CPUE) by survey station location, also indicating how regularly juveniles were captured at that haul station.

Variable	Sub-variable	Metric	Data source	File	Year	Res	Description
		Percentage occurrence in surveys (%)	Cefas	.shp	2010	Vector	Species specific polygon vector data identifying nursery grounds, with an 'intensity' metric of 'high' and 'low'. Reported in Ellis et al., 2012 – "Updated nursery ground layer based on half ICES statistical rectangles, with sites of higher perceived importance noted for selected species. This layer was based on the evidence provided by the trawl survey data and the layers provided by Coull et al. (1998)."
	Presence of target species	Abundance (n)	The Crown Estate Marine Data Exchange	.pdf	n/a	n/a	Qualitative and quantitative data on abundance of target fish species, reported in environmental impact assessments and environmental statements as part of wind farm designation process
	Historical presence of target species	Presence / absence	MarLIN / NBN Atlas	.csv / .shp	n/a	100m – 10km grid	Point and gridded data highlighting historical occurrence of species, drawn from a variety of surveys / data sources (e.g., Seasearch, JNCC). Key fields include; species name, occurrence status, survey date and data provider
Abiotic	Wind farm site agreement	Area (km2)	The Crown Estate, Wind site agreements	.shp	2022	Vector	Polygon data highlighting location and area (km^2) of all current offshore wind farm agreements in pre-planning, planning, construction and operational phases in English, Welsh and Northern Irish waters
			EMODnet, EU Offshore Wind Farms	.shp	2022	Vector	Polygon data highlighting location and area (km^2) of all (and planned) offshore wind farm agreements in planning, approved, construction and dismantled phases in European waters. Data has been extracted for just UK EEZ. This meets the data gap for Scottish waters in the above data set
	Wind farm cable agreement	Area (km2)	The Crown Estate 'Wind cable agreements'	.shp	2022	Vector	Polygon data highlighting location, area (km^2) and number of turbines of all current export cables for offshore wind farm agreements in pre-planning, planning, construction and operational phases in English, Welsh and Northern Irish waters
	Wave energy site agreements	Area (km2)	The Crown Estate	.shp	2022	Vector	Polygon data highlighting location and areas (km^2) of all current wave agreements in English, Welsh and Northern Irish waters

Variable	Sub-variable	Metric	Data source	File	Year	Res	Description
	Tidal stream energy site agreements	Area (km2)	The Crown Estate	.shp	2022	Vector	Polygon data highlighting location and areas (km^2) of all current tidal stream site agreements in English, Welsh and Northern Irish waters
	Tidal stream cable agreements	Area (km2)	The Crown Estate	.shp	2022	Vector	Polygon data highlighting location and areas (km^2) of all current tidal stream cable agreements in English, Welsh and Northern Irish waters
	Scotland Energy Infrastructure agreements	Area (km2)	The Crown Estate, Scotland	.shp	2022	Vector	Polygon data highlighting the location of various energy-based offshore infrastructures in Scottish waters e.g., cables, wind farms, tidal, pipelines. An additional layer called 'Scotwind_offers' is also available, containing features with areas of floating and fixed farms, corresponding to 'planned' windfarm sites within the 'EMODnet EU Offshore Wind Farms' data layer
	Distance to coast	Km	Global Fishing Watch	.tiff	2020	1km	Raster data set providing, at one kilometre resolution, the distance from shore (in kilometres) of every point in the ocean. These data are derived from the Pacific Islands Ocean Observing System's Distance to Nearest Coastline: 0.01-Degree Grid: Ocean dataset
	Distance to port	Km	Global Fishing Watch	.tiff	2020	1km	Raster data set providing, at one kilometre resolution, the distance from port of every point in the ocean. The port distances are calculated using the Global Fishing Watch Anchorages dataset. As a result, the distance from port raster will be updated periodically in coordination with updates to the anchorages dataset. The `vYYYYMMDD` file suffix matches the version of the Anchorages dataset used to create the raster.
	MPA	Presence / absence or Area (km2)	JNCC	.shp	2021	Vector	Polygon data highlighting different designations of marine protected areas in England, Scotland, Wales and Northern Ireland. Data layers include information on area (km^2) of polygon, designated species and conservation objective. MCZs for England, Wales and NI; Scottish Nature Conservation MPAs; UK SACs; UK SPAs; Ramsar sites (Eng, Wales, NI, Scot)
	Distance to nearest MPA	Km	JNCC	.shp	2021	Vector	Distance to nearest MPA can be calculated by applying the 'nearest neighbour' tool to the MPA layer provided by JNCC, as above, within QGIS

Variable	Sub-variable	Metric	Data source	File	Year	Res	Description
	Interference with MPA conservation objectives	Expert judgement	Natural England	.pdf	2021	n/a	Review of MPA conservation objectives to review whether selected restoration / habitat enhancement methods do not have a negative impact on conservation objectives.
	Fishing effort	Fishing hours (hr)	Global Fishing Watch (GFW)	.csv	2012 - 2020	100th° by flag / gear 10th° by mmsi	Anonymised AIS data with labelled fishing positions, classified by gear type providing an indication of fishing effort in hours.
	Coastal habitat	Presence / absence / Area (km2)	Environment Agency	.shp	2021	Vector	Vector data describing the geographic extent and location of Natural Environment and Rural Communities Act (2006) Section 41 habitats of principal importance. Data is in the form of three large shapefiles that cover the extent of UK terrestrial area, including coasts.
	Coastal habitat	Presence / absence / Area (km2)	Environment Agency	.shp	2022	Vector	A habitat map (of Sand dunes) derived from airborne data, specifically CASI (Compact Airborne Spectrographic Imager) and LIDAR (Light Detection and Ranging) data. The habitat map is a polygon shapefile showing site relevant habitat classes. Geographical coverage is incomplete because of limits in data available. It includes those areas where the Environment Agency, Natural England and the Regional Coastal Monitoring Programme have carried out sufficient aerial and ground surveys in England. The classification uses ground data from sites collected near to the time of CASI capture. Ground data is used to identify the characteristics of the different habitats in the CASI and LIDAR data. These characteristics are then used to classify the remaining areas into one of the different habitats.
Oceano-graphic	Bathymetry (depth)	m	General Bathymetric Chart of the Oceans	.tiff	2021	Meters, 15-arc second grid	Global terrain model for ocean and land, providing elevation data. It is accompanied by a Type Identifier (TID) Grid that gives information on the types of source data that the GEBCO_2021 Grid is based
	Temperature	°C		Net CDF	2021	The spatial	The Level-3 standard mapped image (SMI) products are representations of binned data products generated from SeaWiFS,

Variable	Sub-variable	Metric	Data source	File	Year	Res	Description
						resolution is 4 km	MODIS (Terra and Aqua), OCTS, CZCS, OCM2, VIIRS and Aquarius data.
	Salinity	Soil Moisture and Ocean Salinity - L3 OS debiased products		Net CDF	2021	The spatial resolution is 1/4 degree	The SMOS single payload is the Microwave Imaging Radiometer using Aperture Synthesis (MIRAS), an L-band 2D synthetic aperture radiometer, with multi-angular and full polarization capabilities.
	Currents	Global Ocean Forecasting System (GOFS) 3.1 output on the GLBy0.08 grid		Net CDF	2021	GLBy0.08 grid is 0.08 deg lon x 0.04 deg lat that covers 80S to 90N.	The HYCOM consortium is a multi-institutional effort sponsored by the National Ocean Partnership Program (NOPP), as part of the U. S. Global Ocean Data Assimilation Experiment (GODAE), to develop and evaluate a data-assimilative hybrid isopycnal-sigma-pressure (generalized) coordinate ocean model (called HYbrid Coordinate Ocean Model or HYCOM).
	Waves	WAVEWATCH III		Net CDF	2021	16km	Operational global wave model (GFS-Wave)
	Chlorophll-a			Net CDF	2021	4km	The Level-3 standard mapped image (SMI) products are representations of binned data products generated from SeaWiFS, MODIS (Terra and Aqua), OCTS, CZCS, OCM2, VIIRS and Aquarius data.
	Secchi	OCEANCOLOUR_GLO_OPTICS_L4_NRT_OBSERVATIONS_00		Net CDF	2021	4km	Optics products refer to Reflectance (RRS), Suspended Matter (SPM), Particulate Backscattering (BBP), Secchi Transparency Depth (ZSD), Diffuse Attenuation (KD490) and Absorption Coef. (ADG/CDM).
	Suspended Matter	OCEANCOLOUR_GLO_OPTICS_L4_NRT		Net CDF	2021	4km	Optics products refer to Reflectance (RRS), Suspended Matter (SPM), Particulate Backscattering (BBP), Secchi Transparency Depth (ZSD), Diffuse Attenuation (KD490) and Absorption Coef. (ADG/CDM).

Variable	Sub-variable	Metric	Data source	File	Year	Res	Description
		_OBSERVATIONS_00					
	Oxygen	GLOBAL_ANALYSIS_FORECAST_BIO_001_028		Net CDF	2021	1/4°	The Operational Mercator Ocean biogeochemical global ocean analysis and forecast system at 1/4 degree
	Tidal		British Oceano-graphic Research Centre	.txt	1993 - < 3 months	46 stations	Quality checked tide gauge data are freely available for download via BODC website. This includes 15-minute data values for January 1993 onwards and hourly values prior to 1993. Monthly mean, surge and extreme values are also available for some or all of this period. Please note there is a delay of three months from date of data collection until these data are available on the website.

Annex 5 Identified species of conservation and commercial importance

Common name	Species name	Blue Marine	UK	SCO	WAL	IRL
Curie kelp	Unknown	x				
Sugar kelp	*Laminaria saccharina*	x				
Dabberlocks	*Alaria esculenta*	x				
Oarweed kelp	*Laminaria digitata*	x				
Bearded red seaweed	*Anotrichium barbatum*		x		x	
Wig wrack/Sea-loch ggg wrack/knotted wrack	*Ascophyllum nodosum ecad mackaii*	x	x		x	
A Red seaweed	*Cruoria cruoriaeformis*		x		x	
A Red seaweed	*Dermocorynus montagnei*		x		x	
Brown algae	*Fucus distichus*		x			
Coral maërl	*Lithothamnion corallioides*		x		x	
Peacock's tail	*Padina pavonica*		x		x	
Common maërl	*Phymatolithon calcareum*		x		x	x
Lemon sole	*Microstomus kitt*	x				
European bass	*Dicentrarchus labrax*	x				
Black sea bream	*Spondyliosoma cantharus*	x				
Common sturgeon	*Acipenser sturio*		x			
Allis shad	*Alosa alosa*		x		x	
Twaite shad	*Alosa fallax*		x		x	x
Lesser sandeel	*Ammodytes marinus*	x	x	x		
Greater sandeel	*Ammodytes tobianus*	x		x		
European eel	*Anguilla anguilla*		x	x	x	
Black scabbardfish	*Aphanopus carbo*		x	x		
Herring	*Clupea harengus*	x	x	x	x	
Spined loach	*Cobitis taenia*		x			
Vendace	*Coregonus albula*		x			
Pollan	*Coregonus autumnalis*		x			
Whitefish	*Coregonus lavaretus*		x		x	
Roundnose grenadier	*Coryphaenoides rupestris*		x	x		
Cod	*Gadus morhua*	x	x	x	x	
Long-snouted Seahorse	*Hippocampus guttulatus*		x		x	
Short-snouted seahorse	*Hippocampus hippocampus*		x			
Atlantic halibut	*Hippoglossus hippoglossus*		x	x		
Orange roughy	*Hoplostethus atlanticus*		x	x		
Sea monkfish	*Lophius piscatorius*		x	x	x	
Burbot	*Lota lota*		x			
Whiting	*Merlangius merlangus*		x	x	x	
European hake	*Merluccius merluccius*		x		x	
Blue whiting	*Micromesistius poutassou*		x	x		
Blue ling	*Molva dypterygia*		x	x		

Common name	Species name	Blue Marine	UK	SCO	WAL	IRL
Ling	*Molva molva*		x	x	x	
Smelt (sparling)	*Osmerus eperlanus*		x	x	x	
Plaice	*Pleuronectes platessa*	x	x		x	
Greenland halibut	*Reinhardtius hippoglossoides*		x	x		
Atlantic salmon	*Salmo salar*		x	x	x	
Brown/Sea trout	*Salmo trutta*		x	x	x	
Arctic charr	*Salvelinus alpinus*		x		x	
Mackerel	*Scomber scombrus*		x	x	x	
Sole	*Solea solea*	x	x		x	
Bluefin tuna	*Thunnus thynnus*		x			
Horse mackerel	*Trachurus trachurus*		x		x	
Gulper shark	*Centrophorus granulosus*		x			
Leafscraper shark	*Centrophorus squamosus*		x	x		
Portuguese dogfish	*Centroscymnus coelolepsis*		x			
Basking shark	*Cetorhinus maximus*		x	x	x	
Kitefin shark	*Dalatias licha*		x			
Common skate	*Dipturus batis*		x	x	x	
Tope shark	*Galeorhinus galeus*		x		x	
Shortfin mako	*Isurus oxyrinchus*		x			
Porbeagle shark	*Lamna nasus*		x	x	x	
Sandy ray	*Leucoraja circularis*		x			
Blue shark	*Prionace glauca*		x		x	
Thornback ray	*Raja clavata*	x			x	
Undulate ray	*Raja undulata*	x	x		x	
White or bottlenose skate	*Rostroraja alba*		x		x	
Spiny dogfish	*Squalus acanthias*		x	x	x	
Angel shark	*Squatina squatina*		x		x	
Sea-fan anemone	*Amphianthus dohrnii*		x			
Scarce tube-dwelling anemone	*Arachnanthus sarsi*		x	x		x
Ivell's sea anemone	*Edwardsia timida*		x		x	x
Pink sea-fan	*Eunicella verrucosa*		x		x	
Tall sea pen	*Funiculina quadrangularis*		x	x		
A stalked jellyfish	*Haliclystus auricula*		x		x	x
Sunset cup coral	*Leptopsammia pruvoti*		x			
A stalked jellyfish	*Lucernariopsis campanulata*		x		x	x
A stalked jellyfish	*Lucernariopsis cruxmelitensis*		x			
Fireworks anemone	*Pachycerianthus multiplicatus*		x	x		
Brackish hydroid	*Pachycordyle navis*		x			
Northern sea fan	*Swiftia pallida*		x	x		

Common name	**Species name**	**Blue Marine**	**UK**	**SCO**	**WAL**	**IRL**
European lobster	*Homarus gammarus*	x				
Brown crab	*Cancer pagarus*	x				
A deep-sea shrimp	*Arrhis phyllonyx*		x			
An amphipod shrimp	*Gitanopsis bispinosa*		x			
Gooseneck barnacle	*Mitella pollicipes*		x			
Crayfish, crawfish, spiny lobster	*Palinurus elephas*		x	x	x	
River lamprey	*Lampetra fluviatilis*		x	x	x	
Sea lamprey	*Petromyzon marinus*		x		x	
Blue mussel	*Mytilus edulis*	x				
Fan mussel	*Atrina fragilis*		x		x	
Native oyster	*Ostrea edulis*	x	x	x	x	
Lagoon sea slug	*Tenellia adspersa*		x		x	
Loch goil sea squirt	*Styela gelatinosa*		x			
Ross worm	*Sabellaria spinulosa*	x				
Honeycomb worm	*Sabellaria alveolata*	x				

Annex 6 Brief description of how to use the feasibility decision tool for nature-inclusive designs in UK OWF

The tool has three tabs which allows Blue Marine to identify offshore wind farm(s), species or NID solution(s), depending on their objective. Under each tab, the tool has three major components (i) a side-panel, which gives the end-user the ability to enter data values for each biotic and oceanographic variable upon which to filter the underlying data; (ii) the output data table, which shows the OWF(s), species or NID solution(s) that aligns with the inputted data variables and (iii) download function, which allows the end user to download the output data table as a .csv file and select which data variables to include within that .csv file.

For example, using the 'Offshore Windfarm' tab as an example, where the end-user is in-essence asking the tool which offshore wind farms could be feasible for restoration of a particular species of interest (e.g., oysters). As data is entered under each variable, the tool filters out the offshore wind farms that fall outside the tolerance of that species. The resultant table on the right, will only show offshore wind farms that could be biotically and oceanographically feasible for restoration of that species. Additional variables characterizing OWFs that have not been used as a selection criterion but may be important to consider (e.g., presence of an MPA, historical presence of a fish spawning site) can be visualized in the output data table by selecting additional columns next to the download function (a list of these have been provided below).

Term	Description	Source
Bath_min	Minimum depth (m)	General Bathymetric Chart of the Oceans
Bath_max	Maximum depth (m)	General Bathymetric Chart of the Oceans
T_min	Minimum temperature ('C)	Ocean Biology Processing Group
T_max	Maximum temperature ('C)	Ocean Biology Processing Group
S_min	Minimum salinity (psu)	Atlantic European North West Shelf Ocean Physics Reanalysis
S_max	Maximum salinity (psu)	Atlantic European North West Shelf Ocean Physics Reanalysis
Chla_min	Minimum primary productivity (mg m3)	Global Ocean Biogeochemsity Analyis and Forecast
Chla_max	Maximum primary productivity (mg m3)	Global Ocean Biogeochemsity Analyis and Forecast
Wave_min	Minimum wave height (m)	Atlantic European North West Shelf Ocean Wave Analysis
Wave_max	Maximum wave height (m)	Atlantic European North West Shelf Ocean Wave Analysis
Secchi_min	Minimum secchi depth (m)	OCEANCOLOUR_GLO_BGC_L4_MY_009_104
Secchi_max	Maximum secchi depth (m)	OCEANCOLOUR_GLO_BGC_L4_MY_009_104
SPM_min	Minimum suspended particulate matter (g m3)	OCEANCOLOUR_GLO_BGC_L3_MY_009_103

SPM_max	Maximum suspended particulate matter (g m3)	OCEANCOLOUR_GLO_BGC_L3_MY_009_103
Vel_x_min	Minimum current velocity (x) (ms-1)	Atlantic European North West Shelf Ocean Physics Analysis and Forecast
Vel_x_max	Maximum current volcity (x) (ms-1)	Atlantic European North West Shelf Ocean Physics Analysis and Forecast
Vel_y_min	Minimum current velocity (y) (ms-1)	Atlantic European North West Shelf Ocean Physics Analysis and Forecast
Vel_y_max	Maximum current volcity (y) (ms-1)	Atlantic European North West Shelf Ocean Physics Analysis and Forecast
Ox_min	Minimum oxygen concentration (mmol m3)	GLOBAL_ANALYSIS_FORECAST_BIO_001_028
Ox_max	Maximum oxygen concentration (mmol m3)	GLOBAL_ANALYSIS_FORECAST_BIO_001_028