Photo: Emily Baxter

Nature Inclusive Design:

Challenges and Opportunities for UK Offshore Wind Farms

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1. Acknowledgements

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Any questions regarding the Marine Futures Internship can be directed to livingseasnw@cumbriawildlifetrust.org.uk

2. Introduction

2.1. Background

In 2019, the UK Government was the first major economy to pass legislation stating a commitment to bring greenhouse gas emissions to net-zero by 2050, compared to previous targets of at least 80% reduction from 1990 levels (UKGOVa). In April 2021, the Government further committed to reducing greenhouse gas emissions by 78% by 2035 (UKGOVb). The oceans will play a key role in meeting these targets, with offshore wind, tidal and wave energy offering a cleaner more sustainable alternative to fossil fuels. Offshore wind is one of the UK's biggest growing industries and is set to become the cornerstone of a clean, reliable and affordable energy system. There are currently 10GW of offshore wind installed in the UK, this is required to increase to 75GW by 2050 if we are to reach emissions targets. The UK Government has set interim targets to reach 40GW by 2030 with the Republic of Ireland committing to installing a further 5GW. This unprecedented scale of development offshore must be managed correctly.

The marine renewable energy sector will need to work closely with conservation experts, decision makers and coastal communities to ensure their developments minimise impacts on wildlife, seabed habitats or other ocean users. The marine environment is already facing a multitude of compounding pressures that have led to biodiversity loss, degradation of key habitats, and threatened ecosystem service provision (Coleman and Williams, 2002; Crain et al., 2009). A healthy, thriving marine environment can play a key role in tackling climate change (Roberts et al., 2017). Habitats such as seagrass beds salt marshes (Siikamäki,, 2013), muddy subtidal sediments and biogenic reefs (Fodrie et al., 2017), all play a crucial role in carbon sequestration and storage. The marine environment therefore, has the potential to contribute to net zero targets but it needs to be better understood and integrated into marine management. The ability of the marine environment to contribute to carbon storage is improved by restoring and maintaining productive, healthy and biodiverse ecosystems. On the other hand, disturbing marine ecosystems through fishing pressure and unsustainable development is hugely detrimental (Roth and Gustafsson, 2021).

The UK Government has committed to halting terrestrial biodiversity loss by 2030. Industries have a responsibility to ensure their developments are carried out sustainably with no net losses. New legislation now requires new energy developments to enhance local biodiversity and habitats, in a process termed ‘biodiversity net-gain’. Biodiversity net-gain in a marine context is yet to be defined or legislated for. Renewable energy companies are anticipating this to be set out in the near future and have expressed an interest in how they can prepare for it.

Incorporating Nature Inclusive Design into UK offshore wind farms (OWFs) has the potential to positively impact marine biodiversity and to contribute towards future anticipated requirements for marine net-gain, while simultaneously increasing the capacity to produce renewable energy and reduce carbon emissions. In this report, Nature Inclusive Design (NID) principles are ‘measures that are integrated into or added to the design of offshore wind infrastructures to increase suitable habitat for native species (or communities) whose natural habitat has been degraded’ (Hermans et al., 2020). NID options must be ‘inclusive’, meaning the offshore wind structures themselves must include nature benefiting designs. NID options can be integrated into the design of different elements of OWF including on the wind turbines, offshore substations, scour protection or cable protection measures.

It is predicted that soon, enhancing nature within offshore windfarms will be the new standard. This report aims to draw together current research on NID, and assess the feasibility of incorporating it into OWFs in the Irish Sea. The report also highlights the challenges and barriers anticipated by the key stakeholders, to implementing NID in the UK.

2.2. The Irish Sea and Marine Planning

This work focusses on the Irish Sea. The Irish Sea currently hosts 13 operational OWFs with four more Round 4 sites that are in the early stages of development. There are also 14 Marine Conservation Zones (MCZs), 17 Special Protection Areas and 16 Special Areas of Conservation with marine components, 10 Marine Nature Reserves (Isle of Man) and 3 Scottish Nature Conservation Marine Protected Areas (MPAs). This regional sea area also supports important fisheries for shellfish, flatfish, gadoids and elasmobranchs.

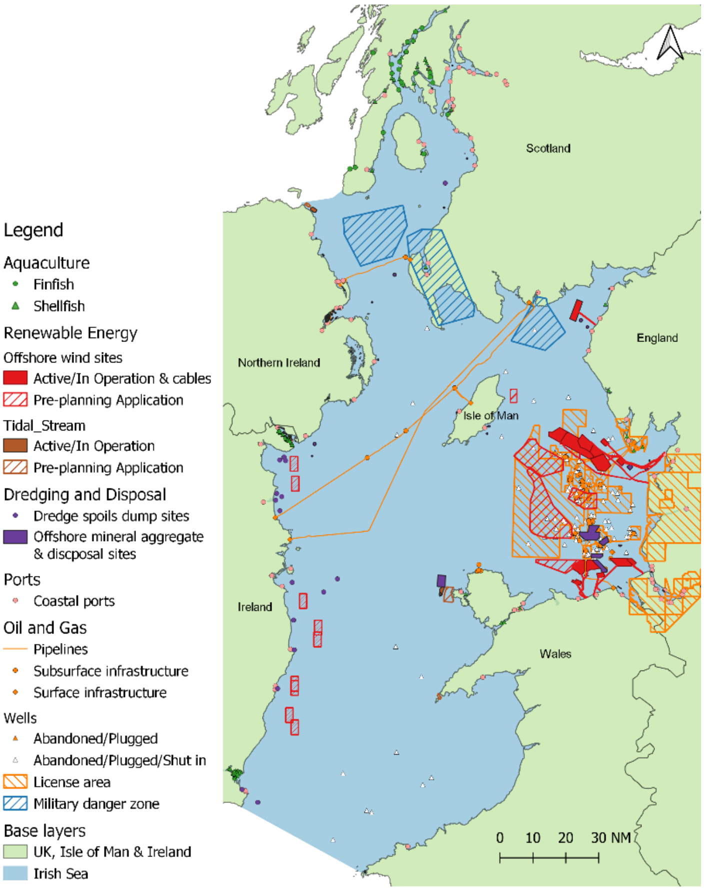


Figure 1 Developments within the Irish sea. (de Jong Cleyndert, G. Cumbria Wildlife Trust, 2021)

The Irish Sea is becoming extremely busy, with huge demands on space from competing industries (Figure 1). The development of OWFs can lead to conflict with other marine stakeholders. Offshore wind developments must take into consideration their impact on the fishing and other industries and marine wildlife, especially within MPAs. The implementation of NID, if done correctly, has the potential to result in OWF development that can benefit fisheries, contribute to conservation and enhance marine biodiversity through targeting commercially important and policy relevant species and habitats, as well as providing a substrate for biogenic reefs.

3. Nature Inclusive Design Literature Review

3.1. Ecological Impacts of Offshore Wind Farms

3.1.1. Artificial Reef Effect of OWFs

Solid structures from offshore developments including oil platforms, pier pilings, bridge pillars and turbine foundations can have a similar effect to purpose built artificial reefs (Degraer, S. et al., 2020). Artificial reefs are solid man-made structures placed on the sea floor to mimic characteristics of natural reefs. They are often used to enhance biodiversity and fisheries or rehabilitate certain habitats (Svane and Petersen, 2001). OWF structures and their associated scour protection provide two new and distinct, hard substrate habitats into an otherwise soft sediment environment:

- Hard vertical substrates along the turbine monopile foundation;
- Complex horizontal habitats formed by the associated scour protection- this habitat varies depending on the foundation type and the type of scour protection measure used

These new habitats provide increased shelter and attachment sites for many organisms and can result in structural and functional changes to local ecosystems (Degraer, S. et al., 2020). Newly introduced habitats occur throughout the entire water column from the splash zone at the surface down to the seabed. The assemblage of organisms that colonise the structures are often predicable, with vertical zonation that reflects the zonation observed in intertidal and subtidal rocky shore communities (Degraer et al., 2020; Linley et al., 2007). Succession occurs on these newly introduced surfaces (Degraer et al., 2020; Kerckhof et al., 2019) and the process begins with biofouling species. At the top of the turbine, biofouling communities are typically dominated typically by mussels and macroalgae, however these are absent in the top 1m (splash zone) where barnacles tend to dominate instead (Degraer et al., 2020; Maar et al., 2009). In the intermediate zone, filter-feeding arthropods dominate, and then anemones at deeper locations (Degraer et al., 2020).

There has been one long term-study on the colonisation and succession of offshore wind turbines by marine life (Kerckhof et al., 2019). This study looked at Belgian OWFs over a 10-year period following installation. Initially the species composition was different on each turbine, likely due to differing times of installation and geographical location, however, over time, the species compositions converged into a common assemblage dominated by the same suspension feeders (Kerckhof et al., 2019). The study showed three distinct succession stages.: 1) Pioneer stage (2 years) rapid colonisation by opportunistic species; 2) Intermediate stage (3-5 years) higher diversity characterised by large numbers of suspension filter feeding invertebrates; 3) 'Climax' stage (6+ years) lower diversity with turbines becoming co-dominated by plumose anemones (*Metridium senile*) and blue mussels (*Mytilus edulis*) (Kerckhof et al., 2019). This study highlights the issue with assuming OWFs can become hotspots for biodiversity. Often the studies suggesting this are short-term and refer only to the second stage of succession where diversity is high and do not consider the following years where competitive species become dominant. Kerckhof et al., (2019) concludes that the artificial hard substrate surfaces provided by OWFs do not resemble natural hard substrates and therefore do not create the same levels of biodiversity found in natural ecosystems. Highlighting that OWFs, as they are, cannot act as a substitute for natural hard substrate habitats.

The presence and absence of certain species colonising OWF structures depends largely on the proximity of the site to rocky substrates and the hydrographic conditions of the site. Community development also depends on the season during installation, the site depth, and the type and amount of larval supply to the site. Species colonisation is also limited by currents, proximity to parental populations, water temperature and presence of conspecifics (Linley et al., 2007). This can lead to communities being dominated by more robust species which may arrive in small numbers but have the ability to self-recruit and establish communities (Linley et al., 2007). Once settled, pressures such as predation, physical burial and abrasion, and intraspecific competition can lead to lower levels of species diversity. Modifying hard structures using NID to increase a population's carrying capacity is an active area of research (Linley et al., 2007).

It is likely that the communities colonising OWF structures exhibit low diversity because there is a lack of habitat complexity and availability of microhabitats provided by the smooth, hard surfaces of the turbine. It may also be due to the spatial patchiness and unnatural vertical structures and surfaces of OWF infrastructure (Svane & Petersen 2001). It is well known that increased habitat complexity results in greater biodiversity (Torres-Pulliza, D., et al 2020). Therefore, integrating NID options that provide greater surface complexity, more similar to natural substrates could lead to more diverse and natural assemblages, resulting in greater biodiversity on and around wind turbines.

3.1.2. Attraction vs. Production

The attraction hypothesis states that artificial reefs attract nearby mobile species causing them to aggregate around newly introduced habitat. Existing limits on fish populations (e.g., limited food and larval supply) mean that where fish have moved towards a new structure, they will not be replaced in their original habitat. If this is the case, the introduction of new reef-like structures will not necessarily result in increased local fish populations but merely changes in species distributions (Brickhill et al., 2005).

The production hypothesis envisions a more positive outcome of artificial reef deployment, where additional habitat creation leads to an increase in an area’s carrying capacity. Increased shelter and feeding opportunity around artificial reefs attract fish, like in the attraction hypothesis. However, the addition of habitat also allows a greater number of juveniles to settle, survive and spawn as adults. This results in a net increase in the local fish population (Brickhill et al., 2005).

Whether an artificial reef fulfils the attraction or production hypothesis will depend on the characteristics of the surrounding habitat, especially in terms of spatial heterogeneity and nutrient availability. It will also be influenced by the type of management in place. Adding more complex reefs and having restricted fishing activity is more likely to result in production by reducing mortality and increasing growth rates (Brickhill et al., 2005; Pickering and Whitmarsh, 1997).

Where a reef increases food availability, feeding efficiency, larval and spore survival and increased protection from predation, then it is likely that the production hypothesis is playing out (Petersen and Malm, 2006).

High densities of several fish species (pouting (*Trisopterus luscus)*, cod (*Gadus morhua)*, horse mackerel (*Trachurus trachurus)* and two spotted goby (*Gobiusculus flavescens))* have been found to aggregate around current OWF turbines (Bergstrom et al., 2013). This effect is thought to alter species distributions rather than causing population level changes (Inger et al., 2009). Monitoring on OWFs in the Irish Sea has shown that any reef effects caused by OWFs only cause localised changes to fish assemblages (NE, 2014).

If NID projects set goals to increase the marine biodiversity or populations of target species then it will be crucial for NID features to meet the production hypothesis. Implementing NID options that provide hiding places and shelter could reduce mortality rates of fish and having structures suited to juvenile settlement should help to increase local populations.

3.2. NID Options

3.2.1. Biodiversity Enhancement Strategies

The Rich North Sea Project (Bureau Waardenburg, 2020) highlighted three broad biodiversity enhancement strategies for OWFs that can be applied to the UK. Implementing some or all of the following options will be required for successful biodiversity enhancement in OFWs:

Detect and protected biodiversity that is already present

These steps are considered to be compulsory. The likely outcome for biodiversity enhancement is moderate however, it will be over a large scale.

1. **Baseline survey:** Survey of the biodiversity present around natural (shells and gravel) and artificial (turbines, scour and cable protection) hard substrates at OWFs.
2. **Locate and conserve biodiversity hotspots**: Where baseline surveys have detected biodiversity hotpots such as biogenic reefs within the OWF, it will be important to implement protection measures. It is also useful to detect biodiversity hotspots in the surrounding areas as they can act as source populations for any added enhancement measures.

Introduce and restore natural reefs and reef building species

This is considered optional. The biodiversity outcome of this strategy is high and it can be achieved at an intermediate scale.

3. **Deploy natural substrates:** Add reef enhancing substrates, such as shells or gravel, to increase areas of settlement substrate for epibenthic species.
4. **Re-introduction of reef building species:** This will be achieved by introducing mature adults or small spat, along with substrate, for larval settlement. In the Irish Sea, the focus may be on blue mussels, honeycomb worm and ross worms. In the North Sea, and at locations around the UK, the reintroduction of native oyster reefs is being trialled (Kamermans et al., 2018; Robertson et al.,2021).

Construction of artificial reefs

This is also an optional strategy. These options can enhance the reef effects in OWFs through adding reef structures around turbines or optimising the scour protection. This will result in high levels of biodiversity of hard-substrate associated species at a smaller scale.

5. **Deploy artificial substrates on soft sediments:** Add artificial reef structures to the seabed. These will create settlement substrate for epibenthic species and habitat for hard substrate associated species such as Atlantic cod (*Gadus morhua*), Edible crab (*Cancer pagurus*) and European lobster (*Homarus gammarus*).
6. **Deploy artificial substrates at scour protection:** Add artificial reef structures on scour protection layers. Current scour protection measures can enhance biodiversity by providing settlement substrates and habitats for epibenthic and mobile species. Improving the design of scour protection can further enhance biodiversity by creating specific habitat requirements for target species. (See section 3.4.1 for details).

(Bureau Waardenburg, 2020**)**

When selecting the most appropriate strategy, the type of biodiversity within the focal OWF, and the scale and ambitions of the project must be considered. Where it is possible, implementing all three strategies will result in maximum biodiversity enhancing outcomes.

These steps reflect the mitigation hierarchy that is used in development and aims to achieve biodiversity net-gain. The sequential steps of the mitigation hierarchy focus first on avoiding and minimising any negative impacts of development on baseline biodiversity. Where development causes unavoidable loss or degradation of an ecosystem, rehabilitation or restoration may need to be carried out to produce positive net impacts to biodiversity. Only after these steps have been implemented would offsetting and compensation be considered.

Understanding the environmental conditions and biodiversity already present in the OWF is required before any goal or targets can be set. Therefore, options 1 and 2 should be carried out before setting project goals. In the early stages of a biodiversity enhancing project, it is necessary to highlight specific objectives for the OWF, for example determining which species to target and over what time scale. This information can be the basis for deciding which enhancement option to use. It will be important to ask:

- Which species are suited to enhancement? Will the focus be on one species or a community of species? What are the target species?
- Over what temporal and spatial scale is the project?
- What are the natural environmental conditions in the OWF?
- What substrate type will be used (i.e., artificial or natural)?
- What will the costs be? What is the project budget?

Once objectives are clear it will be possible to choose the most appropriate enhancement option (see Figure 2).

During the stakeholder workshop held to inform this research (see section 5.4), it was agreed that from the perspective of Natural England (NE) and TWT, using natural materials over synthetic materials, particularly plastics, is preferred. Therefore, options 3 and 4 may be favoured over options 5 and 6.

Moreover, it is worth noting that in the UK option 5 is unlikely to be viable. Unlike in the Dutch North Sea, in the UK there is coexistence between the fishing industry and OWFs. If developers introduced hard substrate structures on the seabed within an OWF there may be significant impacts on fishing activities- as such, option 5 would not be viable without further legislation or restrictions being implemented or significant consultation with the fishing industry.

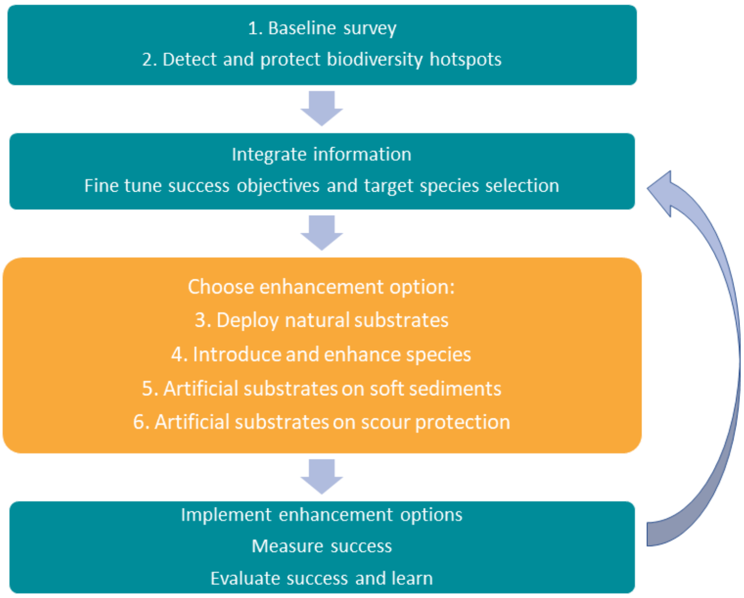


Figure 2 is adapted from Bureau Waardenburg, (2020). It shows a representation of the selection process of biodiversity enhancement options within OWFs. It shows a 'learning by doing' approach with consistent monitoring of biodiversity and the success of added structures.

3.3. Target Species and Habitat Selection

OWF structures have become an attachment site and feeding ground for a range of mobile and sessile species (Hiscock et al., 2002). We have chosen target species and habitats for this project based on their occurrence at hard substrate habitats in the Irish Sea, their policy relevance and commercial importance (see section 4.1 for more details on the process).

The following species have been considered further as they have been identified as relevant and in need of protection:

- Atlantic cod (*Gadus morhua*)
- Whiting (*Merlangius merlangus*)

The following species were identified as commercially important and have been considered further:

- Edible crab (*Cancer pagurus*)
- European lobster (*Homarus gammarus*)
- Haddock (*Melanogrammus aeglefinus*)

The following biogenic reef-forming species in the Irish Sea were identified:

- Blue mussels (*Mytilus edulis*)
- Honeycomb worm (*Saballeria alveolata*)
- Ross worm (*Saballeria spinulosa*)

Details can be found on the biological requirements (adult and juvenile habitat requirements, and diet) and locations (presence in Irish Sea and association with OWFs) of each target species in Annex A

3.4. Biodiversity Enhancement Options

Biodiversity enhancement can be achieved incorporating NID features into the OFW's scour or cable protection layers, they can be added onto the assets themselves or they can be in the form of standalone units which can be placed around the base of the foundations. Examples of each option are listed in table 1 and more detail on each can be found in sections 2.4.1-2.4.4 and Annex B.

Table 1 Adapted from Hermans et al., 2020. List of Nature Inclusive Design options for each proposed category

NID category	Specific NID measure
1. Optimised scour protection layer	Additional rock layer Adapted grading armour layer Seeded scour protection layer

2. Optimised cable protection layer	Filter Units (bags filled with rocks) Basalt bags ECO Mats® Reef cube® filter bag™ Reef cube® mattresses™ Prefab collar SCP
3. Standalone units i.e. artificial reefs	Habitat pipes Fish hotel (WUR) Reefball® and Layer cakes Reefcube® 3D printed units Rock patches ECO armour block® Biorock™ Oyster gabions Biohut® Seacult reef system SubCon artificial reefs Cotel
4. Add on units (integral part of the asset)	Biohut® Cotel

As previously mentioned (see Section 3.2.1), in the UK it is currently not feasible to add standalone units between turbines. Doing this may not be compatible with other sea users, would require additional licenses and permits, and would bring about issues with altering natural ecosystems from soft sediment to hard substrate. It is therefore more favourable to add NID options to the scour protection layers or integrated into the assets themselves, where reef effects are already taking place. Standalone units mentioned in Table 1 have the potential to be added around the turbine on top of scour protection layers, but proper testing would be required to assess the impacts on scour protection and to highlight any risks such as movement.

In the marine environment, hard substrates provide a range of ecological functions from settlement substrates and attachment surfaces to shelter and hiding spaces. Reef building organisms further add to the habitat complexity of hard substrate environments.

Scour protection layers in an OWF often add necessary hard substrate into a soft sediment environment from an engineering perspective. Optimising the design of scour protection layers has the potential to create new habitats that could lead to a diverse range of species settling, attaching and sheltering around the turbine and therefore improving biodiversity within the OWF. This new habitat creation could compensate for the loss of habitat caused during the OWF construction, however, it is not like-for-like. Newly created habitat on scour protection is likely to be very different to the original habitat that it has been situated upon. Careful planning and design are needed to ensure that this results in positive habitat creation (Wilson and Elliot, 2009).

Based on basic ecological principles, Lengkeek et al. (2017) proposed four design principles that can be considered eco-friendly designs of scour protection. These options could be incorporated into the design of a new OWF. These designs are relevant to the selected target species for the North Sea, however, they are also applicable to the potential target species in the Irish Sea.

1. **Adding larger structures** than conventional scour protection to create large scale habitat complexity. Creation of large holes and crevices which will provide habitat and shelter for large mobile species such as Atlantic cod and large crustaceans. Holes and crevices should be 1-2m in diameter.
2. **Adding smaller structures** than conventional scour protection to create small-scale habitat complexity. Creation of small holes and crevices which will provide habitat, shelter and attachment surfaces for egg, larvae and/or juvenile stages of species such as Atlantic cod. As well as creating habitat for smaller species. Holes and crevices should be just a few centimetres- decimetres.
3. **Providing or mimicking natural chemical substrate properties** to facilitate settlement of species that are known to seek chemical cues associated with their natural settlement substrate. E.g. shellfish that are more likely to settle on shell material. Using natural substrates over mimic substrate is preferable as many chemical cues are still unknown.
4. **Active introduction of specimens of target species** to enhance establishment of new populations. This is necessary in locations where there isn’t a natural population of reproducing adults. Active introduction of a small population of adults can facilitate recruitment to these locations.

For many, if not all, of the NID features using artificial substrates, it will be important to consider whether the technology is ready for deployment; has it been well studied, and is there evidence to show that the technology will work. These structures will also have small-scale effects limited to the unit itself and the surrounding area. It is therefore important to consider how much of the artificial substrate needs to be deployed in order to reach biodiversity enhancement goals. So far, artificial substrates have only been studied in small-scale pilot studies and it is not yet feasible to extrapolate the results to a larger scale.

In the UK, the following strategies for NID could be explored further (See Figures 2 and 3 for examples of each):

3.4.1. Strategy 1: Optimising Scour Protection Layers Using Natural Materials

The most common method of scour protection is placing rock layers on the seabed around the base of a turbine. This method is also commonly used to protect export and array cables. The scour protection layers can be made up of a filter layer (smaller graded rocks, added pre- foundation installation) and an armour layer (larger rocks/boulders, added post installation). It is also possible to use just one layer of rock pre-installation by using heavier rocks with wider gradation (GoBe Consultants Ltd, 2018). Optimising scour protection layers can be achieved by adding a third layer of rock with adjusted grading to a standard scour protection layer or by replacing the typical armour layer with an adapted grading armour layer. The grading requirements will be specific to the target species; however, the overall aim is to provide habitat niches for crab, lobster and juvenile cod. There has already been significant research into the optimum size of stone for creating habitat for shellfish (Halcrow Maritime et al., 2001). See Figures 3 and 4 for visual representations for NID options 1-24 below:

1. Boulders
2. Gravel

3. Loose shell material

Advantages:

- Uses natural materials.
- Can be easily integrated without having to change the existing work method.
- Will not interfere with fishing activities.
- Long lifespan as rocks do not degrade.
- Inexpensive.
- Increases habitat complexity, adds more holes and crevices.

Ecological considerations:

- Size and grades of additional rock layers should be specific to the requirements of target species.
- Seeding the material could increase success (e.g. at Gemini wind farm in the North Sea, scour protection was seeded with oysters to facilitate reef restoration (Sas et al., 2019)).
- Randomised patterns in the armour layer could have ecological benefits (Hermans et al 2020).
- Using rocks will alter existing habitats from soft sediment (sand and gravel sediments in most Round 4 sites) to hard substrate environments. Impacts to local ecosystem need to be understood.

Technical considerations:

- Need to understand the stability of added rocks.
- Rocks may limit access to the monopile for maintenance.

Risks/Conflicts:

- Larger rocks may have bigger loads.
- Uncertainty around whether rocks will damage the OWF assets.
- Rock armour may replace existing habitat which could mean this option is unfavourable.
- Scour may be removed during decommissioning, removing the habitat created for marine life.

3.4.2. Strategy 2: Standalone Units Incorporated into the Scour Protection

Units include both small and large structures that increase habitat complexity by providing holes and crevices:

4. Habitat pipes
5. Fish hotels (WUR)
6. Reefballs®
7. Reefcubes®
8. 3D printed reef units
9. ECO armour blocks®
10. Oyster gabions
11. Biohut®
12. Seacult reef system

_13._ SubCon artificial reefs
_14._ XBlocs, Dolos, Tetrapods and Concrete jacks
_15._ Biodegradable Ecosystem Engineering *(BESE) Elements*®
_16._ BESE-reef paste

Advantages:

- Shouldn't impact the structural integrity of the asset.
- Could lead to increases in biodiversity which may have appositive impact on other marine users such as fisheries.

Ecological considerations:

- Creation of more complex habitats can lead to increased biodiversity.
- Using optimised, eco-friendly materials can increase ecological success, without harming the environment.
- Mesh and hole sizes in the designs need to fit the requirements of target species.

Technical considerations:

- Must be able to ensure the stability of the units so they are not washed away.
- Knowledge of the local conditions is required to understand the best placements and shape, and material of the units.
- Use local materials where possible.
- It must be proven that units don't negatively impact the scour protection.
- Using units which interlock is advantageous as it increases stability.
- The closer the units are placed to the turbine foundations the higher the load is to the structure.
- Units need to be spaced away from the cables and wind farm assets to ensure easy access.

Risks/Conflicts:

- Using artificial materials (steel and concrete) can have potential negative impacts to the marine environment.
- May only result in small and local impacts which may not reach the scale required to meet conservation goals.
- Decommissioning requirements unclear at this stage.

3.4.3. Strategy 3: Optimising the Cable Protection Layer

Where cables cannot be buried and protection is needed, using optimised protection measures over the standard rock armour may be advantageous.

_17._ Filter units (rock filled bags) and basalt bags
_18._ BESE mesh bags
_19._ ECO Mats®, Reef cube® filter bag™ and,
_20._ Marine Matt®
_21._ Prefab collar SCP

Advantages:

- Can adapt already standardised cable protection measures.
- Rock filled bags mould to the shape of the seabed which creates stability.

Ecological considerations:

- Need to be species-specific adaptations.
- Need to use eco-friendly materials where possible (not concrete or plastic bags).

Technical considerations:

- Need to be able to access cables for maintenance.
- If maintenance work needs to be carried out, the units may need to be removed and replaced.

Risks/Conflicts:

- Need to be able to ensure the stability of units that are added to cables.
- Can the installation or potential movement of units damage the cables.
- Cable maintenance will require removing the layers from the cables.
- May interfere with fishing activities. E.g. could increase risk of snagging fishing gear.
- Decommissioning requirements unclear at this stage.

3.4.4. Strategy 4: Add-on Units

NID features can be added to the turbine foundations themselves.

11. *Biohut®*
22. *Cod hotel*
23. *Living SeaWalls*

Advantages:

- No additional installation is required

Ecological considerations:

- Must consider species specific designs.
- Mesh and hole sizes in the designs need to fit the requirements of target species.

Technical considerations:

- Asset must be able to withstand the added load of both the unit and marine growth.
- Unit must be able to withstand the pile driving force.
- Could add challenges during the transport of the foundations.

Risks/conflicts:

- Piling force during installation could damage the units.
- Risk to structural integrity of the foundation.
- Hydrodynamic load of the unit on the structure.
- Increased current velocity may not be tolerated by the target species.

- The scale of the structure limits any positive effects.
- Decommissioning requirements unclear at this stage.

3.4.5. Other NID Options

Other scour protection measures that use harmful materials (e.g. plastics) but have claimed to have biodiversity enhancing properties.

24. *Frond mats*

Figure 3 Visual representation of NID options 1 – 12. Strategy 1 (orange) and strategy 2 (light blue). Table of image sources can be found in Annex C.

Figure 4 Visual representation of NID options 13 – 24. Strategy 2 (light blue), strategy 3, (green), strategy 4 (dark blue) and other option (red). Table of image sources can be found in Annex C

3.5. Layout

The composition, arrangement and location of artificial reefs are important factors affecting the success of a reef (Lan et al., 2004). The design of an artificial reef includes the design of the artificial reef unit itself, an artificial reef community (a group of reef units) and an artificial reef ecosystem (multiple reef communities) (Lan et al., 2004). Greater complexity of the design (both the units themselves and the spatial complexity of the reef community) will increase the ecological effectiveness of a reef, with greater species diversity and biomass. A layout of artificial reef communities (LARCs) model produced by Lan et al. (2004) suggests that artificial reefs should be placed in a fractal pattern order to increase complexity and therefore increase diversity.

However, there are many considerations that go into deciding the layout of an OWF, most importantly the spacing which maximises energy capture. Other considerations include keeping the overall footprint of the OWF to a minimum to reduce stakeholder conflict, leasing costs and to optimise infrastructural requirements for example, cables (Linley et al., 2007). These factors have resulted in turbines generally being spaced at 500-1,000m apart on the axis of the prevailing wind. Despite it being recognised that these technical and operational challenges are very important for the OWF sector, it has been suggested that designing OWF layouts in a way that optimises biodiversity and fisheries benefits during the early stages of site planning and development, has the potential to be advantageous for all stakeholders. As the offshore wind sector becomes more established, there could be potential for such challenges to be considered, particularly where there is potential to benefit financially or reduce management time from dealing with fisheries conflicts (Linley et al., 2007).

4. Smart Monitoring at Offshore Wind Farms Literature Review

4.1. What is Smart Monitoring?

Our increasingly digitalised world is resulting in increased efficiency and productivity through smart systems. Smart systems are able to sense and operate in order to define a situation, then make decisions based on available data. These decisions are able to predict or adapt, which makes the actions smart. Smart monitoring systems can autonomously monitor an interconnected mesh of assets, adapting to data learned through individual contextual awareness and past outcomes.

4.2. Where Does Smart Monitoring Currently Exist Within Offshore Wind?

Smart monitoring systems are utilised throughout the offshore wind industry to assist with the operation and development of assets. Turbines are fitted with around 1000 sensors each. Sensors are used to monitor turbines include pressure transducers, temperature sensors, accelerometers and tachometers. These sensors are able to gather live measurements that allow the turbine to control itself. For example, wind speed and direction are measured; the turbine then responds to this dynamically, this response could include starting up, stopping or yawning. Live data is also used to shut turbines down if a sensor takes a reading that is out of permissible range for a specific component.

Machine learning is utilised in the offshore wind industry to predict faults on turbines before they occur. This is achieved by gathering and analysing data through complex algorithms, computers can then autonomously learn from the outputs and adapt in an agile manner. A further data analysis technique used at OWFs is outlier detection. This method of analysis identifies unusual events and outliers in order to improve the efficiency of predictive maintenance efforts (Dienst and Beseler, 2016).

Smart monitoring is widely utilised in the offshore wind industry, it is not commonly used in an ecological capacity. One instance where smart monitoring is used for conservation is through bird detection systems such as DTBird. DTBird is an automatic bird detection system that monitors birds in the turbine area. The system uses 360° daylight and thermal imaging cameras to track moving birds and estimate the distance to them based on the size of the detected bird species. The system is then able to take two independent actions to mitigate against bird collision risk: 1) activate warning sounds emitted from speakers on the turbine tower to deter birds; and/or 2) shut down the turbine completely (H. T. Harvey & Associates., 2018).

4.3. Monitoring Platforms

Research platforms, or met masts, are often installed prior to the construction of a windfarm to gather data on the local environment. FINO1, 2 & 3 are research platforms located within the North and Baltic Sea which were constructed on potential and active windfarm sites from 2002. The research platforms are able to transmit a huge amount of live data. More monitoring equipment is added to the platforms as required to gather data on key ecological areas of interest such as bird strikes, marine mammal presence and effects on benthic communities.

Some examples of existing monitoring occurring on monitoring platforms are listed below:

Meteorological

Platforms can be fitted with sensors that record a number of meteorological variables such as wind speed, wind direction, air temperature, atmospheric pressure, atmospheric humidity, atmospheric density, rainfall, total radiation, UV insolation, visibility and number of lightning strikes.

Hydrography

It is common for monitoring platforms to measure the local hydrographic conditions through sensors that are able to measure water level, current (speed and direction at various water depths), sea conditions (wave height, wavelength, wave period, wave direction), water layers, water temperature, oxygen content and salt content.

Bat Monitoring

Acoustic bat monitoring equipment is installed on the FINO1 platform to monitor the behaviour of bats within OWFs.

Underwater Noise

Hydrophones can be deployed at monitoring stations to monitor underwater noise. The FINO1 platform incorporates a hydrophone located 150m from its base, which monitors underwater noise. The monitoring is run as part of the Joint Environment Noise Monitoring Program North Sea (JOMOPANS) programme which aims to develop a framework for joint ambient noise monitoring in the North Sea.

Songbird Migration

The FINO1 platform houses a receiving station for various songbird species that are equipped with miniaturised radio telemetry transmitters as part of the BIRDMOVE project. These send a coded signal which is received by receiving stations that are positioned around the German coast. The BIRDMOVE project aims to help better understand individual bird migratory route reasoning, and the impact of the rapid growth of offshore wind development on individuals.

Bird Monitoring

Crucial data on bird interactions within OWFs can be gathered at monitoring platforms. Fixed beam radar, thermal imaging and high-resolution video cameras can be mounted to platforms to allow automatic monitoring of birds within the wind farm area. This kind of monitoring can help to better understand the cumulative effects of OWFs on migratory birds, which factors increase the risk of collision, and whether a predictive model could be developed for avoiding mass collision events.

4.4. Marine Monitoring Techniques Suitable for Offshore Wind

4.4.1. Active Acoustics – Imaging Sonar

Active acoustics generate a sound that is received as it returns from an object. Imaging sonars are able to provide high-resolution images in a range of sea states, with no need for artificial illumination (Copping, et al., 2020). There are many types of imaging sonar, and the correct outputs (frequency, field of view, functional range) must be chosen depending on the site requirements. Sonar has been installed on the underside of vessels to survey large areas. Other applications for imaging sonars include installing them on subsea platforms like the Flow, Water Column and Benthic Ecology (FLOWBEC)-4D platform. These platforms were installed at three locations within the UK, and were used to gather a range of data through many different means. During 2012, the system was deployed, with subsea sonar installed at the European Marine Energy Centre (EMEC) tidal test site to monitor fish and other marine life, and assess how they interact with tidal installations. The results were used to better understand how the local hydrodynamics influence the behaviour of marine predators and their prey (Bell, 2016).

4.4.1.1. Active Acoustics – Imaging Sonar – Issues and Barriers

The main challenges of active sonar monitoring in the marine environment are associated with long-term deployment. The deployments of imaging sonar over a long period of time can result in biofouling of the device's transducer. Biofouling does not always degrade the quality of imagery recorded by the device, instead, it is the risk of damage to important components that poses the highest risk for malfunction. To minimise biofouling, regular maintenance of the device is the best solution. For most marine renewable instillations long-term imaging sonar monitoring is not a practical solution due to the cost associated with regular maintenance, and the fact that the device is likely to be installed in a hard to access locations. Alternative low-maintenance biofouling mitigation methods are available, which include automated wipers, ultraviolet lights, antifouling paint and zinc oxide paint.

The response of marine mammals to the sound of the sonar pings must also be considered. Most marine mammal communication frequencies tend to be well below the frequencies of an imaging sonar ping. However, marine mammals can produce sound at lower frequencies and therefore it is possible that their behaviour may be affected (Cotter et al., 2017).

A further challenge is that multiple electrical instruments in one monitoring location can produce interference that would affect the outputs of imaging sonar.As such it is important to ensure systems are synchronised to stop active acoustic instruments from interfering with each other.

4.4.2. Active Acoustics – Echosounder

Echosounders have been used for decades to locate fish and to quantify their abundance for both fishing and monitoring purposes. Echosounders work by transmitting a sound pulse into the water and recording the reflected sound, in a similar way to imaging sonars. Echosounders can be installed on the underside of ships, ROV’s, moorings and static subsea platforms. The advantages of stationary deployment include the opportunity to generate long-term, detailed datasets in key areas that may change over a project’s lifespan.

4.4.2.1. Active Acoustics – Echosounders - Issues and Barriers

In particularly turbulent locations, issues with bubbles present in the water column are common. Air bubbles in water reflect sound energy emitted from echosounder transceivers due to a change in acoustic impedance of the water (Copping, et al., 2020). When there is a large scattering of air bubbles in the monitoring zone, the detection of biological and non-biological targets can be impeded. Offshore wind farms are not typically turbulent areas, however, the presence of tidal currents and wave action on the turbine tower could create air bubbles.

4.4.3. Passive Acoustics

Passive acoustic monitoring (PAM) involves surveying and monitoring wildlife and environments through the use of hydrophones (E. Jones, et al., 2021). These are deployed to record the sounds of echolocating clicks used by some marine mammals for navigational purposes. Technological advancements have led to PAM being much more accessible in recent years. PAM has been commonly used during the preliminary and construction stages of OWF projects to monitor marine mammal activity and minimise the impact on them. There are limited instances of permanent PAM devices installed at operational OWFs. This could be due to a lack of requirement for data on marine mammal behaviour around wind turbines. However, there is an abundance of PAM data around tidal stream turbines. There is a level of uncertainty between regulators and stakeholders about whether tidal stream turbines pose a risk to marine mammals (Copping, et al., 2020). Hence, the industry is gathering a vast amount of data to properly understand the environmental implications of tidal stream turbines. The techniques used to monitor marine mammals around tidal stream turbines using PAM over long periods of time can be easily adapted for use at OWFs. Likewise, the PAM monitoring of wind farms during construction could also be adapted to operate on a permanent basis during wind farm operation.

4.4.3.1. Passive Acoustics Issues and Barriers

One considerable challenge for PAM in the marine environment is the identification and mitigation of flow noise generated by tidal currents and pressure changes around the device. This creates interference and makes It more difficult to quantify the ambient sound levels and human-made noise, reducing the range for detecting echolocating marine mammals. To mitigate flow noise arrays of PAM devices can be installed. As flow noise is usually generated locally on each device, the true sound observed will be present across the array.

PAM devices must have memory capacities large enough to store the vast amount of data that is gathered whilst the device is in operation – and permanent device installations will collect extremely large amounts of data. However, it is also possible to export data in real-time from marine hydrophone installations to terrestrial-based storage system through the existing turbine export cable. A tidal turbine in the MayGen array located in Scotland deployed a 12-hydrophone PAM system mounted on its foundations. The PAM system was connected to the turbines' power and data export infrastructure meaning that data could be processed in real-time (Copping, et al., 2020). The system was in operation for two years, starting in October 2017 and collected 1Tb of raw data per day.

4.4.4. Underwater Video Cameras

Video cameras (VCs) can be used to monitor, identify and determine the size of marine species. These data could be extremely useful to monitor the effects of NID implementation at OWFs and to document species interactions with man-made structures. Remote-controlled VC's can be installed to assist with collecting useful data. Wide-angled field-of-view cameras are best suited to installations at OWFs where the camera is mounted onto the structure, in order to capture the largest viewing region. The correct choice of lens for the site specifications is an important factor to consider. For close species, detection a wide-angled lens should be used, and for longer range detection, a fixed zoom lens can be used (Copping, et al., 2020).

There are various commercial off-the-shelf VC systems specifically designed for research, the majority of which are tailored for remotely operated vehicle (ROV) deployments. These camera systems could be easily adapted for use at mounted positions within OWFs. There are a range of other camera types to choose from for marine monitoring applications; the most inexpensive camera types are high definition, mass-produced action cameras (e.g. GoPro©). These cameras are improving the accessibility for marine VC monitoring schemes because of their affordability, small size and durability (Bicknell et al., 2016). However, action cameras are most suited to clear, well-lit marine environments, which are not common traits of the Irish Sea. More expensive, commercial VC setups consist of 4K ultra-high-definition cameras in high-pressure rated waterproof housings made from titanium, acrylic or aluminium. These types of cameras can record in monochrome, which is best suited to low-light conditions. There are also cameras available that are able to shift from colour to low light settings depending on the conditions they are operating within.

Stereo-VC systems are able to determine the size and swimming speed of fish by setting up two cameras adjacent to each other at a known distance. When fish move through both of the camera's views, their size can then be calculated (Harvey et al., 2002). An alternative method of measuring marine species through VC systems is to use a combination of a camera and two parallel-mounted lasers. The lasers are fixed at a known distance and shine onto target objects in the cameras field of view. This allows objects to be scaled on the basis of the laser separation distance during video analysis. This method is limited to gaining measured values only during times where the lasers are shining on the target, whereas stereo-VC systems can measure multiple targets in one frame (Copping, et al., 2020).

4.4.4.1. Underwater Video Camera Issues and Barriers

One of the main challenges associated with VC monitoring systems is the large data files that are created. Long-term VC monitoring schemes will require sufficient storage space for large video files. It is also difficult to transmit and analyse the large files created through VC monitoring. There are approaches used in industry to reduce the size of the video files and make the data more manageable. VC systems can be installed in combination with active acoustic instruments that trigger VC operation when an object of interest is detected in the monitoring area. Further to this, a circular buffer can also be added to the system that allows video data to be captured and stored for a short cycle and deleted if there is no trigger from the active acoustics. If a trigger is implemented, the VC keeps recording and the data is stored. This method drastically reduces the amount of data stored as the VC is only operational during moments of significance, rather than recording continuously. This also streamlines data analysis by eliminating the need to search for points of interest in the data set and making file sizes more manageable.

Due to variables in the depth of VC installation and water clarity, lighting systems are often required to improve image quality during monitoring. Light-emitting diodes (LEDs) are most commonly used in conjunction with VC monitoring systems as they have a long lifespan, low operating temperature and have a broad light spectrum. It is important to use a light source that will not affect species behaviour, thus altering the monitoring results. Infrared (IR) lights can be useful as they operate at wavelengths longer than 800 nm, which is outside the spectral range for many fish, however, it is only effective in up to around 1.5m in water. Lighting systems require a lot of power to operate, this can be an issue at remote monitoring locations. For long-term deployments, battery systems are not practical due to maintenance requirements, therefore the system would have to be connected to the turbine's power system, which is difficult and expensive to do retrospectively.

4.5. Machine Learning and Artificial Intelligence

Machine learning and artificial intelligence (AI) are now integral to most everyday services that we take for granted. In the marine space, machine learning has been common practice in the oil and gas industry for years, from predictive maintenance models to deep-sea oil seep detection robots (Sircar et al., 2021). AI is also used within offshore wind operations for things such as predictive maintenance and weather forecasting. AI is also now beginning to be utilised by the offshore wind industry for conservation means, mainly through bird detection and marine acoustic monitoring projects. The emerging interest in how AI can simplify ecological monitoring is leading to advancements that could be utilised by the rapidly growing offshore wind industry.

Automatic species recognition is a feature that would be extremely useful for monitoring species in the marine environment. Automatic bird and bat recognition systems are starting to be utilised in offshore wind, however, automatic recognition of other marine life is not. This could be due to one of the main perceived negative connotations of offshore wind being their interactions with birds, and therefore the high importance and need for data relating to this. In comparison, there is a relatively low requirement for data on turbine interactions with fish and other marine species. Nevertheless, algorithms that can automatically detect species of fish, marine mammals and benthic creatures through VC systems do exist. There are various open-source variants of automatic fish recognition software that perform well and could be deployed in various locations including on offshore wind infrastructure (Blowers et al., 2020).

Automated detection and recognition of vocalising marine mammals through PAM systems is another area where AI could improve monitoring at OWFs. PAMGuard is an open-source software package that automates the processing of marine mammal acoustic data. PAMGuard is used commonly in the offshore wind industry and is supported partly by SMart Wind. PAM is frequently used in the construction stage of wind farm projects to manage and monitor the effects of piling noise levels on marine mammals. The introduction of software packages such as PAMGuard make analysing PAM data much more manageable in long term deployments by only saving data when a vocalisation is detected. This simplifies the analysis of PAM data and makes long term and permanent PAM deployments much more accessible.

5. Methodology

5.1. Identifying Target Species

An initial long list of policy relevant species and biogenic habitats occurring in the Irish Sea was drawn together (see Annex A). Species and habitats included those under protection from The Conservation of Habitats and Species (Amendment) (EU Exit) Regulations 2019, Biodiversity Action Plan Priority species and habitats, IUCN Red List species and OSPAR List of Threatened and/or declining species and habitats. For selected benthic species, it was noted whether they were classified as ‘important to society’ based on the ecosystem functions they play (information supplied from OneBenthic).

Table 2 Commercially important target species

Species group	Crustacean	Crustacean	Bony fish
Scientific name	***Cancer pagurus***	***Homarus gammarus***	***Melanogrammus aeglefinus***
Common name	**Edible crab**	**European lobster**	**Haddock**
OSPAR species/ habitat	N	N	N
BAP species /habitat	N	N	N
IUCN red list	Not evaluated	Least concern	Vulnerable
Protected / Conservation feature	N	N	N
Commercially important	Y	Y	Y
Present in Round 4	Y		Y
Spawning ground in Irish Sea			N
Nursery ground in Irish Sea			Y
Large hard structure	Y	Y	
Gravel beds			Y
Primary function of the substrate	Hiding spaces and shelter	Hiding spaces and shelter	
Benthic species important to society	N	Y	N

Table 3 Policy relevant target species

Species group	Bony fish	Bony fish
Scientific name	***Gadus morhua***	***Merlangius merlangus***
Common name	**Atlantic cod**	**Whiting**
OSPAR species/habitat	Y	N
BAP species/habitat	Y	Y
IUCN red list	Vulnerable	Least Concern
Protected /Conservation feature	N	N
Commercially important	Y	Y
Present in Round 4	Y	Y
Spawning ground in Irish Sea	Y	Y
Nursery ground in Irish Sea	Y	Y
Large hard structure	Y	
Gravel beds	Y	
Primary function of the substrate	Nursery ground	
Benthic species important to society	N	Y

Table 4 Biogenic reef forming species

Species group	Polychaeta	Polychaeta	Mollusc
Scientific name	**Sabellaria spinulosa**	**Sabellaria alveolata**	**Mytilus edulis**
Common name	**Ross worm**	**Honeycomb worm**	**Blue mussel**
OSPAR species/ habitat	Y	N	Y
BAP species /habitat	Y	Y	Y
IUCN red list	Not evaluated	Not evaluated	Not evaluated
Protected / Conservation feature	Habitat of principle importance	Habitat of principle importance	Habitat of principle importance
Commercially important	N	N	
Present in Round 4			
Spawning ground in Irish Sea			
Nursery ground in Irish Sea			
Large hard structure	Y	Y	Y
Gravel beds	Y		Y
Primary function of the substrate	Attachment	Attachment	Attachment
Benthic species important to society	N	N	N

Information on habitat requirements and the function of hard substrate to the species (nursery, attachment surface, foraging, reproduction, hiding space, shelter, etc.) was then provided. Along with their known presence in Round 4 sites and whether important spawning or nursery grounds for each species were within the Irish Sea (Aires et al., 2014; Coull et al., 1998; Ellis et al., 2012) The following policy relevant species were considered but are not the focus of the project for the following reasons:

- European spiny lobster (*Palinurus elephas*) - while these may not occur in the Irish Sea, principally this could be a good species to consider for other areas (commercial species, priority species, vulnerable species and it uses rocks and crevices etc.)
- Native/Flat oysters (*Ostrea edulis*) – In the Irish Sea there is evidence of historic, vast subtidal oyster beds (Olsen, 1883) that were self-sustaining. Today, just a fraction of historic native oyster beds remains in the UK (Helmer et al., 2019). In the Irish Sea, active reintroduction, management and large-scale habitat restoration efforts would be required, as well as closing areas to fishing, this would be incredibly challenging. Creating settlement substrate through NID in OWFs alone is unlikely to be enough to bring them back. There is a lot of work currently happening on the restoration of native oysters in the UK through the Native Oyster Network. The correct conditions and requirements need to be fully understood before OWFs can be used as sites for native oyster reef restoration projects (see Robertson et al., 2021).
- Species that are policy relevant but pelagic species, even if they use hard substrate for egg laying or foraging. Designing structures specifically for these species would be challenging. It would be more beneficial to conserve their current spawning grounds that trying to recreate new ones (pers. comms- Browning, L.- NE).

5.2. Desk Based Review of Challenges to NID Implementation in the UK

A desk-based review was carried out to outline the potential benefits of NID implementation in the UK, highlighting the challenges and opportunities faced by partner organisations. An in-depth review of literature has been undertaken to give an overview of the different NID options currently on the market. The review also considers existing NID projects outside of the UK and their ecological impacts. A second review of literature was compiled to outline the potential for smart ecological monitoring at OWFs, giving an overview of the current and future smart monitoring potential at OWF sites.

5.3. Partner Discussions

Working closely with each of the four partner organisations (The Crown Estate, The Wildlife Trusts, Ørsted and Natural England) has enabled discussions with a variety of specialists. The purpose of the partner discussions was to explore each partners own views on the challenges to NID implementation. By speaking to individuals from a range of teams within partner organisations, a comprehensive inventory of the challenges, caveats and perceived opportunities were compiled.

5.4. Partner Workshop

A collaborative partner workshop was held on 28 September 2021, with over 20 representatives from Ørsted, Natural England, The Crown Estate, and The Wildlife Trusts. The main objectives of the workshop were to:

1. Provide partner organisations with an overview of the potential NID options available;
2. Highlight each partner organisations' views on the challenges to implementing NID in the UK;
3. Facilitate discussions between partners to understand different stances on NID deployment;
4. Discuss potential solutions to the challenges faced by partner organisations and the steps required to make NID more common within UK OWFs.

The workshop was composed of three main sections, the first was a brief presentation giving an overview of NID at offshore wind farms. The second section involved breakout groups discussing a number of prepared scenarios including:

- Artificial reefs within an OWF;
- Co-location of a biogenic reef, MCZ and an OWF;
- Retrofitting smart acoustic monitoring devices within an OWF;
- Retrofitting reef enhancing NID features to an existing OWF;
- Enhancing biofouling communities on the monopile structure;
- Scour protection enhancement methods.

The third section of the workshop involved an interactive task, where attendees could plan and discuss a NID pilot project within UK waters. Following this, the break-out groups were brought back into a plenary session where the outcome of the task was discussed.

6. Site Suitability

Following the initial preparatory stages of NID implementation, the most appropriate NID option must be chosen based on a range of factors. These include target species, licencing, cost, wider environmental impact, and conflict with other marine stakeholders. However, local, abiotic and biotic environmental conditions within an OWF can dictate the available NID options suitable for deployment.

Following a baseline survey of a site, the presence of biodiversity hotspots can be mapped. Knowing the location and presence of any existing biodiversity hotspots will give an insight into the suitability of an area for other species in terms of abiotic factors, larval distribution, recruitment options, predation and competition. The presence of a natural rocky reef or shipwrecks in close proximity to the OWF will increase the success of creating a reef within the OWF. If the area is deemed suitable for reef creation or biodiversity enhancement, then protecting what is already there will also be crucial. If the area is not found to be suitable then the enhancement options in Table 1 will need to be considered to provide suitable habitat or settlement for target species.

Table 5 Details of site requirements for biodiversity enhancing options

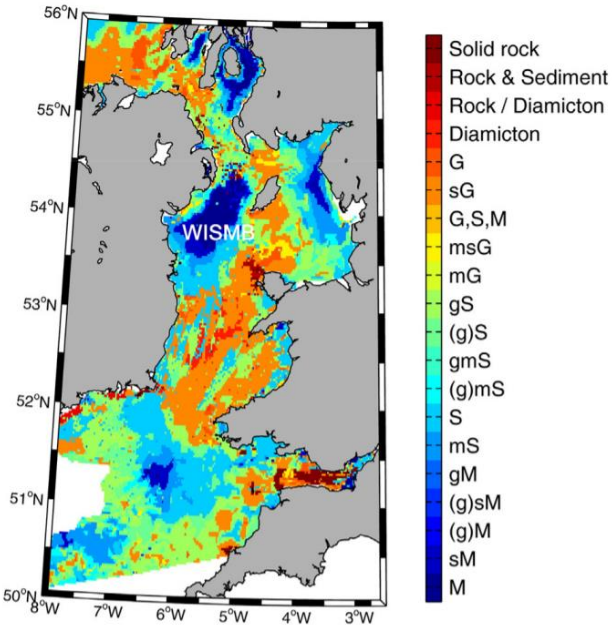
NID option	***Environmental requirements***
Deploy natural substrates	Only suitable in sites with low currents and where the seabed is not too dynamic, to ensure substrate stays in place and does not become buried. Deploying natural substrates where the site conditions are suitable but substrate is lacking should facilitate the settlement of target species. Requires a nearby source population or an influx of larva on the currents to be effective.
Re-introduction of reef building species	Where the larva of target species cannot naturally reach the site then the species can be introduced. There are many species-specific factors to consider when introducing a species e.g., timing, age of specimens, predation risk, the amount of source material etc.
Deploy artificial substrates on soft sediments	Each artificial substrate has its own requirements but generally they need conditions without strong currents or high sedimentation rates. It is also important to consider any erosion that could occur around the structure or the development of sand waves.
Deploy artificial substrates at scour protection	The requirements for the above option are also relevant here. The hydrodynamic performance of the artificial substrates on the scour protection must be tested. Placing structures on the outer edges of the scour protection will be the most beneficial as the currents can be too strong closer to the monopile (Lengkeek et al 2017).

6.1. Abiotic Conditions

6.1.1. Substrate Type

The substrate type and sediment composition within a site directly affects the likelihood of biogenic reef formation and recruitment. Having a presence of shells and a relatively large sediment size on the seabed are important facilitators for biogenic reef formation. If the site does not contain these characteristics, i.e. sites with smooth sand or mud seabed complexions, a relatively inexpensive NID method is to deploy shell, gravel or rocks at optimum locations within the OWF to provide hard substrate for reef building species to colonise (Bureau Waardenburg, 2020).

The Irish Sea is composed of a variety of sea floor sediment types (Figure 5). The sediment type for round 4 and existing OWF sites in the Irish Sea range from mud to sand to gravel. The sediment composition within current and planned OWFs is largely not suitable for recruitment of biogenic reef forming species. For these species to become established within the windfarms, substrate must be added to provide larvae with objects to latch onto and grow.



M	Mud
sM	Sandy mud
(g)M	Slightly gravelly mud
(g)sM	Slightly gravelly sandy mud
gM	Gravelly mud
S	Sand
mS	Muddy sand
(g)S	Slightly gravelly sand
(g)mS	Slightly gravelly muddy sand
gmS	Gravelly muddy sand
gS	Gravelly sand
G	Gravel
mG	Muddy gravel
msG	Muddy sandy gravel
sG	Sandy gravel

Figure 5 Map of the seabed sediment in the Irish Sea (Ward et al., 2015) and classification of sediment (derived from Folk, 1954) (Bayliss-Brown, 2012)

6.1.2. Seabed Shear Stress

The semi-diurnal tides within the Irish Sea are the dominant physical process contributing to seabed shear stress. Tidal waves propagate into the Irish Sea from the Atlantic Ocean through the North Channel and the St. George's Channel. As the two tidal waves enter the Irish Sea, they pass through narrow passages and around headlands, resulting in high tidal currents and resultant seafloor shear stress. The two tidal waves meet south-west of the Isle of Man and to the east of the Isle of Man, forming a standing wave. As a consequence of this standing wave, these areas have a very weak tidal current and thus a low seabed shear stress. The lack of shear stresses in these areas has resulted in sediment preservation and existence of the western and eastern Irish Sea mud belts (Howarth, 2005).

The successful deployment of NID options depends on the mobility of the seabed within an OWF. If the seabed is highly mobile, the NID features could move over time, or become buried in sediment. For successful NID deployment on the seabed, a site must have intermediate bottom shear stress and current speed, with a low sedimentation rate and sand/gravel wave movement (Bureau Waardenburg, 2020).

It can be seen in Figure 6 that Round 4 and existing OWFs in the northern Irish Sea are placed in areas of relatively low seabed shear stress. The seabed shear stress predicted to occur 90% of the time, modelled by Williams et al., (2019) is ≤ 1.0 Nm^{-2} in all cases. Where the seabed shear stress is < $0.4Nm^{-2}$, there is a risk of small NID features being covered by sediment. In some cases, the seabed shear stress within a site is between 0.4 and 0.6 Nm^{-2}. These conditions are described as intermediate levels of seabed shear stress by Bureau Waardenburg (2020) and the conditions are therefore favourable for deploying small NID options on the seabed, such as biogenic reef promoting shells. However, the maximum shear stress modelled by Ward et al., 2015 has been shown to reach up to 5.0 Nm^{-2} as seen in Annex D, therefore morpho-dynamic modelling at each site would be required to better understand the local seabed conditions and whether they are suitable for NID deployment.

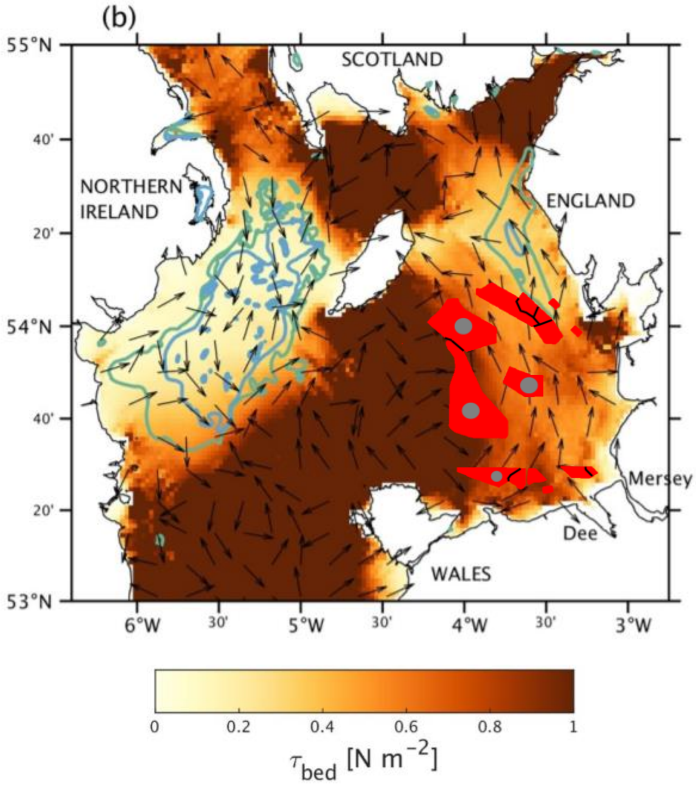


Figure 6 The calculated 90% exceedance seabed shear stress of the Irish Sea, including polygons of existing (red) and round 4 (red with grey circle) wind farm locations (adapted from Williams et al., 2019)

6.1.3. Seabed Mobility

Some areas of seabed are mobile, high/moderate energy due to wave and current action. For sediment transport to occur, the shear stress created by currents and waves must exceed the resisting forces holding the seabed sediment in place (J. White, et al., 2018). Placing structures on the seabed disturbs the natural hydrodynamics, which can result in sediment transportation close to the object. Resultant phenomena include scour or sedimentation around the structure. The rate and extent of these phenomena depends on the seabed shear stress and substrate type (J. White, et al., 2018). In terms of NID, scour and sedimentation could lead to object undermining, instability or burial.

The map shown in Figure 7, created using British Geological Survey (BGS) regional reports, considers the bedform type within the Irish Sea and outlines the typical characteristics of each. This map gives a general indication of the mobility levels for areas in the Irish Sea. In practice, model scale experiments, field data and localised numerical models should be used to develop more accurate predictions of seabed mobility and resultant scour and sedimentation.

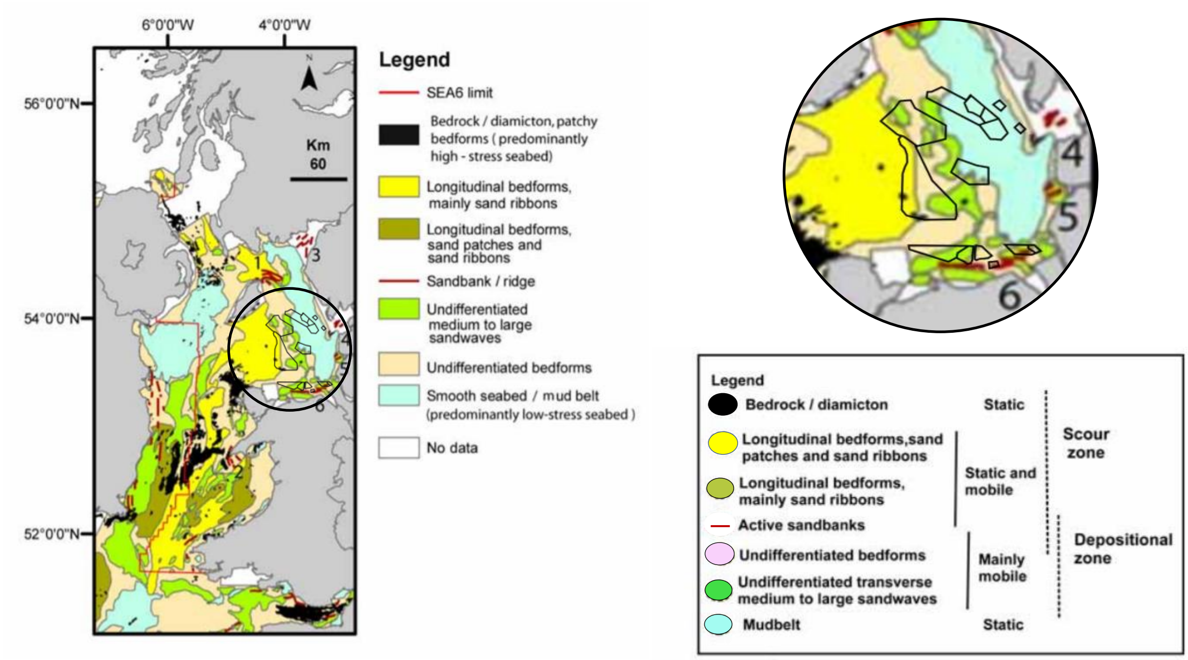


Figure 7 Distribution patterns of mobile bedforms in the Irish Sea with wind farm locations overlaid and schematic explaining the relationship between bedform type and mobility (Holmes and Tappin, 2005)

6.1.4. Suspended Particulate Matter

It is important to consider the Suspended Particulate Matter (SPM) levels in the Irish Sea when considering the installation of biogenic reef promoting structures. The SPM concentration in the water column dictates the penetration depth of light, which influences the production of plankton. As all three reef building target species in this study (*Mytilus edulis, Sabellaria alveolate,* and *Sabellaria spinulosa*) are filter feeders who primarily feed on plankton, the SPM levels are significant to their successful establishment.

Average SPM levels at wind farm locations within the Irish Sea range from 1-2 mg^{-1} for the Isle of Man and Awel y Mor sites to 20 mg^{-1} within Bubo Bank and extension (Figure 8). These SPM concentrations are within the boundaries for successful biogenic reef formation. Bureau Waardenburg (2020) states that higher SPM concentrations of >50mg/l are detrimental for filter feeders due to the low content of phytoplankton and high levels of particles ingested by individuals.

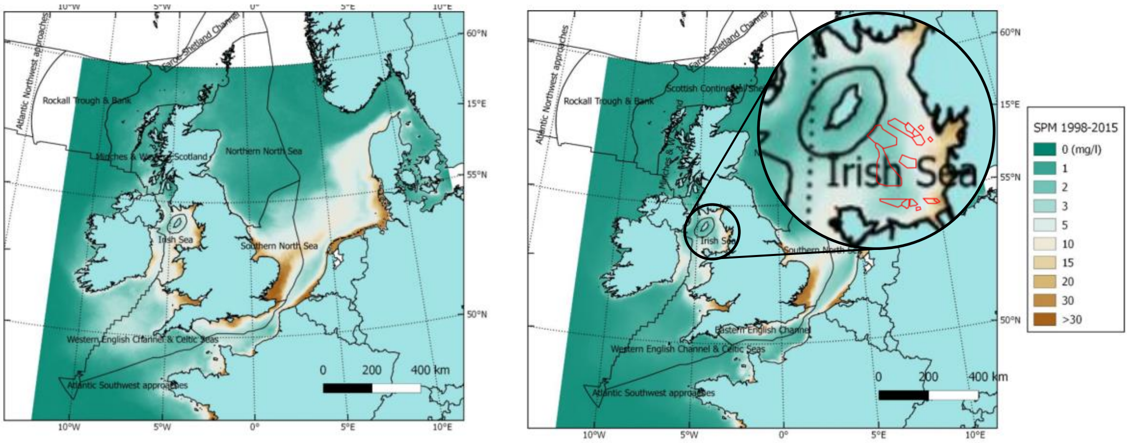


Figure 8 Maximum (left) and average (right) Suspended Particulate Matter (SPM) for the northwest European continental shelf with wind farm locations in red, during the period of 1998-2015 (adapted from CEEFAS, 2015)

6.1.5. Abiotic Conditions Summary

The site conditions outlined in Table 1 can be used to determine the most effective NID options, however, a number of other factors must also be considered. Table 6 presented below is only a rough guide to the local conditions within each OWF.

Table 6 The approximate characteristics of 13 planned and operational OWFs in the Irish Sea

OWF Name	Project Phase	Substrate Type	Avg SPM	Shear Stress 90% Exceedance	Seabed Mobility
Walney 1&2	Operational	Mud	4.5	0.3	Static, mud belt
Walney Extension	Operational	Mud	3.5	0.4	Static, mud belt - mainly mobile in NW
West of Duddon Sands	Operational	Clayey silt to silty sand	5.0	0.5	Static, mud belt
Barrow	Operational	Medium to fine sand	9.0	0.5	Static, mud belt
Burbo Bank & Extension	Operational	Sand, sandy mud and muddy sand	20.0	0.6	Mainly mobile, medium to large sand waves and active sandbanks
Isle of Man	Round 4	Gravely sand, slightly gravely sand, sand	1.0	0.5	Mainly mobile, undifferentiated bedforms
Morgan	Round 4	Gravely sand, slightly gravely sand, sand, sandy gravel	2.0	0.8	Mainly mobile, medium to large sand waves and undifferentiated bedforms
Morecambe	Round 4	Sand to muddy sand	4.5	0.5	Static, mud belt - potentially sand waves to the S
Mona	Round 4	Gravely sand, sandy gravel, gravely muddy sand	2.5	1.0	Static and mobile, sand patches - medium to large sand waves to SE - undifferentiated bedforms
Awel y Mor	Round 4	Gravely sand, slightly gravely sand	2.0	1.0	Mainly mobile, medium to large sand waves - undifferentiated bedforms to the W

6.2. Biotic Conditions

6.2.1. Food Concentrations

Phytoplankton are the primary producers of the oceans, and are their abundance is key to successful biogenic reef formation. As phytoplankton are plants, they contain chlorophyll a, this can be measured to give a proxy for phytoplankton biomass.

The variations in depth, tidal currents and surface water run-off influences the timing and production phytoplankton in the Irish Sea. Spring bloom in inshore waters such as Morecambe Bay can result in chlorophyll concentrations of over 50 $\mu g l^{-1}$, whilst offshore waters tend not to exceed 15 ugl^{-1} (Kennington et al, 2005). The 90th percentile chlorophyll levels in the Irish Sea during the period of 2006 – 2014 range from 3 $\mu g l^{-1}$ in offshore regions, to 7 ugl^{-1} in coastal regions (Painting, et al, 2018). The current OWFs in the Irish Sea are relatively close to the shore and experience relatively high phytoplankton levels. The Round 4 site proposals are in deeper water where phytoplankton concentrations are slightly less, although concentrations are still within suitable levels for filter feeders to inhabit successfully. The water depth, salinity, and temperature affect the abundance of phytoplankton, so local models should be considered when undertaking biogenic reef promoting activities.

6.2.2. Larvae Dispersion and Retention

For biogenic reefs to form, the availability of larvae is crucial. In the eastern Irish Sea, there are a range of tidal processes that influence larvae dispersion. Liverpool Bay is a shallow region with a high tidal range and an offshore flow. Morecambe Bay is also very shallow with a high tidal range, which creates significant tidal currents (Phelps, 2015). The dispersion of the reef forming larvae targeted in this study have the potential to reach all OWF locations within the Irish Sea. Blue mussels, Honeycomb worm and Ross worm have 1-1.5, 1-6, and 1-2 month long larval phases respectively, therefore it is very likely that these species' larvae will reach Irish Sea OWFs from their established, mainly coastal communities.

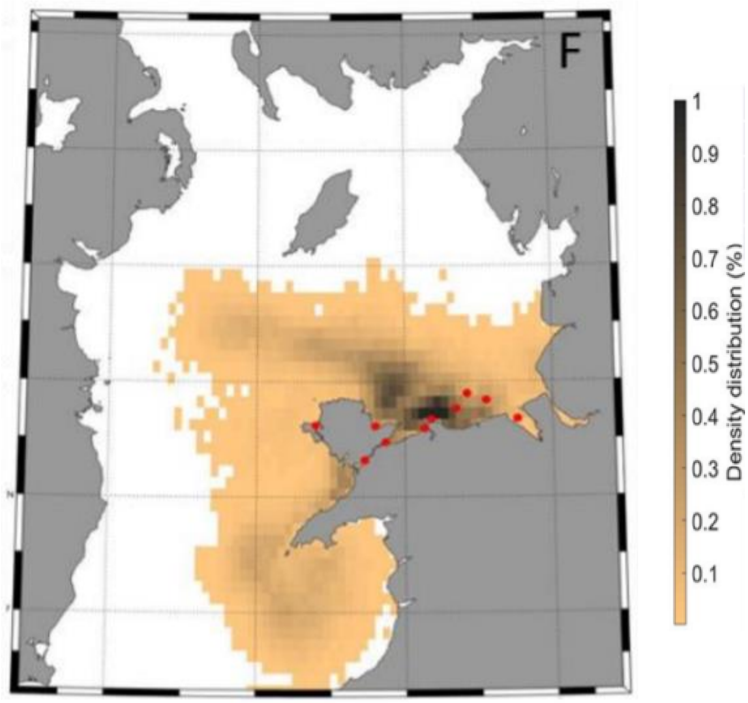


Figure 9 Map showing the modelled density distribution of mussel larvae released March - April 2018 from 10 locations in North Wales (red points) after six weeks (Demmer, 2020)

The retention of larvae within OWFs depends on the tidal current speeds and local hydrodynamics. A numerical model, like the one shown in Figure 9, of the site conditions would be required to dictate the level of larvae retention, and whether it is enough to sustain a healthy biogenic reef.

7. NID Challenges

The following challenges to implementing NID in the Irish Sea were highlighted through discussions with the partner organisation and the stakeholder workshop.

7.1. Retrofitting NID Features

Retrofitting NID features within existing OWFs is expensive due to the logistics required to transport, deploy and maintain features in challenging conditions in UK seas. Although more expensive than installing during the construction phase of an OWF project, developers such as Ørsted do not see retrofitting costs as an insurmountable challenge and will assess future NID options on a case-by-case basis. Due to the growing pressure to protect biodiversity at significant infrastructure projects in terrestrial and marine environments, Ørsted has committed to a net positive biodiversity impact by 2030 for new projects (similar commitments have also been made by a number of other developers). Whilst this commitment is focussed on new projects, it strengthens the possibility of cost implications being accepted for existing OWFs and will contribute to national marine Net Gain targets once they have been announced.

7.1.1. Cost Estimation

Installing NID features on existing turbines can become expensive due to uncertainties in deployment methods, risk and large costs associated with chartering vessels capable of undertaking the work and carrying materials.

In order to install items on the scour protection layer such as Biohuts or optimised rock armour, the materials or units must be acquired, transported to a vessel, then to the OWF site, and finally deposited on the existing scour protection.

The following cost estimation (Table 7) was completed for the installation of optimised scour protection and for the installation of add-on options on the existing scour protection.

Methodologies and assumptions used when estimating costs can be found in Annex E.

Table 7 Cost estimation for retrofitting NID scour protection and add-on items on 6no turbines

Item	Description	Quant	Unit	Rate (£)	Total (£)
	Scour protection optimisation				
	Rock armour engineering design	1	Design	10,000 - 30,000	10,000 - 30,000
	Rock armour	150	m^3	2,000 - 4,000	300,000 - 600,000
	Rock delivery	20	Wagons	100	2,000
	Rock storage	5	Days	100	500
	Identify optimum rock locations	5	Days	500	2,500
	Mobilisation	2	Days	60,000 - 120,000	120,000 - 240,000
	Offshore work to deploy rock armour	6	Days	60,000 - 120,000	360,000 - 720,000
	Weather downtime whilst offshore	2	Days	60,000 - 120,000	120,000 - 240,000
	Demobilisation	1	Days	60,000 - 120,000	60,000 - 120,000
Total (£)					**975,000 - 1,955,000**
	Add-on option installation				
	Purchase stock add-on items	12	Units	420 - 860	5,040 - 10,320
	Add-on item delivery	1	Deliveries	100	100
	Engineering design for fixing to turbine	1	Design	20,000 - 50,000	20,000 - 50,000
	Mobilisation	2	Days	60,000 - 80,000	120,000 - 160,000
	Offshore work to crane units into position	6	Days	60,000 - 80,000	360,000 - 480,000
	Weather downtime whilst offshore	2	Days	60,000 - 80,000	120,000 - 160,000
	Demobilisation	1	Days	60,000 - 80,000	60,000 - 80,000
Total (£)					**685,140 - 940,420**

It is important to note that the lower estimates in Table 7 is more appropriate for operations that require smaller vessels due to smaller size or quantity of materials. However, the upper and lower bounds of vessel day rates and engineering designs have been included to allow estimations for projects of larger scale which may require larger vessels to carry more materials. Deploying add on options would require a smaller vessel due to less material being transported, hence a lower cost for offshore work.

7.2. Lack of Legislative Guidance for NID in the UK

During the research stage of this project, various interviews and workshops were undertaken with project partners. The views of other OWF developers were not considered, however, it was clear that Ørsted are committed to minimising their environmental and ecological impact throughout OWF development and operation. To achieve net-positive biodiversity status, Ørsted have already commissioned NID pilot installations within some of their OWFs investing in artificial reefs created from concrete pipes at Borssele 1 & 2 OWFs located in the Netherlands. The initiative is designed to support Atlantic cod stocks, which were once found in great abundance in the North Sea. Although, their populations have subsequently suffered significant declines, they are still of great commercial importance and initiatives such as this could support their recovery. Further biodiversity enhancing deployments include creating artificial reefs within the Dutch OWF, Anholt. The reefs were created with boulders cleared from the site to allow for development of wind farm assets.

The UK is the world’s largest offshore wind market, however, NID is not installed at any UK OWFs. Other European countries that border the North Sea are leading the way in terms of enhancing biodiversity at OWFs. A significant reason for the UK’s minimal involvement in NID is due to the lack of legislative guidance for NID installation at OWFs in the UK. Observing the Dutch NID model, it is apparent that clear government legislation is a great catalyst for improving the uptake of OWF NID installations. In 2020, the Dutch Ministry of

Agriculture, Nature and Food Quality published a catalogue outlining successfully trialled NID options for offshore wind infrastructure that are deemed ecologically successful and practically applicable. The Dutch Government has also made it mandatory for OWF developers to undertake measures that increase the suitable habitat for species naturally occurring in the North Sea (Witteveen Bos, 2020). This clear legislation, accompanied by well-structured guidance is helping support developers to increase biodiversity within their OFWs.

On 14 June 2021, the UK Government announced it would legislate mandatory biodiversity Net Gain standards for nationally significant infrastructure projects (UKGOVc). The legislation includes the creation of a biodiversity metric which allows the user to measure the biodiversity value of an area, and the potential biodiversity gains following a project's completion. There is significant interest from Ørsted to use NID as a tool for achieving biodiversity Net Gain status at OWFs in the UK. However, the UK's current Net Gain legislation and metric only applies to terrestrial and intertidal zones. Defra have suggested that an approach for marine Net Gain is currently under development. Marine Net Gain legislation and metrics would likely provide some incentive and guidance for developers to implement NID options at OWFs in the UK. However, for NID to be applied in the UK key risk areas should be identified, and national marine biodiversity goals should be set.

7.3. Access to Assets

The primary function of a windfarm is to generate electricity and almost all OWFs in the UK are considered to be Nationally Significant Infrastructure Projects (NSIPs). Any biodiversity enhancements incorporated within the OWF site must not interfere with this primary function. If permission was given to deploy artificial substrate, reefs or NID features between turbines, consideration would have to be taken to ensure features were not placed above buried or exposed cables. It is not uncommon for cables to require maintenance due to scour or snagging. Therefore developers require access to their cables at all times as any obstruction could result in transition downtime and a consequent loss of revenue. Further to this, access to the turbine may also be required for jack-up vessels to undertake maintenance work. Jack-up vessels are equipped with extendable legs that lift the vessel above the water, providing a stable platform for installation, decommissioning and maintenance work. Jack-up vessels must have clear areas on the seabed around the turbine where they can deploy their feet. These areas must be kept clear of reef or other protected features that would impede access for jack-up vessels. Finally, when maintenance vessels transfer crew to a turbine, they push onto the monopile which allows crew members to safely walk onto the turbine. The intertidal zone of the monopile needs to be free of biofouling to allow access for crew transfer vessels. NID implementation should therefore not promote the growth of biogenic species in this area of the turbine monopile.

A further aspect that must be evaluated, is the potential extent of reef growth due to artificial enhancements. By installing artificial reef structures, one goal is to recruit biogenic reef building species which could over time become independent of the artificial enhancements. Biogenic expanse must not develop over critical cable routes, or block access to areas requiring regular maintenance. Removing life that NID is implemented to accommodate would be unproductive, and therefore locations for NID deployment should be carefully determined through numerical models and field tests.

Any regular maintenance of turbines both above and below sea level must be compatible with the ecosystem promoted by NID on the seabed. If NID measures are implemented to increase biodiversity, there may be an increase in protected species and habitats that are sensitive to some aspects of OWF maintenance and operation. The enhancement and protection of flora and fauna at OWFs as a result of NID deployment is the optimal goal for achieving carbon Net Zero targets and facilitating the recovery of the marine environment. However, the presence of these species and habitats must not affect access to turbines or any maintenance that may be required throughout their lifespan.

7.4. Decommissioning

Although some UK OWFs were installed almost two decades ago and decommissioning plans are in place, such plans have not yet been put into practice due to the long lifespan of turbines. The Crown Estate's leasing policy for developments at sea requires the sea bed to be left as it was found following the lease completion. For OWFs, this involves removing the turbines, substations, scour protection and in some cases, subsea cables. Further to this, all subsea foundations must be removed to a distance of 1m below the seabed.

Decommissioning procedures are likely to have similarly disruptive environmental effects to those experienced during construction. These effects could also have detrimental impacts on marine communities who have inhabited the hard substrates provided by the wind turbines and the scour protection surrounding it. If NID features such as artificial reefs and Biohuts were installed at an OWF, under the current guidance the developer would have to remove these following the project's completion, even if they were providing habitats that support newly recruited marine life.

The debate between partially or fully removing OWF infrastructure is complex. In some perspectives, it will be beneficial to fully remove hard substrates from originally soft sediment environments as this will enable a site to return to its natural state. However, complete removal of these structures would incur loss of newly developed reefs and any associated species and disturbance to the surrounding soft sediments during removal. It may therefore be seen as more beneficial to leave turbine foundations in place. It may be particularly beneficial and more cost effective if they are supporting a productive and diverse community or if they are acting as a nursery ground for commercially important species (Hiscock et al., 2002). Nevertheless, leaving infrastructure in situ makes the site unfit for future development, reducing the already small area of suitable seabed available for new OFWs or other development. This could be seen as improper use of wind resources, as sites that are most suited for OWF development would instead be used as artificial reefs.

7.4.1. Cables

The removal of cables is usually only undertaken if the is cable buried at a depth is less than 1m (Topham and McMillan, 2017). In most cases cables will be left in situ as their removal causes disturbance and destruction to benthic habitats. If a cable lies below NID features that have facilitated reef formation, removal of this cable would be detrimental to the new habitat and its inhabitants. Removal of such cables would go against biodiversity enhancement objectives.

7.4.2. Turbines

Above the waterline, turbines are disassembled and removed in as close to one piece as possible. Removing monopile foundations involves cutting the monopile at a depth of at least 1m below the seabed, and the monopile is then lifted off in one piece. Monopile foundations extend to an average of 20m below the seabed, so most of the pile will remain buried following decommissioning. For less-common gravity and suction foundations, there is no cutting involved and the entire foundations are lifted off and removed from the seabed.

The removal of monopile foundations would cause localised disruption in the centre of the scour protection. Excavation would have to take place through the scour protection and then at least 1m below the seabed surface to facilitate cutting of the monopile. This action would cause significant vibrations and high sound levels in the scour protection area and beyond. The removal also has the potential to release sediment into the water surrounding the pile foundation. All of these actions have the potential to impact upon, displace or harm marine life that has inhabited areas around and within the scour protection, as well as the surrounding sediment and water column. However, in contrast to construction, decommissioning does not involve activity as intensive as pile driving, so the effects may be much more localised. Due to hydrodynamic forces around the turbine foundations, it is recommended to install NID options away from the centre of the scour protection (Lengkeek, et al., 2017).

7.4.3. Substations

Substations are supported by rectangular substructures that are fixed to piled foundations at each corner. The decommissioning methodology for substation foundations is the same as monopile removal and it comes with the same environmental impacts. While in place, substations protect the areas of seabed beneath them from destructive fishing activities, so they can become important habitats and refuges for a range of species. It is important to try to minimise the environmental impacts of decommissioning these structures. However, with the decommissioning of windfarms being a largely unexplored practice, the decommissioning procedures and recommended best practice are not yet fully determined.

7.4.4. Scour Protection

Under The Crown Estate’s leasing terms, scour protection must be removed from the seabed following a project’s completion. However, it can be difficult to remove aggregate from the seabed, so in most cases it is either left on site or, if it is deemed a hazard, it is dredged. Scour protection creates the ideal environment for reef species to inhabit, and removing this after a 25-year long project may cause disruption to a well-balanced community who depend on the artificial shelter to survive.

7.4.5. Decommissioning Solutions

NID structures that can be left in the sea rather than being decommissioned would be beneficial if their removal results in biodiversity or habitat loss. However, the aim of NID is to kick-start nature’s recovery and biodiversity Net Gain, not create ecosystems that are dependent on the structures. Using biodegradable NID features (e.g. BESE-elements) would overcome this problem as the structures degrade once a natural reef has formed around them. The best-case scenario would be creating a self-sustaining reef that no longer depends on NID structures and will survive following decommissioning of the assets and NID features.

7.5. Licensees, Permitting and Fisheries Closures

Deploying NID features within a new or existing OWF would not require any further permitting if the features were deployed on the scour protection, below substations or in the turbine 50m exclusion zone. However, NID plans should be incorporated within the project's initial submission where possible.

The deployment of NID features between turbines on the seabed would be much more complicated. For a new OWF development, the NID features would have to be included in the original application of consent. Then, standalone marine licences would have to be obtained in order to deploy features on the seabed. Following this, the developer would have to go through the consultation process where organisations can provide recommendations on how they think a project could be optimised or improved. In this case, environmental NGOs may object to deploying reef structures on the seabed if the wind farm is to be constructed in soft sediment habitats such as sandbanks or muddy areas. For minimum conflict during the consultation stage, the OWF location should be outside of any protected areas and should not house any protected soft seabed features. Ideally, the OWF would be in close proximity to areas of hard substrate on the seabed, although these are not common features of the western Irish Sea.

If NID features were deployed between turbines on the seabed, they would only be successful in establishing productive, healthy reef communities if the seabed was also closed to bottom trawling and dredging. To do this would require the implementation of a byelaw, which would be challenging. Not only would it likely receive opposition from the fishing industry, but it would also go against Ørsted's current coexistence policy. Nevertheless, closing OWFs and introducing reef and biodiversity enhancing structures would be beneficial to local commercial fish populations. Including the fishing industry in early stages of project planning and consultations would be vital. Through this, it may be possible to agree on a small-scale pilot project where the impacts of closing an area of an OWF with NID structures installed could be monitored,. However, this is not something that an OWF developer could do without Government support and leadership. Any pilot project would have to take place over many years to identify any potential benefits and therefore, it may not be seen as feasible by local fishers. Ørsted have shown that through collaboration with the fishing industry, positive projects can be achieved (i.e. Westernmost Rough OWF lobster fisheries monitoring project in partnership with Holderness Fishing Industry Group).

7.6. Post Deployment Monitoring

Measuring the success of NID deployment within an OWF is an essential action that must be undertaken to study the effects on local ecosystems. These data can then be used to feed into future projects to make NID more effective. However, undertaking in-depth monitoring of a NID installation over many years requires investing additional resources into a scheme that is not guaranteed to yield positive results. Therefore, there could be a lack of motivation for developers to undertake this monitoring themselves.

The aim of NID installations within OWFs is to enhance biodiversity. Therefore, the success of NID deployments can be measured by collecting data on the abundance diversity of marine life communities before and after NID installation. Other, more-detailed questions can then be asked about measuring the success of specific enhancement options, the impact of artificial reefs, any changes to ecosystem services, and the potential ecological risks (Bureau Waardenburg, 2020). These questions could include:Wwhat conditions are optimum for specific NID feature success?; Which options contribute most to valued natural capital and ecosystem services?; Could these features be used for achieving marine Net Gain targets?; Which options are feasible and which factors are most relevant for success?; and can these enhancement options be applied outside of OWFs?

Effectively measuring the success of NID deployment within an OWF will require preconstruction baseline surveys. This will allow data to be gathered on any changes to the ecosystem, which can be used to dictate future NID projects.

Financial constraints, weather conditions, and time can restrict offshore monitoring activities. Therefore, the correct monitoring methods should be selected depending on the resources available and the local site parameters. The size of vessel and the time required for survey works are the main factors affecting survey costs, therefore, monitoring excursions should be efficiently planned, considering the optimum time to carry out specific surveys, local tide times and other site characteristics. However, cost implications may not be the primary considerations for offshore wind monitoring programmes. The main consideration could be (from a health and safety perspective) that the level of risk involved with operatives working offshore on a continuous monitoring project, could be deemed disproportionate to the value of the data being collected.

A guide to potential monitoring approaches following NID deployment can be found in Annex F.

7.7. Changing Local Habitat

The main impact of an OWF development is the introduction of hard substrates into predominantly soft mud and sandy sediments (Leohard and Birklund, 2006). As a result of this increased habitat heterogeneity, benthic communities around turbines are altered from typical soft bottom communities to hard substrate associated communities. The assemblages that colonise artificial structures usually differ significantly to those on adjacent natural reefs (Connell, 2001). New patches of hard substrate habitats can also alter the distribution of marine organisms. Sessile organisms with poor dispersal may use these structures as ‘stepping stones’, allowing them to cover greater distances (Connell, 2001). Changing the distribution and abundance of organisms can have wide scale ecological impacts. For example, the increased abundance of bivalve molluscs such as blue mussels and oysters can alter ecosystem functioning. These species play a key role in the flux of particles between sediment and the water column, and in nutrient recycling. Changes in abundance of these species may therefore result in substantial changes in phytoplankton and larvae in the water column (Connell, 2001). However, they also play a significant role in carbon fixing and storage.

Providing more complex habitats that provide shelter and hiding places can increase species abundance and richness. However, caution and a good understanding of the ecosystem is required before this NID approach is taken. In an example from a terrestrial setting, efforts to restore the habitat of a lizard population through increasing habitat complexity rather than mimicking natural environmental conditions, led to increased predation of the lizards and therefore greater mortality (Hawlena et al. 2010). There are similar risks in the marine environment. Where NID in OWFs lead to an increased population of predatory fish, there may be negative and cascading impacts on the natural ecosystem, and losses to benthic diversity. Foraging by reef-associated fish species around artificial structures on sandy seabed ecosystems in Southern California, resulted in altered sea pen (*Stylatula elongate)* populations. Within 5 months of artificial reefs being deployed, sea pen densities close to the reefs declined from 4-10m^{-2} to 0 m^{-2}. Reductions in density were observed at over 100m from the reefs. Grazing damage was observed to be significantly higher around structures that harboured reef fish populations (Davis et al., 1982). Sea pens are a protected feature within the West of Walney MCZ. There is uncertainty around whether increasing predatory fish populations in and around this site will alter the condition of sea pen populations. This needs to be better understood before NID options can be installed. *Nephrops norvegicus,* are a commercially important species in the Irish Sea, out of their relatively few fish predators, cod is its most significant (Pinnegar & Platts 2011). Increasing habitat for cod through NID at OWFs may lead to an increase in the predation of *Nephrops* and have an influence on the fishery (NE, 2014). However, this may not be detrimental to the wider ecosystem as *Nephrops* can dominate in a highly disturbed environment where other more sensitive species cannot. Reducing the abundance of *Nephrops* could ultimately open up available space for the recolonisation of other burrowing megafauna species.

In a Swedish OWF, where piscivorous fish abundance increased around the turbine foundations, reef-associated prey species showed no or low levels of aggregation. The increase in predatory fish species around turbines may have a top-down effect on the ecosystem (Bergstrom et al., 2013).

Monitoring at Irish and North Sea OWFs has shown reef effects are localised to the turbine and scour protection rather than large scale impacts across the entire array (NE, 2014). It needs to be carefully considered as to whether introducing NID to OWFs will create larger scale impacts. The positive and negative environmental impacts of NID features need to be fully understood in order to properly design effective NID (Degraer et al., 2020). Actions such as changing scour protection designs to match the surrounding natural habitats will reduce changes to the local ecosystem. For example, in coarse sediment environments, the best method of scour protection would be using gravel; in areas with nearby rocky outcrops, boulder protection should be added; in shallow, sandy sediment areas, fronds could be used to reflect the natural environment. However, the target species should also be considered. In addition, if the turbines are placed in an area where there is a lobster or edible crab fishery, adding boulders to a soft sediment seabed would benefit the target species despite it not matching the current seabed (Wilson and Elliot, 2009).

7.8. Introduction of Non-Native and Invasive Species

Artificial structures provided by OWFs can also create habitat for non-native invasive species and the ‘stepping stone’ effect may facilitate their spread. Pilings, pontoons, oil rigs and other artificial structures have been shown to host significant numbers of non-native invasive species, in some cases significantly more than on nearby natural reefs (Daforn et al., 2012; Wilhelmsson and Malm, 2008). The introduction of non-native organisms can have catastrophic effects to native species and lead to the collapse of local fisheries (Charlton and Geller, 1993). The homogenous design and material composition of artificial structures is a key driving force in the dominance of non-native species (Dafforn et al., 2015). Other abiotic and biotic factors that influence the likelihood of artificial structures being colonised by non-native species include, the level of shading, orientation, sedimentation and surface texture (Dafforn et al, 2012; Dafforn et al., 2015). These should be considered when planning for NID. Options that minimise environmental changes and mimic natural local habitats could help to reduce the invasion of non-native species and maintain native communities (Dafforn et al., 2015). Well-designed surfaces can also reduce the ratio of invasive to native species. Ido and Shimrit (2015) compared breakwater antifers made from ECOncrete and standard

Portland based concrete. ECOncrete antifers showed greater abundance, richness and diversity of benthic invertebrates and fish communities. Importantly the ECOncrete surfaces also showed a lower ratio of invasive to native species. Altering the design of artificial structures could reduce the likelihood of facilitating the spread of invasive species.

7.9. Technical and Ecological risks

The top five ecological and technical risks from The Rich North Sea project's expert consultations (Hermans et al., 2020) are presented below in Table 8. These risks need to be considered early on in the design process and monitored throughout the operational phase.

Table 8 Technical and ecological risks of NID deployments

Type	Risk	Details	Mitigation
Technical	Structural failure of primary structure	Uncertainties around environmental loads and the behaviour of the structure when introducing non-essential add-ons.	– Conduct frequent inspections and maintenance where required. – Design NID features to be modular so they can be removed if structure is in danger of failing.
	Structural failure of NID	NID structure may displace or detach from the primary asset potentially causing damage to the asset.	– Frequent inspection, maintenance and, if needed, removal of the NID feature.
	Biofouling	Marine growth may prevent the target species from utilising the NID feature. Biofouling of the NID feature may also cause additional drag.	– Account for additional drag in the design. – Frequent inspection and removal of NID where necessary. – Design the NID specifically for the target species as much as possible. – Create enough space between surfaces so that some inevitable growth can occur without loss of function.
	Design failure in placement phase	Incorrect placement due to unexpected environmental circumstances or use of suboptimal equipment.	– Select ideal weather window for installation. – Use optimal equipment.
	Unforeseen costs	This is associated with the uncertainties during every project phase caused by a lack of experience with NID implementation.	– Good communication with experts and regulatory bodies throughout. – Include a buffer in the project's budget.
Ecological	Lack of ecological success	Results aren't desired due to lack of experience or unpredictable environmental conditions. This results in wasted resources. This may also lead to the concept of NID gaining a poor reputation making uptake by developers even more challenging.	– Unpredictable environmental factors and multiple complex variables make this risk difficult to mitigate for. – Don't define project objectives based on 'net' ecological success but in terms of learning and gaining experience with NID.
	Settlement of non-indigenous species	Hard substrate can attract non-native species that will compete for space with native species	– Time placement to be optimal for the settlement of desired species. – Optimise surfaces for the settlement of target species.
	Competition between target species	It is difficult to design NID options for multiple target species. Overlapping habitat or predation can result in increased mortality of one of the target species as the other outcompetes it.	– Gain a better understanding of the habitat requirements of target species. – Better understand how the NID option functions for each species.
	Absence of target species	Lack of larvae or juveniles of the target species due to a lack of stock population, unsuitable environment or lack of settlement cues. This will result in the NID having little success.	– Chose NID option based on the specific site and chosen target species. – Consider enhancing the stocks of the target species.
	Food limitation for target species	Sufficient food must be available for the target species to succeed. Lack of food available of an increase in competition could result in failed ecological success.	– Carry out baseline monitoring to establish levels of food availability. – Select sites based on food availability.

8. Smart Monitoring Challenges

8.1. Retrofitting Smart Monitoring Devices

Turbines are fitted with over 1000 sensors that are able to transmit live information back to a terrestrial base. The infrastructure required within a turbine to retrofit new sensors does exist, however, there are issues that must be mitigated when installing new sensors that can be costly.

8.1.1. Cyber Security

The digitalisation of the modern world has led to a new age of criminal activity that is increasingly targeting digital devices and systems through cyber-attacks. The reliance on big data and digital systems has provided something for attackers to exploit. Attacks are usually incentivised by financial gain, but other motivations could include political ‘hacktivism’ or espionage.

Offshore wind installations have increased considerably on a global level over the past decade. This rapid growth has led to a dependence on offshore wind assets to provide power to communities. As noted above, OWFs are considered NSIPs and, according to the Office for National Statistics, wind power equated to 24% of total electricity generation in the UK (13% generated offshore) in 2020. This dependency on offshore wind is making the industry an attractive target for hackers. A cyber-attack could cause wind farm downtime, which would result in financial losses and potential power loss for dependable areas. Estimates for one day of downtime for a 500MW wind farm, based on exporting electricity at £60 per MWh, equates to a loss of £360,000 (Wilkinson, 2021).

Retrofitting new, smart sensors to a turbine comes with considerable cyber security risk. Sensors are not designed with cyber security in mind, they are designed simply to collect and send data. Hackers could exploit sensor hardware though physical attacks, like exposing devices to acoustic or electromagnetic waves that alter data for their own gain. More commonly, vulnerabilities in sensors allow gateways for hackers to launch attacks internally through software bugs. Due to the increased interconnectivity of technological devices on wind turbine assets, there is the potential for hackers to access information and have control of assets through systems that integrate their data. More data often means a higher security risk. This must be assessed and mitigated against as a priority when it affects essential infrastructure.

It is possible to install new sensors on a turbine by utilising Internet of Things (IoT) systems. The IoT is a system of interconnected computers, devices and objects that have the ability to transfer data over a network without the need for human-to-human interaction. An IoT system consists of smart devices that are able to connect to the web. These devices are equipped with sensors, processers and communication hardware to collect, send and respond to data they gather from their environments. The data are collected and either analysed locally or sent to the cloud. In some situations, these devices can prompt responses and adapt in an agile manner to data gathered by other ‘things’ in the IoT system. The devices operate largely without human intervention. The reason that an IoT system could mitigate the risk of cyber-attacks when installing a new device to an offshore wind asset is that the IoT can be set up in a separate system to the control systems, therefore no malware would be able to access and control the asset. However, for existing assets where an IoT system is not already installed, it must be retrofitted to each turbine. The system itself is expensive, and retrofitting it to operational assets amplifies the cost. A full scale roll-out of IoT systems on each turbine at an operational windfarm would come at a large financial cost.

8.1.2. Physical Space

Turbine design is precise and conservative to reduce unnecessary material and foundation costs. As turbines are not designed to have sensors fitted retrospectively, it can be difficult to find space on a turbine for a sensor to be installed. The type of new monitoring data required is a large factor to the practicality of fitting a new sensor to an existing turbine, as some sensors are much larger than others. Smaller sensors will be more likely to have suitable positions on the turbine in which they can be installed. If a suitable place is found to install a new sensor, the user must be sure that the sensor will not be displaced through processes like wave action, adverse weather conditions and animal interactions. As such, it is much more convenient to include a sensor or device within the initial turbine design. However, with the correct planning and design, it is possible to retrofit suitable sensors to turbines.

8.2. Maintenance of Sensors

Keeping sensors in working order is critical to ensuring complete datasets are gathered and key events are not missed due to downtime. Non-submerged sensors will be exposed to the elements and must be designed to withstand this, particularly the high concentration of salt that will be present due to sea spray. Other scenarios are more difficult to design against, like the accumulation of guano on sensors. The site-specific conditions must be assessed so that sensor designs are robust and built to last in the conditions in which they will be exposed to. Inevitably, the malfunction of some sensor components may occur due to reaching the end of their lifespan or for other reasons. The maintenance of these sensors can then be completed by a wind farm technician. The maintenance of wind turbine sensors is common practice, therefore as long as the sensor is fitted in an accessible place, maintenance should align with standard operating procedures.

All submerged sensors on a turbine will be subject to biofouling. The type of biofouling sensors may be exposed to will vary depending on the depth of installation and the time of year. Biofouling can interfere with various elements of a sensor or monitoring device, depending on its type. For example, underwater video cameras could have their field of view compromised if biofouling takes place on the lens, and passive acoustic sonars could experience transducer failure due to biofouling on key components. For permanent subsea monitoring device installations, measures should be taken to reduce biofouling. There are many different strategies to combat biofouling, from chemical-based coatings to electrical currents. It is important that the most effective solution is developed depending on the site conditions and deployment characteristics. Although the extent of biofouling can be reduced, it is almost impossible to fully mitigate against in a permanent subsea deployment. Therefore, access to the device will be required to carry out biofouling removal at times. However, there are examples of subsea sensor deployments operating over long periods of time with no maintenance requirements. For example, the MeyGen Atlantis tidal stream turbine was fitted with 12 hydrophones to gather data on interactions with harbour porpoises. The system was operational for two years without maintenance and only had minor issues with one hydrophone, and this did not impact the quality of data recorded (Hastie, et al., 2018).

Subsea monitoring devices would either be placed on the scour protection area or fixed to the turbine tower at a certain depth. A system to recover and reinstate the monitoring device should be incorporated into the design, in order to carry out essential maintenance such as biofouling removal, component replacement and general servicing. This kind of maintenance is much more complex and time consuming when compared to non-submerged components, therefore it will be more expensive to carry out and will only be feasible if the data collected will be valuable to the business.

8.3. Data Storage and Analysis

When installing new sensors on a turbine, it can be challenging to find space on existing networks for data collection and transfer. This is due to the large amounts of data created by a single monitoring system. The introduction of a new monitoring device can lead to huge amounts of new data being created, which then needs to be transferred to a terrestrial site and stored. In the case of passive acoustics and video camera recording, file sizes can become so large that they may become unmanageable without the correct measures being taken. Simpler forms of data collection like taking hydrographic and metrological measurements creates much smaller, more manageable file sizes.

Once data has been collected, transmitted, and stored, it must then be analysed either automatically or manually. Automated data analysis through specialised software packages requires far less resources, and is therefore considerably less expensive than manual processing. Most simple forms of monitoring are able to be automatically analysed, like sensors measuring heat, vibrations, water salinity, wind speed and sea state. The more complex and less advanced forms of data collection can be analysed through semi-autonomous and fully manual processes. In terms of subsea ecological monitoring, underwater video, active acoustic and passive acoustic technologies are typically not compatible with fully autonomous analysis. Although artificial intelligence is assisting with the transition into automatic recognition and classification of species and behaviours, the wider use of artificial intelligence in this field is still relatively new and not fully developed. Manual analysis of data through these means is still required in most cases, which increases the cost of data collection. Singular deployments of acoustic or video monitoring devices are much easier to manage, however, if these devices were deployed at each turbine within an array, vast amounts of data would be generated, requiring a substantial amount of resources to analyse.

8.4. Collaborative Monitoring

To fully capitalise on environmental smart monitoring installations at OWFs, a collaborative approach between developers should be adopted to create a network of stations across the UK. Smart, real-time ecological monitoring across all wind farms within the UK would give an overview of ecological occurrences taking place around most of the UK’s coastline and territorial waters. Installing a range of devices at each wind farm to monitor underwater noise, marine mammal behaviour, bird interactions, meteorological phenomena, local hydrography, and more, would provide extremely useful data that would increase understanding about the positive and negative environmental impacts of OWF installations. More generally, a network of monitoring stations would give continuous data on the marine environment, filling data gaps and monitoring the subsea environment, which is still relatively unknown.

A collaborative monitoring scheme between multiple developers has many challenges associated with it. Firstly, data collected by one company may be deemed commercially sensitive and unfit to be shared with other developers or the public. Monitoring data collected within a wind farm may contain data that would reveal undisclosed information to other developers, eliminating any advantage over competitors. Furthermore, environmental data that could be used against the developer undertaking the monitoring would likely not be shared. For example, data that could impede future consent or development opportunities within a site. This is particularly relevant within offshore wind as developments are often associated with negative environmental impacts, especially during the construction phase. Any risk that the data collected and shared could be used to portray negative environmental impacts of offshore wind development could impede future applications for development. There is also a risk that other users of the monitoring data could misinterpret the results, which would increase the risk of negative repercussions on the developer.

A large, inter-developer, continuous monitoring scheme would require vast amounts of resources to deploy sensors, maintain systems, and analyse and store data. Although it would be highly beneficial to have a network of monitoring stations, there is no motivation at present for developers to invest in the initial start-up and on-going costs. If there was motivation or incentives provided by the Government or key stakeholders to gather marine environmental data through smart monitoring networks, resources would be more likely to be made available. However, developers are unlikely to invest in environmental monitoring that has no direct benefit to their business requirements.

9. Next Steps

9.1. Need for More Research

The offshore wind industry is still in its infancy and there is very little empirical data that confirms the long-term impacts of OWFs on the environment. In many of the studies found on the potential reef effects of OWFs, the information used was based on wider ecological knowledge or information still in early stages of development. Many of the studies and information on the effectiveness of artificial reef units were based in tropical seas.

There is need for detailed studies on the colonisation and wider ecological impacts of NID in OWFs. Research should also analyse the impacts of timings and design of development.

It is not currently possible to accurately predict the ecological benefits of incorporating NID into the Irish Sea as the effects of each NID option has not yet been researched in the context of the Irish Sea (and in many cases in the UK). It is therefore recommended that more studies, experiments, trials and pilots are carried out to increase our knowledge and understanding of the effects of each NID option.

9.2. Need for Further Development of Smart Environmental Monitoring Systems

Smart ecological monitoring systems that are able to autonomously record environmental information and transmit the data in real-time do exist, however, the commercial viability of rolling out systems across multiple turbines is uncertain. The MayGen Atlantis tidal stream turbine was installed with a network of passive acoustic monitoring devices over the course of two years to gather data on marine mammal interactions. The monitoring program was successful, however, the system collected over 1 Tb of data per day. A system such as this could not be rolled commercially on a larger scale due to the vast amounts of human analysis that would be required to sift through the raw data. There are programmes available that use AI to assist with analysis, such as PAMGuard, but they do not make the process fully automated.

The rapid and continued development of AI within ecological monitoring will reduce the level of human data analysis required for continuous monitoring systems. Technology such as automated species recognition through video or sound analysis is improving the efficiency of environmental monitoring systems and reducing the costs associated with analysis and data storage. Furthermore, advancements in technology have led to smaller, more reliable, less expensive sensors and equipment that is increasing the commercial viability of such systems. Ørsted have installed DTbird systems on selected turbines, showing that environmental smart monitoring systems are becoming more viable for installation within commercial projects. However, before it can become common practice to incorporate smart environmental monitoring systems within OWF design and build a network of monitoring stations around the UK, continued development of systems that incorporate AI to diminish the amount of human analysis and resources is required.

9.3. Pilot Studies

The analysis in this study found that a number of windfarm sites in the Irish Sea could be suitable locations for NID deployment. However, data on artificial reef effects on flora and fauna in the Irish/North Sea are lacking, and therefore information on factors affecting success of NID deployments is not fully understood. To verify the suitability of NID installations at UK OWFs empirical tests are needed before large-scale deployment.

Uncertainties in success factors can be reduced by conducting pilot studies in the field. Lessons can then be leaned and applied to future NID deployments to improve their effectiveness. A pilot project is currently being undertaken by Ørsted to understand cod and lobster behaviour around artificial reefs in Borselle 1 and 2 OWFs (WUR, 2021). BLUE Marine Foundation in partnership with Ørsted, are exploring the potential for OWFs to contribute to marine habitat restoration (Robertson et al., 2021). They have trialled oyster restoration projects within Gunfleet Sands OWF in Essex, UK. Other pilot projects exploring reef effects and biogenic reef promotion in the North Sea are being undertaken by the Rich North Sea programme. Using the experience gained from these schemes will provide a basis for the development of similar pilot projects in the UK.

Pilot studies should install a range of NID options described in this report at locations within an OWF. By installing different options at different locations within a wind farm, the effectiveness of each option and location can be observed. The objectives of such a pilot study could be formulated as follows:

- To find which features are most successful at increasing biodiversity,
- To find which NID options are most beneficial for target species,
- To find optimum locations for deploying NID features within an OWF,
- To find how long it takes to recruit species following installation.

Additionally, hydrodynamic conditions should be monitored. Scour, sedimentation and strong currents can affect NID installations even if placed on the scour protection. Therefore, analysis should be undertaken to understand how to minimise the effects of long-term exposure to local hydrodynamic conditions.

10. Conclusions

This report has identified the various NID options that are suitable for deployment at UK OWFs and the potential benefits and risks associated with each. These included options that can be added to the scour protection, cable protection, the turbine monopiles and the turbine foundations. NID options should create more habitat complexity, hiding spaces, shelter, and attachment and settlement sites for target species, compared with what is currently provided by conventional OWF structures and scour protection measures. The recruitment of target species should lead to greater biodiversity within the OWF.

A list of species that would benefit from NID in the Irish Sea based on their policy relevance and commercial importance were identified as:

- Atlantic cod (*Gadus morhua*)
- Whiting (*Merlangius merlangus*)
- Edible crab (*Cancer pagurus*)
- European lobster (*Homarus gammarus*)
- Haddock (*Melanogrammus aeglefinus*)
- Blue mussels (*Mytilus edulis*)
- Honeycomb worm (*Sabellaria alveolata*)
- Ross worm (*Sabellaria spinulosa*)

Further research is required into the effectiveness of NID options before the most suitable options can be determined and that will depend on the site-specific conditions, the chosen target species and the project’s aims. Using natural materials and enhancing infrastructure that is already being deployed, is most desirable so as not to cause any negative environmental impacts in comparison to adding new, artificial hard substrates. Options such as Reefballs® and Reefcubes® that can be incorporated into the scour protection layer, and can be designed specifically with target species in mind, could further enhance habitat complexity and result in greater ecological benefits. Where the seabed is particularly sensitive to changes, using add-on options will be more beneficial as they can be added to the turbine foundations with little impact on the benthos. However, as previously discussed all these options will come with their own set of ecological and technical considerations, risks and potential conflicts that cannot be ignored.

Barriers to NID becoming standard practice at UK OWFs were identified through discussions and workshops with partner organisations. The main barriers are summarised below:

- Retrofitting NID features to existing OWFs is considerably more expensive than installing them during the construction phase. However, if NID features are shown to be successful then retrofitting would be considered as installations would contribute to biodiversity net-positive targets.
- A lack of legislative guidance from the UK Government on methodologies to increase marine biodiversity is discouraging developers to include NID in their wind farms.
- Installing NID features could create a protected habitat impeding access to offshore assets.
- Decommissioning a wind farm under the current legislation would likely undo any positive impacts of NID features, e.g., removing reef habitats that support new communities around turbines.
- Deploying NID features between turbines in the UK may require restrictions on some fishing activities, which goes against Ørsted’s current fisheries coexistence policy. A marine licence for this activity may be difficult to obtain and could result in objections from local fishers.

- Post deployment monitoring of NID features would require additional resources and would pose a health and safety risks to operatives working offshore.
- Promoting reef species in naturally soft sediment habitats could negatively impact local habitats and species through increased predation of benthic communities.
- Hard substrate provided by OWFs can create habitats for non-native species and may facilitate their spread and impact local fisheries and marine life negatively.

Analysis has showed that a number of planned and operational wind farms in the Irish Sea are physically suitable for the deployment of NID features. However, to verify actual suitability of offshore wind farms in the Irish Sea for NID deployment, empirical tests should be carried out before large-scale deployments are undertaken. Pilot projects should focus on studying which NID features will contribute most to the recruitment of target species and increase local biodiversity, where the optimum locations are for deployment within an OWF, and whether the presence of NID features will have an impact on daily wind farm operations (e.g. access and maintenance).

This report has also explored the potential for smart environmental monitoring at OWFs around the UK, creating a network of monitoring stations that provide real time data. The challenges to deploying a smart monitoring scheme such as this have been identified below:

- Smart, autonomous, real time systems that utilise AI are available for deployment. However, environmental monitoring devices such as active acoustics, passive acoustics and video cameras still require large amounts of human manipulation and analysis.
- Large amounts of raw monitoring data would be created which would require additional resources and teams to analyse and store.
- Retrofitting monitoring devices can leave assets susceptible to cyber-attacks and installing systems to mitigate this is expensive.
- Turbines are not designed to have sensors retrofitted so finding suitable locations for sensors would be challenging.
- A collaborative monitoring approach between multiple developers is logistically challenging and there could be issues with the commercial sensitivity of data being shared between competitors.

Despite the challenges, NID and smart monitoring are going to be required in future developments if we are to promote the sustainable development of the seabed, achieve Net Zero, biodiversity Net Gain and recovery of the marine environment.

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12. Appendix

Annex A - Full table of species considered as target species for NID in the Irish Sea. (LC=Least concern, VU=Vulnerable, NT= Near threatened, EN=Endangered).

Species group	Scientific name	Common name	Habitat	OSPAR species/habitat	BAP species/habitat	IUCN red list	Protected / Conservation feature	Commercially important	Present in Round	Spawning ground in Irish Sea	Nursery ground in Irish Sea	Large hard	Gravel beds	Primary function of the substrate	Benthic species important to
Crustacean	*Cancer pagurus*	Edible crab	Benthic intertidal on rocky, boulder or coarse substrate	N	N	?		Y	Y	?	?				N
Bony fish	*Clupea harengus*	Atlantic herring	Pelagic in its distribution and occurs in the surface waters down to a depth of around 200 m	N	Y	LC		Y	Y	?	Y				Y
Bony fish	*Ctenolabrus rupestris*	Goldsinny wrasse	Rocky weed covered substrate	N	N	LC			?	?	?				Y
Bony fish	*Gadus morhua*	Atlantic cod	Benthopelagic fish	Y	Y	VU		Y		Y	Y				Y
Shark/skate/ray	*Galeorhinus galeus*	Tope shark	Benthopelagic and demersal species	N	Y	VU		N	?	?	Juveniles present				N
Sea mammal	*Galeorhinus galeus*	Grey seal	Offshore, breed on rocky shores	N	N	LC	Annex 2 species-SAC qualifying feature	N	?	?	?				N
Crustacean	*Homarus*	European lobster	Lower shore, benthic, rocks and boulder substrate	N	N	LC		Y	?	?	?	Y		hide in	Y

	gammarus													holes/crevices	
Bony fish	*Lophius piscatorius*	Angler fish/Sea monkfish		N	Y	LC		Y	Y	Y	N				Y
Bony fish	*Melanogrammus aeglefinus*	Haddock		N	N	VU		Y	Y		Y		Y		N
Bony fish	*Merlangius merlangus*	Whiting	The whiting is a benthopelagic species usually found as depths of 30-100 m. It can be found near mud and gravel bottoms, but also above sand and rock.	N	Y	LC		Y	Y	Y	Y				Y
Bony fish	*Micromesistius poutassou*	Blue whiting		N	Y	LC			?	?	N-Juveniles present				Y
Bony fish	*Molva molva*	Ling	Adults are in deeper water but juveniles are found in more littoral waters, those aged 1-2 are coastal (15-20 meters depth) and pelagic.	N	Y	LC	Wildlife and Countryside Act		?	Y- more data needed	Juveniles present				N
Mollusc	*Mytilus edulis*	Blue mussels	High intertidal to shallow subtidal. On rocky shores.	Y	Y	?	Habitat of principle importance		?	?	?	Y		attachment	N
Crustacean	*Nephrops norvegicus*	Neproph/Norway lobster	Live in burrows in the seabed	N	N	LC									Y
Mollusc	*Octopus vulgaris*	Octopus	Rocky coasts and shallow sublittoral	N	N	?		N	?	?	?				N
Mollusc	*Ostrea edulis*	Native/Flat oyster	Shallow coastal water habitats on firm bottoms of mud, rocks, muddy sand, muddy gravel with shells and hard silt.	Y	Y	?			?	?	?	Y		attachment	N

Crustacean	*Palinurus elephas*	European spiny lobster	Bedrock and boulders	N	Y	VU	MCZ Features of Conservation Importance	Y	?	?	?				N
Sea mammal	*Phoca vitulina*	Common/Harbour Seal	Sandflats and estuaries	N	Y	LC	Annex 2 species- SAC qualifying feature	N	?	?	?				Y
Bony fish	*Pleuronectes platessa*	Plaice	Occurs on mud and sand bottom from a few meters down to about 100 m	N	Y	LC		Y	Y	Y	Y				Y
Shark /skate /ray	*Raja clavata*	Thornback ray	A demersal coastal species which inhabits a variety of substrates, including mud, sand, shingle, gravel and rocky areas	Y	N	NT		N	?	DD	Y				N
Shark /skate /ray	*Raja montagui*	Spotted ray	Most common on sandy sediments also common further offshore on sand and coarse sand-gravel substrates	N	N	LC			?	DD	Y				Y
Polychaeta	*Sabellaria alveolata*	Honeycomb worm	Found on hard substrata on exposed open coasts		Y	?	Habitat of principle importance	N				Y		attachment	
Polychaeta	*Sabellaria spinulosa*	Ross worm	Mixed substrata and rocky habitats	Y	Y	?	Habitat of principle importance	N				Y	Y	attachment	
Shark /skate /ray	*Scyliorhinus canicula*	Small spotted catshark		N	N	LC			?	?	?				N
Shark /skate /ray	*Scyliorhinus stellaris*	Nursehound		N	N	NT			?	?	?	Y		hide in crevices	N
Mollusc	*Sepia officinalis*	Common cuttlefish		N	N	LC		N	?	?	?				Y

Bony fish	*Solea solea*	Sole	Burrows into sandy and muddy substrata	N	Y	LC		Y	Y	Y	Y				Y
Bony fish	*Sprattus sprattus*	European sprat	Pelagic	N	N	LC		Y	Y	Y	Y				N
Shark/skate/ray	*Squalus acanthias*	Spiny dogfish	A bentho-pelagic species not known to associate with any particular habitat	Y	Y	EN		N	?	Y	Y				N
Bony fish	*Trachurus trachurus*	Atlantic horse mackerel/scad	A pelagic coastal species	N	Y	LC		Y	Y	Y	Juveniles present				Y

Annex B – Target species selection and requirements

European lobster (*Homarus gammurus*)  Photo: Linda Pitkin/2020VISION	
Location	
Presence in Irish Sea	Lobsters are commercially fished in the North West, mostly around N Cumbria where the seabed is rocky but also around the rock armour of OWFs (Gray et al., 2016; NWIFCA, 2021).
Nursery and spawning grounds	The Coastal Aquarium Maryport, has set up a lobster hatchery where berried females are caught and their eggs removed. Larvae are then kept until they reach the juvenile stage. They are then released back into the sea near to where the female was caught. This is ensuring the greater survival rates of the larval lobster (NWIFCA, 2021).
Presence in OWFs	Evidence using stereo BRUV has shown European lobster to be present in Irish Sea Wind Farms, they have also been found to be in greater abundance around the base of turbines compared to further away (Griffin et al., 2016).
Biological requirements	
Diet	Lobsters are omnivorous and are opportunistic feeders, taking advantage of any nearby food source (Linley et al., 2007). Adults feed typically feed on blue mussels, hermit crabs and polychaete worms (Svåsand et al., 2007).
Habitat	European lobsters inhabit the lower shore up to 60m but prefer water of 10 – 50 metres deep. Boulder habitats are important as both a nursery ground for juveniles and shelter for adult lobsters (Linnane et al., 1999). Mobile sands and gravels are not suitable habitat for lobsters, neither are areas with frequent and strong wave induced currents. Shallow, exposed areas are therefore unlikely to be the most suitable habitat (Linnane et al., 1999). Shelter is a key habitat requirement for lobsters. Preferred shelters provide a roof and shading and are usually more wide than high, they can have one opening or multiple openings (usually two). Openings are usually smaller than the internal dimensions of the shelter (Dybern, 1973).
Juveniles	Lobster larvae settle on the seabed and spend the next 2-3 years entirely within crevices between rocks and boulders or burrowed in mud, as they are highly vulnerable to predators (Cobb and Wahle, 1994). Juvenile lobsters are more abundant on rocky outcrops compared to areas of bare sand due to the provision of shelter (Linnane et al., 2000). Choice tests have shown juvenile lobster will preferentially chose habitats with pre-existing shelter in the form of interstitial spaces such as mussel shells and cobbles, and will chose these habitats over sand (Linnane et al.,

	2000). Cobble can support a stable population density of juvenile lobster through its early benthic phase. Population densities of juveniles in mussel shells decreased significantly over time despite initially having a higher density of individuals compared to cobble. This may be because cobble provides a wider range of size niches (Linnane et al., 2000). The size of available shelter can set an upper size limit to the lobster with those in cobble having larger average carapace length compared to those in mussel beds (Linnane et al., 2000).
Adults	Adult lobsters are found most commonly burrowed in holes and crevices of bedrock, scree or in the sediment under boulders and stones, they have also occasionally been found burrowed in flat, soft sediment (Dybern, 1973). Adult lobsters will select sites that provide sufficient food, oxygen and shelter from currents and predation (Linnane et al., 200). The suitability of a shelter can depend on factors including, den length, entrance size, number of openings (escape routes) and internal aspect ratio (manoeuvring space). Choice tests showed little preference between shelters of different shapes and sizes amongst rock (Halcrow Maritime, 2001). It may be that lobsters will accept whatever shelter is available to them in natural environments. However, lower and wider sized shelters were least favoured possibly due to the limited manoeuvrability of low spaces and the less defendable space of wider holes. Shelters with one opening are preferred over those with two openings (Halcrow Maritime, 2001). As lobsters grow they need to move to increasingly larger crevices. By creating variable sized crevices amongst the scour protection, lobsters can be supported through all life cycle stages (Linnane et al.,2000; Halcrow Maritime et al., 2001).
Interaction with biogenic reefs	Lobsters will feed on blue mussels (Svåsand et al., 2007). Despite mobile sandy sediments not being suitable habitats for lobster, sandy areas around Cromer have been shown to sustain lobster fisheries. It is hypothesised that this may because of the associated Ross worm (*Sabellaria spinulosa)* reefs. The Ross worms can stabilise mobile sediments by constructing tubes that aggregate to form reefs. These reefs offer complexity at a scale relevant to lobsters of all sizes. However, at the present time, it is unclear whether these communities have potential to enhance the growth and survival of lobsters (Linley et al., 2007).

Edible crab (*Cancer pagurus*)
 Photo: Paul Naylor http://www.marinephoto.co.uk/
Location

Presence in Irish Sea	Edible crabs are present in the Irish Sea and are commercially fished off the Cumbria coast particularly around Walney Island where the habitat is more suited to them (rocky/coarse sediment). The increase in OWF development around the Irish Sea and use of rock armour for scour and cable protection has increased the availability of habitat for the Edible crab (NWIFCA, 2021).
Nursery and spawning grounds	Spawning females seek out sandy, gravel substrates to enhance attachment of her eggs to her pleopods (Heraghty, 2013). Local abiotic and biotic factors influence the importance of a nursery habitat, therefore a habitat that is important in one location may not be important in another, if other factors are not similar. Nursery habitats should therefore be considered on a local scale (Heragthy, 2013).
Presence in OWFs	Edible crab are found in Irish Sea OWFs and are more abundant adjacent to turbine bases than the surrounding area (Griffin et al., 2016).
Biological requirements	
Diet	They are both an active nocturnal predator and a scavenger. They feed on anything from other crustacea, molluscs and echinoderms. They will also voraciously consume mussels (NWIFCA, 2021). At the juvenile stage *C. pagurus* will actively predate other crustaceans and blue mussels (*Mytilus edulis*) (Heragthy, 2013).
Habitat	Found from the intertidal to around 100m.
Juveniles	Larvae are planktonic, living in the water column for approximately 60 days (Heraghty, 2013). Once transformed into the juvenile stage, *C. pagurus* will settle in the intertidal, during this stage they are small and highly vulnerable. Settlement will depend on abiotic and biotic factors (i.e. presence of conspecifics, lack of predators and chemical cues given by the substrata). The factors that influence settlement of *C. pagurus* are not well understood but other crab species will actively settle into complex habitats such as mussel beds, rocky shores, eelgrass beds and macro algae as they provide hiding spaces and food availability (Heraghty, 2013).
Adults	Adults live on the benthos and are most abundant on rocky substrates, under boulders, in mixed coarse sediment and muddy sand offshore (NWIFCA, 2021). They hide in holes and crevices or buried in sand and mud. They remain sheltered unless feeding. The crab is generally found in shallow water close to shorelines.
Interaction with biogenic reefs	They commonly feed on blue mussels (NWIFCA, 2021).

Haddock (*Melanogrammus aeglefinus*)

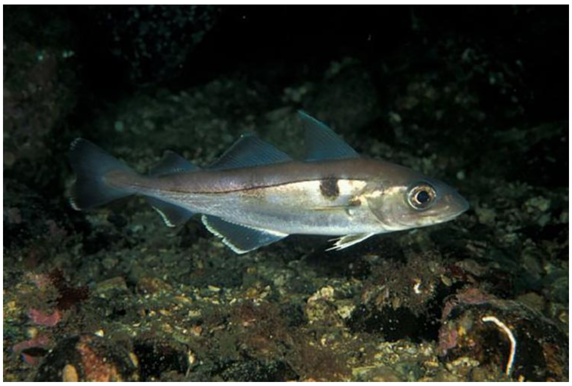
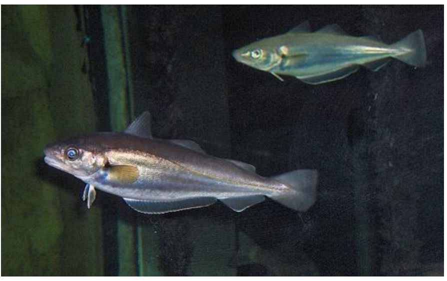


Photo: NOAA Fisheries

Location	
Presence in Irish Sea	Haddock is a commercially important fish, exploited in the Irish Sea (Rowlands et al., 2008).
Nursery and spawning grounds	Spawning occurs in typically between 50 and 150 m depth (FishBase, 2021) from March to May (Marlin, 2021). Nursery areas are present in the Western and Eastern Irish Sea (Coull, 1998).
Presence in OWFs	No available data.
Biological requirements	
Diet	Feed mainly on small benthic organisms including crustaceans, molluscs, echinoderms, worms and fishes (FishBase, 2021).
Habitat	A demersal species, usually 10-200m (FishBase, 2021) but 50-100m is the preferred depth range (Cargnelli, 1999).
Juveniles	Juveniles remain in the epipelagic zone for 3-5 months before settling to the bottom. Once demersal, juveniles and adults occupy similar habitat (NOAA, 2021).
Adults	Adults are found more commonly over rock, sand, gravel, pebble or shells (FishBase, 2021; NOAA, 2021).
Interaction with biogenic reefs	No data found.

Atlantic Cod (*Gadus morhua*)  Photo: Paul Naylor - http://www.marinephoto.co.uk/	
Presence	
Presence in Irish Sea	Cod are present and commercially exploited in the Irish Sea (Gray et al., 2016; Rowlands et al., 2008).
Nursery and spawning grounds	Both spawning and nursery grounds are present in the eastern and western Irish Sea (Coull, 1998; Ellis et al., 2012). Spawning occurs in winter and early spring, in large schools (FishBase, 2021). Spawning sites are in offshore waters 50-200m deep, at or near the bottom, in and 0-12 °C. Nursery areas are in the inner coastal zone. (FishBase, 2021).
Presence in OWFs	Walney OWF and its export cables overlap with Atlantic cod spawning and nursery grounds (Clarkson et al., 2012). Cod can aggregate in high densities around turbines from a few meters to tens of meters away, thought to be foraging and using the turbines as refuge (Wilhelmsson et al 2006; Bergstrom et al 2013). Cod stay within the wind farm long term, some individuals were observed for the entire study period of nine months (Winter et al., 2010).
Diet	The Atlantic cod has a varied diet including benthic invertebrates and fish (Fahay et al., 1999).
Habitat requirements	
Juveniles	The juvenile stage occurs once larvae reach 20mm. At around 2.5-6cm in size they will descend from the water column to bottom habitats. Juveniles prefer complex habitats such as seagrass beds, cobble, gravel or boulder areas as these provide the best protection from predators (Fahay et al., 1999; FishBase, 2021). Juveniles prefer shallow (less than 10-30 m depth) sublittoral waters (FishBase, 2021).
Adults	Adult cod are benthopelagic, typically found in schools on or near bottom along rocky slopes and ledges. Adult cod prefer coarse sediments over finer mud and silt. They occur at depths of 40 -130m (Fahay et al., 1999).
Interaction with biogenic reefs	Cod are attracted to hard substrates including reefs () Atlantic cod abundance increased around restored rocky reefs in the

Whiting (*Merlangius merlangus*)	
Photo:	 Amy Lewis  Georges Jansoone (JoJan)
Location	
Presence in Irish Sea	Whiting stocks are present in the Irish Sea (Ellis et al., 2012; Gerritsen et al., 2003) but there have been significant declines in their abundance since the 1900s due to overexploitation (Gerritsen et al., 2003). Adult whiting are widely distributed throughout the Irish Sea whereas juveniles are generally limited to coastal areas and estuaries (Gerritsen et al., 2003).
Nursery and spawning grounds	Spawning occurs from February to June, with most eggs and larvae being found in the coastal bights of the western and eastern Irish Sea and to the south-west of the Isle of Man (Coull, 1998; Ellis et al., 2012; Gerritsen et al., 2003). Whiting utilises estuarine habitats and other coastal waters as nursery grounds (Ellis et al., 2012). There are high intensities of nursery grounds present in the Eastern and Western Irish Sea (Coull, 1998 and Ellis et al., 2012).
Presence in OWFs	Large shoals of juvenile whiting were observed in North Hoyle OWF, feeding on tube dwelling amphipods on the turbines (Stenberg et al., 2015). Whiting are also present within Hornsea Rev OWF but in greater abundances away from the turbines suggesting a lack of affinity with complex rocky substrates (Stenberg et al., 2015). Whiting is also a dominant species around OWFs in the Dutch North Sea (Stenberg et al., 2015).
Biological requirements	
Diet	Whiting feed on shrimps, crabs, molluscs, small fish, polychaetes and cephalopods (FishBase, 2021). They have been observed feeding on tube dwelling amphipods on OWF turbines (Stenberg et al., 2015).
Habitat	A benthopelagic species, most commonly found at 30-100m on mud and gravel bottoms but can also be present on sand and rock (FishBase, 2021). Whiting are found on fine sediment sea beds that are characteristic of the eastern Irish Sea (Gray et al., 2016).
Juveniles	Juveniles are most common over sandy and muddy sediments in coastal areas and estuaries (Gerritsen et al., 2003).

Adults	Adults are found at greater depths than juveniles (Gerritsen et al., 2003). In an experimental choice study, small adult whiting changed from preferring sand habitat to complex habitat with emergent bryozoan (*Flustra foliacea*), when a predation threat was introduced. Whereas adult whiting preferentially chose sand habitat over gravel and complex habitat made up of emergent bryozoan, even with a predation threat. It is suggested that for large-sized adults, schooling behaviour is more important than shelter when avoiding predation (Atkinson et al., 2004).
Interaction with biogenic reefs	No data found.

Ross worms (*Sabellaria spinulosa*) 	
Location	
Presence in Irish Sea	Are present in the Irish Sea, particularly around the Isle of Man (
Presence in OWFs	Present in OWFs in UK OWFs, construction has no detrimental impacts (Pearce et al., 2014).
Biological requirements	
Diet	Filter feeds on detritus and phytoplankton (MarLIN, 2021).
Habitat/Substratum	10-50m. Occurs in turbid areas where sand is suspended in the water as it requires sand to form its tubes. It is mainly subtidal but may be found in the low intertidal (Marlin, 2021). Is found on hard substrata such as bedrock; boulders, cobbles, mixed substrata; mixed sediment. Typically prefer shell sandy gravel or rocky substrates with moderate tidal flow. Planktonic larvae are strongly stimulated to settle onto living or old colonies of S. spinulosa, although they will eventually (after two or three months in the plankton) settle onto any suitable substratum in the absence of other individuals (JNCC, 2008).

<table>
<tr><td colspan="2"><u>Honeycomb worms <i>(Sabellaria alveolate)</i></u>
</td></tr>
<tr><td colspan="2">Location</td></tr>
<tr><td>Presence in Irish Sea</td><td><i>Saballeria aveolata</i> are present in the Irish Sea. They are a feature of interest in Morecambe Bay SPA and SAC (Egerton, 2014).</td></tr>
<tr><td>Presence in OWFs</td><td></td></tr>
<tr><td colspan="2">Biological requirements</td></tr>
<tr><td>Diet</td><td>Are filter feeders and require sufficient water movement to mobilise large quantities of suspended food (Egerton, 2014).</td></tr>
<tr><td>Habitat</td><td>MLT-10m, typically on the bottom third of the shoreline but also in the shallow sub-tidal (Marlin, 2021).
Found on hard substrata on exposed, open coasts with moderate to considerable water movement where sand is available for tube building.</td></tr>
</table>

<table>
<tr><td colspan="2"><u>Blue mussels (<i>Mytilus edulis</i>)</u>

Photo: Kent Wildlife Trust</td></tr>
<tr><td colspan="2">Location</td></tr>
<tr><td>Presence in Irish Sea</td><td>Large commercial beds are present in Morecambe Bay (MarLIN, 2021).</td></tr>
</table>

Presence in OWFs	Blue mussels are found to colonise and often dominate offshore wind instillations (Degraer et al., 2020; Kerckhof et al., 2019)
Biological requirements	
Diet	Filter feeder, typically feeds on bacteria, phytoplankton, detritus, and dissolved organic matter (DOM) in the water column (MarLIN, 2021).
Habitat	From high intertidal to shallow subtidal ~5m. Fixed by byssus threads to suitable substrate including rocks and artificial infrastructure (MarLIN, 2021). Transport of food by advection, turbulent mixing, primary production, recruitment success and predation pressure influence the biomass of a mussel bed (Maar et al., 2009).

Annex C - Details of NID options

Strategy 1: Optimising Scour Protection Layers Using Natural Materials

The most common method of scour protection is placing rock layers on the seabed around the base of a turbine. This method is also commonly used to protect export and array cables. The scour protection layers can be made up of a filter layer (smaller graded rocks, added pre- foundation installation) and an armour layer (larger rocks/boulders, added post installation). It is also possible to use just one layer of rock pre-installation by using heavier rocks with wider gradation (GoBe Consultants Ltd, 2018). Optimising scour protection layers can be achieved by adding a third layer of rock with adjusted grading to a standard scour protection layer or by replacing the typical armour layer with an adapted grading armour layer. The grading requirements will be specific to the target species however the overall aim is to provide habitat niches for crab, lobster and juvenile cod. There has been significant research into the optimum size of stone for creating habitat for shellfish (Halcrow Maritime et al., 2001).

1. Boulder layers create a heterogenic habitat with an abundance of hiding places, shelter, attachment and settlement surfaces. Because scouring occurs around the turbine foundations, the colonising communities found on the scour protection layers are likely to be ephemeral and fast-growing species such as barnacles, tubeworms and solitary sea squirts (Hiscock et al., 2002). However, with proper planning, the rock layers can promote a diverse community of species to inhabit the ecosystem including hard substrate associated mobile species including reef fish, conger eels, cod (*Gadus morhua*), and mobile crustaceans such as Edible crab (*Cancer pegurus*), European lobster (*Homarus gammarus*), velvet swimming crab (*Necora puber*) and various species of squat lobster (Hiscock et al., 2002; Langhamer, 2012). The size and number of layers of boulders can influence the diversity and biomass of organisms (Guichard and Bourget, 1998; Takada, 1999) (this is based on studies into intertidal communities so effects may be different in subtidal boulder habitats).

The type and abundance of organisms in boulder habitats is influenced by the features of the boulders themselves and/or the substratum they are on (Petersen and Malm, 2006). Initial recruitment of boulder habitats can be by through larvae and spores in the water column or juveniles and adults arriving from nearby substratum (Chaoman, 2002). There may also be potential to seed the scour protection layers before installing (Sas et al., 2019).

2. Gravel is also used at the scour protection layers and it acts in the same way as boulders (Wilson and Elliot, 2019). Due to being a less stable environment gravel beds are typically defined by highly variable species compositions. They are colonised by low numbers of hydrodynamically resistant species such as polychaetes, bivalves, echinoderms, and crustaceans (Liocarcinus spp., Pagurus spp.). In locations where currents are low, hydroids, sea anemones, and bryozoans may occur (JNCC). Compared to boulder habitats, gravel at the scour protection layer is likely to result in lower biodiversity and abundance of organisms (Wilson and Elliot, 2019). From an ecological perspective, this is not the most desirable option.

Gravel beds however, may be more advantageous in locations where the natural sediment type is coarse sediment as this will have less impact on the environment than using boulders. Extending areas of gravel in coarse sediment environments will provide further habitat for naturally occurring species and allow greater distribution for local mobile species (Wilson and Elliot, 2009).

3. *Loose shell material* can be used as an additional layer on the scour protection. Suitable deployment locations have intermediate bottom shear stress and current speed and low sedimentation rate and sand movement. In areas with high sedimentation rate and current speed shells can be contained in metal gabions or biodegradable bags or fixed together using cement or bio-adhesives. Shell material enhances the settlement of shellfish (e.g. blue mussels and native oysters) but it may also enhance the occurrence of the reef building Sand mason worm and Ross worm, which live in soft sediment habitats. (Bureau Waardenburg, 2020). These organisms further increase the habitat complexity and 3D structure of the ecosystem, thereby increasing local biodiversity.

Strategy 2: Standalone Units Incorporated into the Scour Protection

Units include both small and large structures that increase habitat complexity by providing holes and crevices.

4. Habitat pipes can create shelter for organisms including cod, crab and lobster. Pipes can be steel or concrete but steel is more favourable as it is less fragile and more stable. Steel also allows for greater settlement of sessile species. Steel is however unsuitable for oyster settlement (Hermans et al 2020). Pipes should also have an open end and at least four holes 15-30 cm to guarantee water exchange. Placing the pipes in T or X figurations creates a more stable interaction with the scour protection layer (Hermans et al 2020). Sessile species can settle on the pipes and the holes allow the movement of species in and out of the pipes.

5. Fish hotels (WUR) are similar to habitat pipes in that they are hollow tubes with multiple holes along their length. The concrete tubes can be stacked on top of each other, interlocking to create a complex and stable structure. The fish hotels were designed as a habitat for cod however, they also provide shelter for crab and lobster (Hermans et al 2020).

6. Reefballs® are artificial, concrete units designed to mimic a natural reef. The concrete used is ‘marine friendly’ with a lower pH than traditional concrete mixes. Holes are bored into a hollow centre, creating a range of habitat niches and a large surface area. The holes create an upwelling of nutrients which feeds the organisms attached to its surface. They create habitat for fish and other organisms to use as shelter and their rough surface allows settlement of sessile organisms. Reef Balls are the most widely used artificial reef system in the world (Kojansow et al 2013). They were originally designed for coral reef restoration but have been modified for other uses. Shell fragments can be added for oyster reef restoration projects (Paul and Tanner, 2012), the layer cake design creates horizontal surfaces ideal for lobster and crabs, the specially designed ‘lobster cake’ style provides spaces for all stages of the lobster’s life cycle (Reef Ball Foundation). Reef balls can be used to increase the surface area of scour protection layers where boulders would otherwise be used. A reef ball can have almost double the surface area of a similar sized boulder (Wilson and Elliot, 2019). This increase in habitat surface area can lead to large increases in fish biomass (Wilson and Elliot, 2009).

7. Reefcubes® are made with Marine Crete®, a low carbon concrete with ‘marine friendly’ additives. They are robust, interlocking concrete structures which can be stacked and placed around turbine foundations. The cubes have an integral chamber with 6 passages/ holes which provide shelter for mobile organisms such as lobster and crab. Sediment can collect inside the cube which can provide a habitat for a diverse range of species. Research has shown an increase in biodiversity after just one year of installation (Hermans et al 2020) and that they are successful at both reducing scour and benefiting marine conservation (University of Plymouth, 2018). ARC Marine are currently seeking generic regulatory approvals to confirm that decommissioning Reef Cubes® will be unnecessary (University of Plymouth, 2018). If this is approved Reef Cubes® will remain on the seabed, providing a long-term habitat for important marine species.

8. 3D printed reef units are designed to create a habitat with a large, complex surface area for a diverse range of organisms to use as shelter, feeding ground and/or nursery. The shape and size can be altered to fit the needs of target species but will ideally have a complex surface texture and randomly allocated holes which are suited to the size of the target species (Hermans et al., 2020). Research is being carried out on the types of materials that can be used in 3D printing (Dunn et al 2019). While the selected material must be successful in allowing the colonisation of desirable native species, it must also be environmentally sustainable (Dunn et al., 2019). Adding crushed shells as aggregate can enhance the success of the 3D unit while also being a sustainable source of material (Dunn et al., 2019). Using biodegradable materials means the artificial reefs will naturally degrade over time as the live reef grows over it. Research has found that reef associated fish (Damselfish (*Chromis viridis*)) are not preferentially attracted to natural reefs over 3D printed reefs (Ruhl and Dixson. 2019).

9. ECO armour blocks® are made from ECOncrete which integrates by-products and recycled materials to produce a low carbon concrete mix. ECOncrete products are designed to mimic natural features to enhance colonisation of marine organisms. ECOncrete’s antifers have been shown to significantly increase the abundance, species richness and diversity of marine invertebrates and fish compared to typical concrete structures (Ido and Shimrit, 2015). They showed higher dominance of bioengineering species such as oysters, serpulid worms, bryozoans and coralline algae. High levels of bioengineering species result in an even greater habitat complexity for other organisms to colonise. They show less colonisation by invasive species (Ido and Shimrit, 2015).

10. Oyster gabions are made up of a steel cage filled with rocks and shells which is placed on the scour protection. The shells create additional hard substrate for oyster growth but can also benefit small cod, crabs and lobsters. It may be worth researching whether these can be adapted for blue mussels for use in the Irish Sea.

11. Biohut® is an artificial nursery for fish made up of 2-3 cages in succession. The Biohut provides food and shelter to juvenile fish with the aim of increasing the biomass of target species. The inside cage is filled with empty oyster shells, algae and tiny crustaceans will colonise the shells providing food for the fish. The outer cages are empty and provide protection from predators as the mesh size is only small enough for small fish to enter (Oppla, 2015). They are primarily designed for Atlantic cod (Hermans et al, 2020). They can be modified to fit on offshore turbine jackets or to be used as stand-alone units. They can be welded onto the monopile (Hermans et al, 2020). Biohuts are small, flexible and easily adaptable to different locations. They are fully operational with more than 1000 already installed worldwide (Nappex, 2016). Biohuts have been found to double the average abundance of juvenile fish compared to nearby bare surfaces (in a Mediterranean marina, focusing on juveniles of four Diplodus species) (Bouchoucha et al., 2016).

12. Seacult reef system unit is made from a concrete cylinder filled with rocks and polyethylene pipes. The unit provides 300m^2 of new surface area for organisms to colonise. The unit works by reducing the energy from waves and currents. It also provides a habitat for marine organisms including fish and seaweeds. Research has found 0.5-1 ton of seaweed on a unit and up to 15,000 small and large fish per unit. Fish use the pipes as shelter (Seacult, 2012).

13. SubCon artificial reefs are made from marine concrete and Blue-Crete. The different modules all create settlement surfaces, increase habitat complexity and provide hiding places for target fish species. For example, the Reef Pyramids are pyramid-shaped, marine grade concrete structures which incorporate crevices that provide shelter from predatory fish species as well as creating upwelling which is fundamental to sea-floor health. Subcon's artificial reefs alter the marine ecosystem by increasing abundance and diversity of macroalgae, fish and macroinvertebrates (Hammond et al., 2020).

14. XBlocs, Dolos, Tetrapods and Concrete jacks are all multi-pronged blocks made from concrete. They can be placed around the base of the turbine where they absorb the energy from currents. Over time the blocks become deeply interlocked with each other, forming a naturally strong resting position. The intricate shapes and porosity of the materials surface provides a large surface area for colonization and a range of habitats with varied current speeds and degrees of shelter. They may also create habitats within the interstitial spaces between blocks (Wilson and Elliot, 2009).

15. Biodegradable Ecosystem Engineering *(BESE) Elements®* are 3D, interlocking, biodegradable mesh sheets made of potato starch. They provide a temporary structure for attachment and shelter, facilitating establishment of marine organisms and providing a starting point for ecosystem restoration. Once a BESE-element® is colonised, the ecosystem can grow and provide its own structure, over time the BESE-element® breaks down leaving behind only the natural ecosystem (BESE, 2021). They have been found to successfully restore shellfish reefs leading to an increase in the abundance and diversity of fish (Gilby et al. 2019).

16. BESE-reef paste is a paste made from 80% ground shell and 20% natural binding additive. It can be applied to hard structures (e.g. stone/wood) where it functions as a temporary coating. It results in enhanced shellfish recruitment rates as many shellfish species will prefer to settle on other shells. It disintegrates slowly over 1-5years depending on local environmental conditions, leaving only the natural system behind. BESE-reef paste is particularly beneficial where conditions are too dynamic to add loose shell material to the seabed (BESE, 2021).

Strategy 3: Optimising the Cable Protection Layer

17. Filter units (rock filled bags) and basalt bags are flexible mesh bags filled with rocks which can be placed on the seafloor over cables or around turbine foundations to protect against scour. The mesh bags are generally made from synthetic fibres; however, basalt bags are made from basalt which is more ecologically friendly. Compared to loose rock, the bags are highly stable and are more easily removed during decommissioning. If designed well, the rocks within the bags can create crevices which can become a habitat for juvenile fish and crustaceans. The porous structure provides attachment surfaces for epifouling species on the surface of the bags (RockBags, 2017). This can lead to biogenic reef creation, further increasing shelter and food.

18. BESE mesh bags are a biodegradable alternative to the standard plastic mesh bags used for filter units, they are made from cellulose and are fully biodegradable. They remove the need for adding plastic to the environment. The bags can be filled with oyster/mussel shells and placed at the base of a turbine. Following recruitment by oysters/mussels the bag will disintegrate leaving only the biogenic reef behind (BESE, 2021). This can lead to challenges when considering long term feasibility and decommissioning as they cannot be removed like typical rock filled bags at the end of the OWF's lifespan.

19 &20. ECO Mats®, Reef cube® filter bag™ and Marine Matt® all work in a similar way. They are made up of a matrix of concrete units linked together to create a flexible structure that lies on the seabed to prevent scour and protect cables. ECOncrete's ECO Mats® have been designed specifically to enhance the settlement of marine organisms. They also have a lower CO_2 footprint compared to options using conventional concrete mixes (ECOncrete, 2020). The Reef cube® filter bag™ and Marine Matt® are made from Marine Crete® a low carbon alkali activated material. They are designed by ARC Marine, specifically with NID principles in mind. They provide shelter for Atlantic cod, Edible crab and European lobster. They also provide attachment surfaces for sessile species which are a food source for larger, mobile species.

22. Prefab collar SCP - The SeaCult cable and pipe protection (SCP) is placed over cables and pipes, removing the need for dredging the seabed. A bonus feature of the SCP is that it creates habitat for fish and other organisms as well as limiting damage to the seabed (Seacult, 2021). This option has come up in multiple NID reports (Bureau Waardenburg, 2020; Hermans et al 2020; Lengkeek et al. 2019) with limited details on what it is, how it works or how it can be applied. Seacult was contacted for further details on the environmental benefits of SCP however no further information was provided.

Strategy 4: Add-on Units

11. Biohut® same as above but adapted to be welded onto the turbine foundations.

22. Cod hotel consist of three main parts, a saddle which connects the structure to the turbine's jacket, a steel frame, and the ecological unit which consist of a gabion basket filled with steel tubes with holes. The perforated tubes are designed specifically to create shelter and foraging grounds for Atlantic cod. Designed by Witteveen+Bos (Hermans et al., 2020).

23. Living SeaWalls are 3D printed, concrete tiles which to attach to seawalls, creating a more complex habitat for marine life to colonise. Seawalls, like turbine foundations are often flat with no crevices for marine life to colonise. The tiles create microhabitats for native intertidal species. The Living Seawalls are being monitored over time to understand how different designs and their microhabitats can influence community development and how they can enhance ecosystem function (SIMS, 2021). Researchers are planning on expanding the project to other marine infrastructure including pilings (SIMS, 2021). There is therefore potential for tiles to be modified to attach to the upper foundations on turbine monopiles. Designed by Reef Design Lab as part of a SIMS initiative.

Other NID Options

24. Frond mats consist of a dense mattress of polypropylene fronds fixed into mesh or concrete and anchored to the seafloor. These are made to resemble seaweed or seagrass beds and are used to prevent scour. Like natural seaweed and seagrass, the artificial fronds slow down local currents causing sediment to settle and build up, leaving around 10-20cm of frond emerging from the seabed (Wilson and Elliot, 2019). The resulting sedimentation produces sand or sediment banks around the base of a turbine that reinstate and stabilise the seabed (Sub Sea Protection Systems 2021b). This artificial frond environment mimics natural seaweed and seagrass beds and may provide an important 3D habitat in an otherwise flat seabed. Seagrass and seaweed beds act as spawning and nursery grounds for commercially important fish, hiding places and attachment sites for other species (Wilson and Elliot, 2009). The fronds also stabilise sediments that can harbour a diverse community of invertebrate fauna, which in turn, support fish communities. Frond mats reduce the reef effects of turbine foundations compared to rock and gravel scour protection measures, as they do not introduce additional hard substrates. They are therefore more likely to result in a benthic environment that reflects the natural baseline conditions.

The frond mats were deemed ‘environmentally acceptable’ in an independent review (Pilarczyk, 1996). It was concluded that ‘- the sandbank contours follow and blend into the river or seabed, and does not affect marine life or vegetable growth or fishing’. Despite being ‘environmentally acceptable’ they still introduce plastic into the ocean which is a major concern for NE and TWT. UK Fishermen’s organisations have shown support for the frond mats, stating that “SSCS Frond systems are the only technique we are able to endorse as being compatible both with the fishing fraternity and the environmental lobby as a whole” (taken from a letter from The Fleetwood Fish Producers Organisation Limited). SSCS Frond Mats have already been installed environmentally sensitive locations (e.g. Morecombe Bay Area, Duddon Estuary and the Solway Firth area) (Tucker, A. 2015).

The question of whether it would be possible to make frond mats using natural materials was raised during the stakeholder workshop. Using real seaweed or seagrass would not be possible as they both require shallow waters where enough sunlight can penetrate the water in order to grow. They would also be less reliable for developers than plastic as the seaweed could degrade unpredictably.

Annex D - NID Options Sources

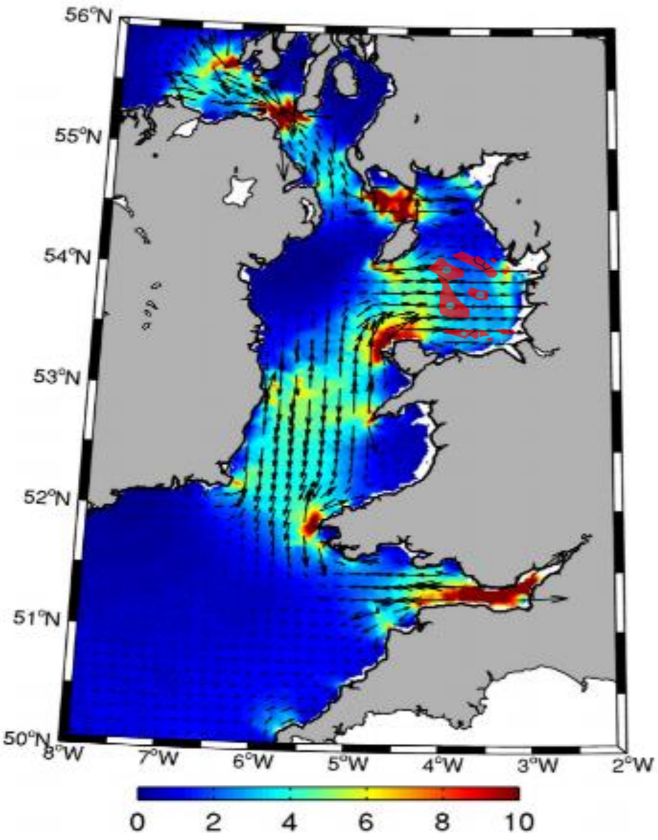
NID option	Source
Strategy 1. Optimising scour protection layers using natural, conventional scour protection materials.	
1. Boulders	Image: Asgarpour (2016) https://doi.org/10.1016/B978-0-08-100779-2.00017-9 https://www.vanoord.com/en/equipment/side-stone-dumping-vessel/
2. Gravel	https://www.vanoord.com/en/equipment/side-stone-dumping-vessel/
3. Shell material	
Strategy 2: Standalone units i.e. artificial reefs incorporated into the scour protection	
4. Pipes	Image: https://reforestation.me/coral-reef-restoration/

5. Fish hotel WUR	Wageningen University & Research Image: Reindert Nijland https://www.wur.nl/en/newsarticle/Building-artificial-reefs-to-be-used-as-fish-hotels-in-Haringvliet-estuary.htm
6. Reef balls	Reef Ball Foundation http://www.reefball.org/reef_ball_styles.htm
7. Reef cubes	ARC marine https://staging.wearestorm.co.uk/Staging/marine/
8. 3D printed reef	Reef Design Lab https://www.reefdesignlab.com/3d-printed-reefs-1/
9. ECOncrete	https://econcretetech.com/applications/offshore-applications/
10. Oyster gabions	https://www.bluemarinefoundation.com/projects/solent/ Robertson et al, 2021: https://www.bluemarinefoundation.com/wp-content/uploads/2021/01/BLUE-wind-farm-feasibility-study-report-FINAL.pdf
11. Biohut	NAPPEX https://www.nappex.fr/le-procede-biohut/la-gamme-biohut/ Image: https://oppla.eu/product/17472
12. SeaCult reef system	SeaCult http://marineagronomy.org/sites/default/files/16.%20SeaCult%20and%20Seacultivation,%20Sverre%20Meisingset.pdf https://www.agriculture-xprt.com/downloads/seacult-model-sbp-beach-and-offshore-protection-system-brochure-749504
13. SubCon artificial reef	SubCOn https://www.subcon.com/portfolio/habitat-enhancement-2/
14. Xbolx, Dolos, Tetrapods and Concrete jacks	Xblox https://www.xbloc.com/en/our-blocks/xstream
15. BESE-Elements	BESE products, Ecosystem restoration products https://www.bese-products.com/biodegradable-products/bese-elements/
16. BESE-reef paste	
Strategy 3: Optimising the cable protection layer	
17. BESE mesh bags	BESE products, Ecosystem restoration products https://www.bese-products.com/biodegradable-products/bese-elements/
18. Filter units/Rock filled bags	KYOWA filter unit https://rockbags.co.uk/what-are-rockbags/ https://rockbags.co.uk/wp-content/uploads/2018/03/FU-Catalogue-Offshore-2017.pdf https://rockbags.co.uk/what-are-rockbags/
19. ECO Mats®, Reef cube® bag™	ECOncrete: https://www.monmouth.edu/uci/wp-content/uploads/sites/58/2021/09/ECOncrete-Product-Pages.pdf ARC Marine- reef cube bag:

	https://www.plymouth.ac.uk/research/esif-funded-projects/arc-marine-a-case-study
20. Marine Matt®	ARC Marine https://staging.wearestorm.co.uk/Staging/marine/#marinematt
21. Prefab Collar (SCP)	SeaCult cable and pipe protection (SCP) https://www.environmental-expert.com/downloads/seacult-model-scp-series-cable-and-pipe-protection-system-datasheet-710951 https://seacult.com/wp-content/uploads/2021/03/Product-sheet-Seacult-rev6.pdf
Strategy 4: Add-on units	
22. Cod hotel	Witteveen+Bos design (www.witteveenbos.com/) https://edepot.wur.nl/518699
23. Living SeaWalls	Reef Design Lab https://www.reefdesignlab.com/living-seawalls
Other options	
24. Frond mats	Sub Sea Protection https://www.subseaprotectionsystems.co.uk/anti-scour-frond-mats

Annex E – Simulated Peak Shear Stress in the Irish Sea

Simulated peak seabed shear stress in the Irish Sea (Nm^{-2}). Wind farm locations of relevance are shown in red. Round 4 sites are indicated with a grey circle. (adapted from Ward et al., 2015)



Annex F – Methodologies and Assumptions for NID Retrofit Calculations

Methodologies and assumptions:

- Vessel charter and offshore working rates are based on discussions with Ørsted.
- Optimum scour protection rock quantity is based on 20% coverage of the existing scour protection layer, assumed to have a diameter (d) of 30 m. The maximum rock diameter (d_{rock}) is taken as 0.5 m.

  Therefore, per turbine,

$$A_{scour} = \frac{1}{4}\pi d^2 = \frac{1}{4}\pi 30^2 = 141.37\ m^2$$

$$and, \qquad V_{optimised\ scour} = 0.2 A_{scour} d_{rock} = 0.2 \cdot 141.37 \cdot 0.5 = 14.14\ m^3$$

- Estimates for add-on items such as reef cubes and Biohuts were taken from those outlined by Hermans et al. (2020).
- Rock armour delivery costs were calculated using 20 t tippers and,

$$W_{rock\ armour} = 2.5/V_{rock\ armour}$$

- Quantities are based on 6 monopiles with:
    - Rock armour installed on 1.5 turbines per day
    - Add-on items installed to monopiles at a rate of 2 per turbine per day

Annex G – Monitoring Methods Following NID Deployment

A combination of four main monitoring approaches should be utilised when undertaking biodiversity monitoring. A non-comprehensive list of monitoring methods has been suggested for each approach (For a comprehensive list please refer to, Lengkeek et al., 2017 and, Bureau Waardenburg, 2020):

Biodiversity observations

- Multi-beam sonar can be used to map hard substrate areas indicating where biogenic reef has formed.
- Video camera ROVs or drop-down cameras can visually survey areas of interest on the seabed.
- Baited underwater video (BRUV) setups can be used to attract species into a cameras field of view for analysis by using bait.
- Divers can be deployed to survey areas using quadrats or video cameras, however this is expensive and requires extensive planning. ROV’s are a less expensive, lower risk option that can be deployed to undertake tasks and gain similar results as divers.

Biodiversity sampling

- Benthic grabs can be taken in strategic locations to collect seabed sediment which can be later analysed in a laboratory.
- Catching live animals using nets or pots can be done to carry out inspections on animals to record their size, growth, development and health.
- Water samples can be taken to analyse important resources for species growth, such as chlorophyll-a, larvae distribution, suspended particulate matter, and other abiotic conditions. Environmental DNA (eDNA), which is genetic material found in water samples, can also be analysed to detect species in the area.

Research equipment

- Data loggers can be attached to buoys, deployed in the seabed, or attached to NID units. They are a cost-effective way of collecting data on abiotic conditions such as oxygen content, sound, light levels, salinity etc.
- Acoustic transponders can be attached to species of interest before releasing them into a site. Antennas in the area then track the movements of the animals and data can be analysed. This method has been deployed by Ørsted and the Rich North Sea programme at Boroselle 1&2 OWFs.

Analysis of data

- All of the methods mentioned above will require some aspect of analysis to determine results from the data collected.
- For video footage, there is software available that uses AI to automatically recognise species. This can be utilised to reduce the time and resources required for video analysis.