Assessment of environmental impacts of proposed floating offshore wind design envelope

May 2024

Natural England Commissioned Report NECR501

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Catalogue code: NECR501

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Keywords

Floating, Offshore, Wind, Environmental, Impacts, Marine, Environment

Acknowledgements

Many thanks to all developers who contributed to this report by providing details of their floating offshore wind developments.

Citation

Genesis. 2024. Assessment of environmental impacts of proposed floating offshore wind design envelope. NECR501. Natural England.

Foreword

Natural England commission a range of reports from external contractors to provide evidence and advice to assist us in delivering our duties. The views in this report are those of the authors and do not necessarily represent those of Natural England.

This report was commissioned by Natural England to gather data on the potential environmental effects of Floating Offshore Wind (FLOW) to develop an evidence base to better inform decision making and spatial planning in relation to the upcoming commercial scale of FLOW in England. The work was undertaken in three phases: the first being a technical review of available FLOW technologies currently in the marketplace, the second was to identify environmental receptors that may be sensitive to FLOW developments and the third being to assess the potential environmental impacts and pressure pathways from FLOW.

Executive summary

Wind-generated electricity has effectively promoted the net-zero carbon emission plan, and gradually developed to the deeper ocean, which leads to the emergence of Floating Offshore Wind (FLOW) technology. Rapid growth in FLOW is expected as the technology, supply chain and infrastructure develop. Following a number of successful prototypes and demonstration projects, FLOW is now taking the first steps in commercialisation.

The British Energy Security Strategy included an aim to bring forward up to 5 GW of floating offshore wind by 2030. The Crown Estate has set out ambitious plans to deliver an initial 4 GW of commercial-scale FLOW capacity in the Celtic Sea by 2035, with the region assessed to have the potential to accommodate up to 24 GW by 2045. In mid-2023, the tender process of seabed leasing for FLOW in the Celtic Sea will begin, with leasing rights to be awarded by the end of 2023.

As such, Natural England have identified that there is an opportunity to gather information on environmental effects from global trial and pre-commercial FLOW projects to provide an evidence base to inform decision making and spatial planning in relation to upcoming commercial scale FLOW in England.

This project was therefore established to produce a comprehensive report that would provide Natural England with an evidence-based assessment of the environmental impacts of the proposed FLOW design envelope. The design envelope is defined by the Crown Estate to provide maximum and minimum values for technical elements of FLOW turbines i.e., hub height, rotor radius, foundation type etc. The design envelope allows developers to begin the consenting process where final details of the project may be unknown. At the time of writing, a definitive design envelope had not yet been confirmed or made publicly available by the Crown Estate.

The first phase of this project delivered a technical review of the available FLOW technologies that exist in the market currently, including case studies and stakeholder engagement with FLOW developers to determine the design envelopes they are currently working with.

The second phase of the project was to identify the environmental receptors that may be sensitive to impacts from FLOW developments, using a number of publicly available sources. The Celtic Sea was prioritised for identifying the environmental receptors due to the upcoming Crown Estate leasing round, with the Celtic Sea as a key area of FLOW development. However, each receptor has also been described more broadly at UK level hence the findings are also applicable to FLOW developments in other locations in the UK and internationally.

The third phase of the project was to assess the potential environmental impacts and pressure pathways from FLOW, using the information obtained from the technical environmental receptor reviews. The environmental impacts assessed correspond with Natural England's Advice on Operations tool to allow any pressures and environmental impacts unique to FLOW (as compared to fixed foundation turbines) to be directly transferable to the tool, allowing them to be risk-profiled separately to fixed foundation offshore wind. A total of 39 pressures are included in the Advice on Operations tool and, of these, 27 were considered relevant to FLOW and were therefore scoped in for assessed in this report.

When compared to fixed foundation offshore wind, the following pressures were found to be of **lower** risk for FLOW:

- habitat structure changes - removal of substratum (extraction)
- underwater noise changes
- above water noise

When compared to fixed foundation offshore wind, the following pressures were found to be of **greater** risk for FLOW:

- smothering and siltation rate changes (heavy)
- collision BELOW water with static or moving objects not naturally found in the marine environment (e.g., boats, machinery, and structures)

In addition, two novel pressures were identified to be relevant to FLOW, which are previously ranked "**not relevant**" for fixed foundation offshore wind:

- electromagnetic changes
- temperature increase

Given that several differences were identified in the impact of pressures from FLOW development as opposed to fixed foundation offshore wind, it was concluded overall that Natural England should consider adding FLOW as a new operation in the Advice on Operations tool.

In addition to assessing the environmental impacts, mitigation measures and evidence gaps were also identified for each pressure throughout this report. Based on the overall objectives of this project, the most significant evidence gaps are considered to be:

- the lack of information relating to the impact of seabed disturbance pressures on specific habitats or sediment types,
- the lack of publicly available information relating to the design envelope for below water elements of wind turbines, specifically, quantitative figures for the seabed footprints of different anchor / mooring line types, and penetration depth of different anchor types.

As these evidence gaps impact the robustness of this report, it is recommended that they are prioritised in further scopes of work.

Contents

1. Introduction

Background

In order to reduce greenhouse gas emissions, it is recognised that there is a need to move away from the fossil fuels as a primary method of energy generation. The expansion of offshore wind is a key element of the UK’s Net Zero commitments and the British Energy Security Strategy. By 2030, the UK Government has committed to producing 50 GW of energy from offshore wind, with rapid expansion anticipated thereafter. By 2050 the total could rise to at least 100 GW (UK Government, 2022). Meeting this target will require a significant acceleration in development and the implementation of new technologies, of which Floating Offshore Wind (FLOW) has an important role to play.

FLOW presents an innovative solution to the exhaustion of near-shore sites for renewable energy generation, with rapid growth in FLOW expected as the technology, supply chain and infrastructure develop (Crown Estate, 2022a).

FLOW offers many advantages over fixed foundation turbines. FLOW can operate in water depths up to 1,000 m, whereas based on today’s technology and industry experience fixed foundation turbines are limited to depths of 60 to 80 m (Paya and Du, 2020). This increases the offshore area available to renewable energy generation, as well as enabling access to more powerful and consistent winds, leading to increased turbine efficiency. With an estimated 80 % of available wind resources sitting beyond the range of fixed foundation turbines, FLOW has the potential to surpass fixed foundation wind as the dominant offshore technology (Jakobsen and Ironside, 2021).

Following a number of successful prototypes and demonstration projects (summarised in Appendix 4), FLOW is now taking the first steps in commercialisation. Globally, FLOW is predicted to remain in the pre-commercial phase until 2025, moving to a commercial phase from 2026 onwards (GWEC, 2022). The British Energy Security Strategy (April 2022) (UK Government, 2022) includes an ambition to deliver 5 GW of FLOW by 2030.

Celtic Sea

The Crown Estate, which manages the seabed around England, Wales, and Northern Ireland, has set out ambitious plans to deliver an initial 4 GW of commercial-scale FLOW capacity in the Celtic Sea by 2035, with the region assessed to have the potential to accommodate up to 24 GW by 2045. In mid-2023, the tender process of seabed leasing for FLOW in the Celtic Sea will begin, with leasing rights to be awarded by the end of 2023 (Crown Estate, 2022b).

Within the Celtic Sea, the Crown Estate initially identified broad “Areas of Search” through engagement with a variety of market, marine, and statutory stakeholders. Further stakeholder engagement and technical analysis allowed the Crown Estate to distil these down to “Refined Areas of Search” i.e., smaller areas of seabed within which projects may be located in the future. Figure 1-1 illustrates the location of the Areas of Search and the

Refined Areas of Search. Area of Search 1 and Area of Search 5 were removed from consideration. The Refined Areas of Search will be further refined into potential “Project Development Areas”. The work of identifying Project Development Areas is being undertaken by the Crown Estate simultaneously with a Habitats Regulations Assessment (HRA), which will assess the potential impact of leasing on environmentally valuable habitats.

At the time of writing (April 2023), the Crown Estate have awarded the first contract in a series of technical and environmental surveys around potential locations for new FLOW farms. The Crown Estate propose to make the data from these surveys freely available to successful bidders (Crown Estate, 2022c).

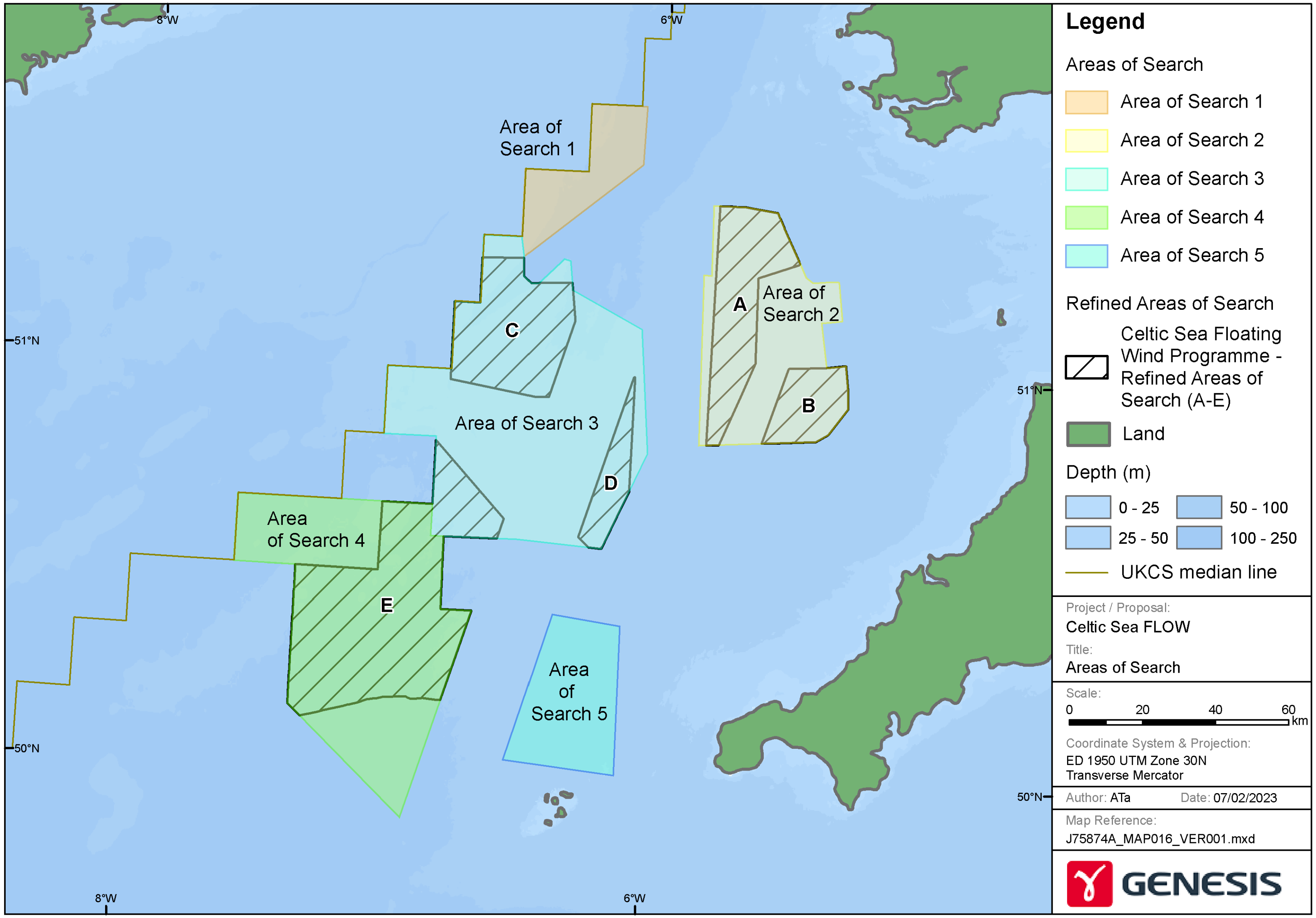


Figure 1-1. Celtic Sea FLOW Refined Areas of Search

Aims and objectives

Natural England have identified that with the rapid growth of the FLOW industry, there is an opportunity to gather information on environmental effects from global trial and pre-commercial FLOW projects to provide an evidence base to inform decision making and spatial planning in relation to upcoming commercial scale FLOW in English waters. Natural England aim to focus on accurate evidenced environmental sensitivity information, with evidence-based mitigation to be implemented at all stages where impact is predicted (as outlined in Natural England's Approach to Offshore Wind (Natural England, 2021).

The aim of this report is to provide a comprehensive report which provides Natural England with an evidence-based assessment of the environmental impacts of the proposed FLOW design envelope (described in Section 2). The objectives of the project were defined by Natural England as:

Objective 1: Review the FLOW foundation design envelope for the Celtic Sea as identified by the Crown Estate, based on technology and design boundaries for above and below water elements.

Objective 2: Identify, assess, and describe potential pressure pathways including new and novel pressure impact pathways associated with FLOW projects, and pressures that will have differing effects to traditional offshore wind foundation types. The identification of pressures should be in line with the Natural England Advice on Operations tool for Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) for Electricity from renewable energy sources and Cables (Natural England, 2023a).

Objective 3: From known and new pressures associated with the development of FLOW design envelope, assess the impacts on habitats and species, including features/sub feature or supporting habitat sensitivity to those pressures. Pressures are to be identified, described, and assessed against established pressure benchmarks where these are available and effect pathways stated.

Objective 4: Assess the worst-case scenario design envelope of FLOW in relation to impacts to each environmental receptor or group of receptors. i.e., benthic, ornithology, marine mammals etc.

Objective 5: Present potential mitigation measures for impacts associated with each design (category of turbine and seabed attachment) within the FLOW design envelope, as identified from trial projects or included within the literature.

Objective 6: Identify evidence gaps and suggest further research.

Method

This section presents the key stages and methodologies involved in the development of this report.

Literature review

The information and evidence presented in this report was obtained through completing a desk-based review of scientific papers and grey literature. In addition, the authors reached out to a number of FLOW developers requesting information on any ongoing monitoring reporting that has been carried out. Further details are provided in the Stakeholder engagement section below.

The methodology for the literature review followed the Collaboration for Environmental Evidence (October 2022) “Guidelines and Standards for Evidence synthesis in Environmental Management” (Collaboration for Environmental Evidence, 2022).

Google Scholar and Web of Science were selected as the most appropriate search engine options due to the high level of reliable cited journal entries; ease of accessibility to third parties; and repeatability of searches. A number of search terms were identified (see Table 1-1 for examples). The search terms encompass individual, or compound words used in a search to find relevant articles, which increases the repeatability of the literature review. This study was completed from December 2022 to February 2023, therefore literature made available after the end of February 2023 has not been incorporated. References were managed by recording search terms used and results in a database.

Table 1-1. Examples of primary and secondary search terms for systematic review

Level	Search term
Primary	“offshore wind” “floating offshore wind”, “floating offshore wind turbine”, "floating offshore wind farm"
Secondary	Impact specific (i.e., "underwater noise", "seabed disturbance”)
Tertiary	Habitat specific (i.e., "benthic", “circalittoral sand", “water column”) Species specific (i.e., "mammals", "birds", "fish") Technology specific (i.e., "spar buoy", "semi-submersible", “catenary”, “drag embedment”, “suction caisson”)

Stakeholder engagement

To support the literature review, and to provide a holistic and accurate evidence base for the environmental impacts of the proposed FLOW structures, the authors reached out to a total of 22 global FLOW developers, advising of the project and gauging their interest in providing information on the following:

- the design envelope (or potential design envelope concepts) for their FLOW turbine subsea structures i.e., spar, semi-submersible, tension leg platform, tensioned or Catenary mooring lines, anchor type and number
- the environmental impacts considered during development, or identified during construction/ operation / decommissioning (if applicable)
- any mitigation measures considered or implemented to reduce environmental impacts
- any future research or evidence gaps in relation to environmental impact of FLOW that the developer had identified

In addition, a copy of their Environmental Monitoring Report(s) for their FLOW development(s) was requested, as well as any other relevant literature they might have.

For confidentiality reasons the FLOW developers contacted have not been identified, however where relevant the information received from those that did respond has been included in the report. Note responses were received from two developers.

As Renewables UK currently coordinate a task force made up of industry looking at the design envelope of FLOW and supply chains for infrastructure, they were also contacted for input, however at the time, they were unable to provide any additional information.

Identification of environmental receptors

Environmental receptors that could potentially be impacted by FLOW (Section 3) were identified using a number of publicly available sources. The Celtic Sea Refined Areas of Search were used as a starting point for identifying the environmental receptors. Although the review focuses on the receptors within the Refined Areas of Search, the findings are generally applicable to FLOW developments in other locations in UK waters.

This report presents a high-level summary of environmental receptors for the purpose of identifying relevant environmental impacts and pressure pathways to be assessed in Section 4.

Assessment of environmental impacts and pressure pathways

Natural England’s Advice on Operations tool, which is available through designated sites view, identifies pressures associated with the most commonly occurring marine activities and provides a detailed assessment of the feature / sub-feature or supporting habitat sensitivity to these pressures. The user of the tool selects a marine activity, and a designated site upon which the marine activity may have an impact. The tool carries out an initial assessment of whether a proposed plan, project, or ongoing activity may have an impact on the protected features within the site (Natural England, 2023a).

A wide variety of marine activities can be assessed using the Advice on Operations tool, such as: aggregate extraction; aquaculture; beach management; cables; coastal development and flood and erosion risk management schemes; commercial shipping; electricity from renewable energy sources; fishing; oil, gas, and carbon capture storage; ports and harbours; and recreation. At present, “offshore wind” (separated into decommissioning, during construction, and operation and maintenance phases) is a subcategory within the “electricity from renewable energy sources” category, however, there is no differentiation between fixed and floating foundations.

The environmental impacts and pressure pathways included in Section 4 of this report have been selected in order to correspond with Natural England’s Advice on Operations tool (Natural England, 2023a). This is to allow any pressures and environmental impacts unique to FLOW (as opposed to those environmental impacts common with fixed foundation turbines) to be directly transferable to the tool, where they can be added to the tool and risk-profiled separately to fixed foundation offshore wind in future.

Natural England provided an exhaustive list of pressures assessed within the Advice on Operations tool for all marine activities and all protected sites. This list was used to carry out a scoping exercise, whereby pressures were scoped in for assessment in Section 4 if they were considered to be applicable to FLOW. Pressures from all lifecycle stages of an offshore wind project i.e., construction, operation and maintenance, and decommissioning, have been included. Table 1-2 presents the outcome of this scoping exercise and outlines which pressures have been scoped in or out of the assessment.

Table 1-2. Scoping exercise to identify relevant pressures

Pressure	Scoped in (yes / no)	Justification
Visual disturbance	Yes	The above-water structures of offshore wind farms can have a potential visual effect on birds. Visual disturbance from increased vessel activity, installation activities, and ongoing maintenance activities has the potential to impact marine mammals and seabirds.
Genetic modification & translocation of indigenous species	No	Not relevant to offshore wind.
Introduction or spread of invasive non-indigenous species (INIS)	Yes	Vessel ballast water, biofouling, and “stepping-stone” effects caused by the presence of offshore wind structures may facilitate the spread of INIS.
Introduction of microbial pathogens	No	Not relevant to offshore wind.
Removal of target species	No	Not relevant to offshore wind.
Removal of non-target species	No	Not relevant to offshore wind.

Pressure	Scoped in (yes / no)	Justification
Habitat structure changes - removal of substratum (extraction)	Yes	Removal of substratum from the seabed may occur during the use of the driven pile anchor type for FLOW.
Penetration and/or disturbance of the substratum below the surface of the seabed, including abrasion	Yes	Penetration/disturbance to the substratum below the surface of the seabed caused by installation of anchors used to stabilise floating foundations. Also, deployment of anchors from vessels used in installation of the wind farm.
Changes in suspended solids (water clarity)	Yes	Seabed disturbance from any cause has the potential to cause sediments to become suspended in the water column.
Smothering and siltation rate changes (Heavy)	Yes	Increased siltation rate occurs during installation of anchors, mooring lines and inter-array cables. In addition, should the anchor system use catenary mooring lines that come into contact with the seabed, there could be continuous impact on seabed during operation in the area over which the mooring lines are in contact with the seabed, as well as during movement of wind turbine structures with wave, current and tide action.
Smothering and siltation rate changes (Light)	Yes	As above.
Abrasion/disturbance of the substrate on the surface of the seabed	Yes	Abrasion/disturbance caused by placement of the infrastructure itself, associated scour protection, the action of scour on structures, as well as the presence of the structures and dynamic movement of mooring lines on the seabed during operation.
Temperature decrease	No	Not relevant to offshore wind.
Temperature increase [note 1]	Yes	Operation of cables in general will result in some heat being emitted from the cable and subsequent warming of the surrounding environment. Concerns inter-array cables for FLOW.
Salinity decrease	No	Not relevant to offshore wind.
Salinity increase	No	FLOW projects themselves does not affect salinity. However, there is the potential for salinity increases where FLOW is co-located with hydrogen production. The production of hydrogen and development of this technology is in early stages of development; thus, it is too early to predict

Pressure	Scoped in (yes / no)	Justification
		impacts. However, in the future this impact pathway may be required to be screened in.
Water flow (tidal current) changes, including sediment transport considerations	Yes	Any structure placed in the marine environment immediately interacts with the local current regime and modifies water flow around it. Presence of wind turbine structures impact atmospheric and oceanographic dynamics, wake effect (wind), upwelling/downwelling, and stratification.
Emergence regime changes, including tidal level change considerations	No	Not relevant to offshore wind.
Wave exposure changes	Yes	Physical presence of a wind turbine could lead to diffraction or funnelling of waves and currents between the turbines, reductions in the wave energy reaching the coast and changes in local wave patterns.
Physical loss (to land or freshwater habitat)	Yes	Habitat loss occurs wherever the placement of structures have a permanent footprint on the seabed. It should be noted that this pressure refers to the physical loss of seabed and marine habitat in this report.
Physical change (to another seabed type)	Yes	Physical changes to sediment structure i.e., soft bottom habitat loss where the subsea components of an offshore wind turbine provide new hard substrate on the seafloor. Artificial reef effect.
Physical change (to another sediment type)	Yes	Change in sediment type resulting in change in the biotope classification. Sediment from beneath the surface of the seabed being brought to surface due to anchor installation.
Litter	Yes	Marine litter can be released into the marine environment by shipping vessels, or by weathering of wind turbine blades during operation.
Electromagnetic changes [note 1]	Yes	Electromagnetic fields are generated by devices and cables that carry an electrical current. Concerns inter-array cables for FLOW.
Underwater noise changes	Yes	Underwater noise during construction from towing (vessel use) and anchoring (including potential piling), operational noise from vessels, wind turbine generators sitting atop the floating foundations (which may radiate

Pressure	Scoped in (yes / no)	Justification
		through the foundation and into the water column), and potential twisting/snapping noises produced by the sudden re-tension in a mooring line following a period of slackness.
Introduction of light	Yes	Introduction of artificial light associated with vessels in the marine environment during construction, operation and maintenance, and decommissioning phases. In addition, there is navigation and operational lighting on the FLOW structures.
Barrier to species movement	Yes	Physical barrier presented by the presence of the wind turbine infrastructure / wind farm.
Collision ABOVE water with static or moving objects not naturally found in the marine environment (e.g., boats, machinery, and structures)	Yes	Bird collision with above water structure.
Collision BELOW water with static or moving objects not naturally found in the marine environment	Yes	Marine mammal, turtle, and diving bird collision with vessels involved in FLOW construction, maintenance, and decommissioning activities, as well as entanglement (primary/ secondary/ tertiary) with wind turbine mooring lines or fishing gear caught in mooring lines.
Above water noise	Yes	Aerodynamic noise from blades slicing through the air, and mechanical noise associated with machinery housed in the nacelle of the turbine.
Vibration	Yes	Vibrations produced by trenching for cable laying, construction activities involving piling.
Transition elements & organo-metal (e.g., Tributyltin (TBT)) contamination	Yes	Cathodic protection systems used for corrosion protection of steel wind turbine structures in the marine environment.
Hydrocarbon & Polycyclic Aromatic Hydrocarbon (PAH) contamination	Yes	Accidental diesel spills from vessels involved in construction, maintenance, and decommissioning. Potential disturbance of seabed sediments contaminated with historic oil and gas drilling activities.
Synthetic compound contamination (incl.	Yes	Measures to prevent biofouling on wind turbine structures.

Pressure	Scoped in (yes / no)	Justification
pesticides, antifoulants, pharmaceuticals)		
Introduction of other substances (solid, liquid or gas)	Yes	Corrosion protection techniques, such as organic coatings.
Radionuclide contamination	No	Not relevant to offshore wind.
Nutrient enrichment	No	Not relevant to offshore wind.
Organic enrichment	No	Not relevant to offshore wind.
Deoxygenation [note 2]	No	Not relevant to offshore wind.

Key:

Yes - Scoped in

No - Scoped out

[note 1] Novel pressures identified for FLOW, that are considered “not relevant” to fixed foundation offshore wind in Natural England’s Advice on Operations tool

[note 2] Whilst deoxygenation is not considered relevant to offshore wind at present, there has been some evidence to suggest that it could become relevant in future as more information becomes available (Daewel *et al.,* 2022).

Following the scoping exercise, all pressures scoped in for further consideration were organised into sub-sections under general section headings to allow for a more efficient assessment. Note that a number of pressures are standalone sections with no sub-sections. The section breakdown is as follows:

Seabed disturbance

- abrasion/disturbance of the substrate on the surface of the seabed
- penetration and/or disturbance of the substratum below the surface of the seabed, including abrasion
- habitat structure changes - removal of substratum (extraction)
- physical change (to another seabed type / to another sediment type)
- physical loss (to land or freshwater habitat)
- smothering and siltation rate changes (light / heavy)
- changes in suspended solids (water clarity)

Physical presence

- visual disturbance
- barrier to species movement
- collision ABOVE water with static or moving objects not naturally found in the marine environment (e.g., boats, machinery, and structures)
- collision BELOW water with static or moving objects not naturally found in the marine environment (e.g., boats, machinery, and structures)

Changes to the atmosphere and ocean

- water flow (tidal current) changes, including sediment transport considerations
- wave exposure changes

Noise and vibration

- underwater noise changes
- above water noise
- vibration

Electromagnetic changes

Temperature increase

Introduction of light

Introduction or spread of invasive non-indigenous species (INIS)

Contamination

- litter
- hydrocarbon & PAH contamination
- transition elements & organo-metal (e.g., TBT) contamination
- introduction of other substances (solid, liquid or gas)
- synthetic compound contamination (including pesticides, antifoulants, pharmaceuticals)

Risk-profiling of pressures

A key element of Natural England's Advice on Operations tool is the Risk Profiling of Pressures (RPP). RPP supports the application of Natural England's marine conservation advice packages to an assessment of the potential impacts of an activity on the features of a designated site. The risk profiling classifications used in the Advice on Operations tool are described in Table 1-3.

Table 1-3. Risk-profiling classifications in the Advice on Operations tool

Risk profile of pressure	Recommendation
Medium-High Risk	Pressure is commonly induced by activity at a level that needs to be considered further as part of an assessment
Low Risk	Unless there are evidence-based case or site-specific factors that increase the risk, or uncertainty on the level of pressure on a receptor, this pressure generally does not occur at a level of concern and should not require consideration as part of an assessment.

In this report, as part of the assessment of environmental impacts (Section 4), a risk profile score has been recommended for all pressures scoped in for each FLOW lifecycle stage. The assigned risk profile scores are based on the evidence collected as part of the literature review. Justifications for the assigned scores have also been provided.

Risk profile recommendations for each pressure are discussed in Section 4, and a summary of all pressures is provided in Appendix 1.

Receptor sensitivity

In addition to RPP, features of designated sites (i.e., receptors) are assigned sensitivity rankings within Natural England's Advice on Operations tool, depending on the sensitivity of each receptor to a specific pressure. When a marine activity and protected area combination is selected in the tool, all of the designated features for that site (which are also considered to be relevant to the pressures presented by the selected marine activity) are given a sensitivity ranking.

Sensitivity rankings (Table 1-4) are based on the Marine Evidence based Sensitivity Assessment (MarESA) approach, which replaces The Marine Life Information Network (MarLIN) approach (MarLIN, 2023). Detailed guidance on the application of the MarESA approach is provided in Tyler-Walters *et al*. (2018). Sensitivity is generally considered to be a product of the following:

- the likelihood of damage (termed intolerance or resistance) due to a pressure
- the rate of (or time taken for) recovery (termed recoverability, or resilience) once the pressure has abated or been removed.

A feature is therefore most sensitive to a pressure when the likelihood of damage is high, and the rate of recovery is slow (if at all) (Oslo and Paris Convention (OSPAR), 2008).

Table 1-4. Sensitivity ranking in the Advice on Operations tool

Sensitivity	Category description
Sensitive (S)	The evidence base suggests the feature is sensitive to the pressure at the benchmark. This activity-pressure-feature combination should therefore be taken to further assessment.
Insufficient evidence to assess (IE)	The evidence base is not considered to be developed enough for assessments to be made of sensitivity at the pressure benchmark. This activity-pressure-feature combination should therefore be taken to further assessment. The best available evidence, relevant to the activity in question, at the time of application, should be sourced and considered in any further assessment.
Not assessed (NA)	A sensitivity assessment has not been made for this feature to this pressure. However, this activity-pressure-feature combination should not be precluded from consideration. The best available evidence, relevant to the activity in question, at the time of application, should be sourced and considered in any further assessment.
Not sensitive at the benchmark (NS)	The evidence base suggests the feature is not sensitive to the pressure at the benchmark. However, this activity-pressure-feature combination should not be precluded from consideration (e.g., thought needs to be given to activity specific variations in pressure intensity and exposure, in-combination and indirect effects). The best available evidence, relevant to the activity in question, at the time of application, should be sourced and considered in any further assessment
Not relevant	The evidence base suggests that there is no interaction of concern between the pressure and the feature OR the activity and the feature could not interact

Assigning a sensitivity ranking for every feature of the protected sites within the Celtic Sea is out with the scope of this report. Instead, receptors considered to be most sensitive to each pressure have been described as part of the assessment of environmental impacts (Section 4). Going forward, this provides the necessary information to allow specific features of protected sites to be assigned a sensitivity ranking.

Receptor sensitivity recommendations are discussed throughout Section 4 and, along with the RPP, a summary of the receptors considered to be most sensitive to each pressure is provided in Appendix 1.

2. Technical description

Understanding the potential design of FLOW structures is essential in assessing the potential impacts on sensitive receptors, as well as the pressure pathways that may lead to those impacts. This section addresses Objective 1 and includes a review of the FLOW design envelope for the Celtic Sea as identified by the Crown Estate, based on technology and design boundaries for above and below water elements. Available information on technical features of FLOW turbines, for both above water (i.e., the tower, hub, nacelle, and blades) and below water (i.e., the floating foundation, mooring lines, anchors, and inter-array cables) have been summarised. In doing so, Objective 4 is also partly addressed by outlining the worst-case scenario design envelope for FLOW above and below water components.

Design envelope approach

For the purposes of this report, the ‘design envelope’ approach (also known as the ‘Rochdale Envelope’ approach (Marine Scotland, 2022; National Infrastructure Planning, 2018)) has been implemented to describe the technical elements of FLOW turbines.

The design envelope approach originally emerged for the purposes of consenting developments requiring an Environmental Impact Assessment, where the final details of a project are unknown or yet to be finalised at the time the application is submitted. This enables a degree of flexibility and is particularly relevant to the FLOW industry, being at such an early stage of development where there is a wide range of possible technology designs available (Marine Scotland, 2022).

Through the design envelope approach, it is possible for an application to set out parameters for the proposed development, including the minimum and maximum extents for technical elements. The likely worst-case impacts of the proposal can then be assessed on that basis, allowing the detailed design of the project to vary within this 'envelope'. The approach taken must be sufficient to enable a proper assessment of effects in the context of the receiving environment. Such an approach will then inform the mitigation measures, which must be adequate to deal with the worst-case scenario (Marine Scotland, 2022).

For the purposes of this report, the design envelope approach is useful to ensure that all potential FLOW turbine designs are captured in the assessment of the environmental impacts of FLOW as a whole, as well as consideration of the worst-case scenario. Throughout this report, the preliminary design envelope has been considered together with the environmental receptors identified in Section 3, to assess relevant environmental impacts and pressure pathways discussed in Section 4.

Above water

At the time of writing, a definitive design envelope for FLOW above water components (i.e., the tower, hub, nacelle, and blades) for the Celtic Sea had not yet been made publicly available by the Crown Estate. However, a preliminary design envelope based on technology and design boundaries has been devised during a workshop run by the Crown Estate, involving several FLOW developers. The preliminary worst-case design envelope for above water components is summarised in Table 2-1 and illustrated in Figure 2-1. Note that this is currently a working draft and may be amended, however, the Crown Estate envisage this FLOW design envelope to be used to Inform Plan level Habitat Regulations and Marine Conservation Zone Assessments.

Table 2-1. Preliminary design envelope for FLOW above water elements

Parameter	Minimum value	Maximum value
Turbine type	3-bladed horizontal axis	3-bladed horizontal axis
Turbine generating capacity (MW)	12	28
Rotor radius (m)	110	170
Hub height (m above sea level)	132	210
Tip height (m above sea level)	242	375
Rotor surface clearance (m above sea level)	22	45
Time averaged rotational speed (rpm)	Not specified	10
Wind Adjusted Availability (%)	90	98
Blade width (m)	4	9
Blade pitch (deg)	6	6

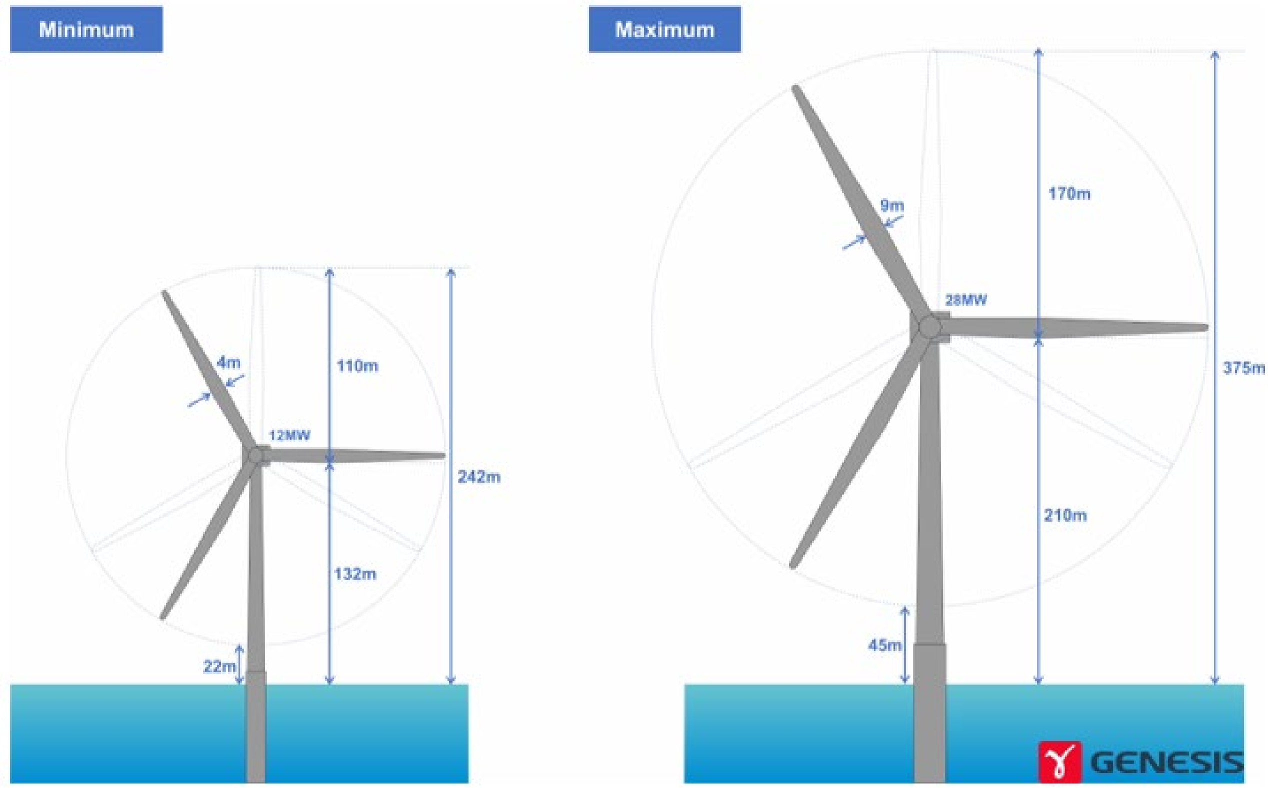


Figure 2-1. Visual representation of Crown Estate prospective above water design envelope (Note this image was created by Genesis)

Types of wind turbine

This subsection aims to establish if there any differences in the wind turbine itself (i.e., above water elements) when installed on a floating foundation, as opposed to a fixed foundation. Consideration is also given to wind farm layout in this section. This information is necessary to determine if there are any differences in receptors (Section 3) or environmental impacts of the above water elements (Section 4).

The basic principle and mode of operation of all wind turbines, with fixed or floating foundations, is the same. The early consensus within the industry is that the wind turbines deployed on floating foundations will be technologically similar to those used in fixed foundation offshore wind, with a limited number of key differences (Offshore Renewable Energy (ORE) Catapult, 2021).

The floating foundation structure must provide enough stability to support weight, pitch, roll and heave of a wind turbine as well as forces exerted by wave and wind action. Although floating foundations employ different stability mechanisms to cope with operational forces, changes to the turbine tower's stiffness may also be required to minimise tower fatigue and to avoid resonances between the turbine's rotor frequency and the frequency of the floating platform's oscillations (ORE Catapult, 2021a).

With full scale commercial FLOW deployment targeted by 2030, it is likely that turbines will grow significantly in that time, both in capacity and dimensions. Turbine capacities are expected to reach between12 MW and 15 MW within the next decade, with 20 MW turbines considered technically feasible in the longer term (ORE Catapult, 2021a). Both fixed and floating offshore wind foundations will be required to support the next generation 15 MW to 20 MW turbine generators, which are significantly higher and heavier than the current wind turbine generators in operation.

Table **2-2** summarises indicative turbine dimensions based on capacity and Figure 2-2 presents the information as a function of time.

Table 2-2. Dimensions of offshore wind turbines by capacity (ORE Catapult, 2021a)

Detail	Description	6 MW	9.5 MW	12 MW	15 MW	20 MW
Hub height (m)	From mean sea level to rotor hub	100	110	135	150	168
Rotor diameter (m)	Full rotor diameter (i.e., including blades and hub)	154	164	220	240	277
Deployment date (year)	Actual and estimated installation dates	2017 (e.g., Hywind Scotland)	2021 (e.g., Kincardine)	Mid 2020s (e.g., Scotwind and Celtic Sea leasing plans)	Early 2030s (e.g., Scotwind and Celtic Sea leasing plans)	Late 2030s

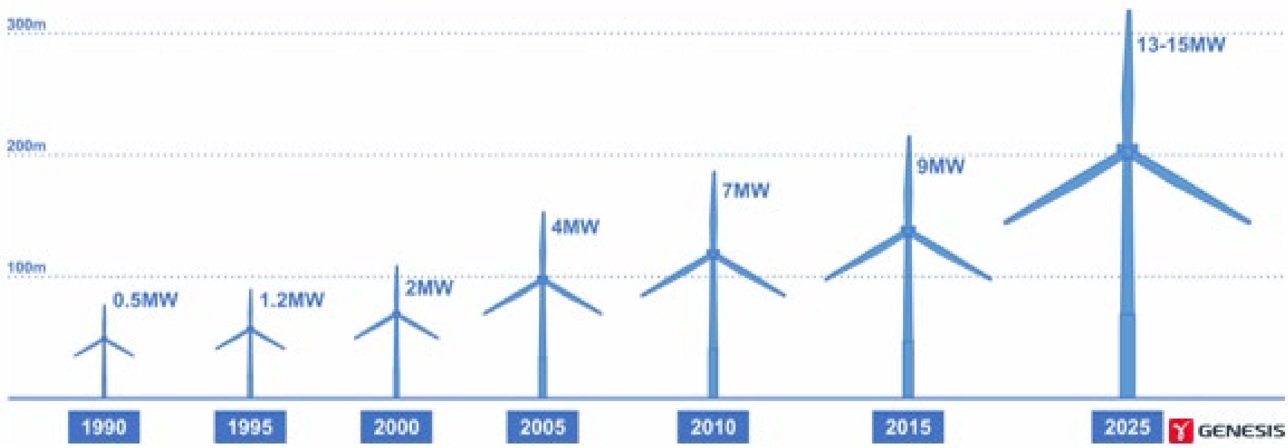


Figure 2-2. Evolution of wind turbine size and capacity (0.5MW/<100m in 1990 to 13-15MW/>300m in 2025) (adaptation created by Genesis, based on Bloomberg New Energy Finance, 2017)

In terms of wind farm layout, turbine spacing is not dependent on the type of foundation selected (Horwath *et al.*, 2020). In order to minimise inter-array wake loss effects and maximise annual power output, offshore wind turbines (both fixed and floating) are typically installed a distance of five to seven rotor diameters apart (ORE Catapult, 2021a).

As the wind turbines deployed on floating foundations are likely to be similar to fixed foundation turbines in terms of capacity, dimensions, and spacing of individual turbines; identified receptors and environmental impacts concerned with the above water wind turbine components are unlikely to differ significantly between fixed and floating foundations.

Below water

At the time of writing, the Crown Estate design envelope for the below water components of FLOW structures in the Celtic Sea is less well-defined than that for the above water elements. The best available knowledge at present on the potential Crown Estate design envelope for below water components of a FLOW turbine for the Celtic Sea is summarised in Table 2-3.

Current understanding from the Crown Estate is that any of the floating foundation types (spar, semi-submersible, tension leg platforms, barge) could be used within the Celtic Sea, whilst the type and number of moorings and anchors will depend upon the selected floating foundation and the loading conditions. Possible configurations of floating foundation structures are provided in Table 2-4.

Any mooring line types (catenary or tensioned) could be used within the design envelope. A maximum of nine mooring lines and a minimum of three mooring lines per turbine is currently advised by the market. In some cases, mooring lines may share anchors (e.g., Hywind Tampen (Lunde *et al.,* 2021)). This may result in an increased mooring line length. Possible configurations of mooring lines are provided in Table 2-5.

In terms of anchor type, there is a wide range of potential technologies available (i.e., driven piles, suction caissons, or drag embedment anchors). The type of anchor will depend on site characteristics such as geology and sediment type. Developers will have preferred technology types; however, the market is not yet mature enough to predict exactly what these preferences will be in the long term. Possible configurations of anchor types are provided in Table 2-6.

In terms of the design envelope for inter-array cables, the arrangement of the cables connecting the turbines into an array is determined by the layout of the wind farm, which is optimised for production of power given the prevailing wind direction on site. Cable array design would be decided upon and optimised once floating foundation type is confirmed for a FLOW farm. For FLOW, the use of dynamic power cables is required between the floating foundations and the seabed, as opposed to the static cables used for fixed foundation. Possible configurations for inter-array cables are provided in Table 2-7.

Further information on each of the below water elements (floating foundations, mooring lines, anchors, and inter-array cables) is provided in the following sections.

Table 2-3. Summary of FLOW below water design parameters from available literature

Parameter	Minimum value	Maximum value
Floating foundation type	Any	Any
Floating foundation draft (m) [d]	7	100
Floating foundation material [e]	Steel or concrete	Steel or concrete
Mooring line type [j]	Any	Any
Mooring line number (per turbine) [c][i]	3	9
Mooring line length (total) (m) [note 3] [j][m]	559 [note 1]	936
Mooring line length resting on the seabed [note 3] (m) [e][j]	0 [note 2]	300
Mooring line radius (m) [j]	800	1,500
Mooring line footprint (km^2) [note 3] [e]	0 [note 1]	2.5
Mooring line material [d] [f]	Steel chain, steel wires/cables, or synthetic/polyester rope	Steel chain, steel wires/cables, or synthetic/polyester rope
Anchor type [j]	Any	Any
Anchor number (per turbine) [a][b][e][i]	3	9 [i]
Anchor footprint (m^2)	Information unavailable	Information unavailable
Anchor weight (tonnes) [note 3] [e][j]	15 [j][l]	300 [e][k]
Anchor penetration depth (m) ([note 3] [j]	Information unavailable	6 [j]
Voltage of inter-array cables (kV) [note 3] [h][g]	33 [h]	66 (potentially up to 132) [g][n][o]

[note 1] Derived from a modelling study of a 15 MW FLOW turbine in 200 m water depth.

[note 2] Footprint on the seabed will be 0 km^2 where taut mooring lines are the selected mooring system, as no part of the mooring line rests on the seabed.

[note 3] Ranges identified from literature review

Sources:

[a] Balakrishnan *et al*., 2020

[b] Timmington & Efthimiou, 2022

[g] Vattenfall and RSK, 2021

[h] Kincardine Offshore Wind Ltd., 2018

[i] Highland Wind Limited, 2022.

[j] Hexicon., 2022 / Hexicon., 2018

Parameter	Minimum value	Maximum value
[c] Maxwell *et al*., 2022 [d] ORE Catapult, 2021a [e] Brocklehurst and Bradshaw., 2022 [f] Monfort, 2017	[k] Lunde *et al.,* (2021) [l] Floatgen (2018) [m] Pan *et al* (2021). [n] ORE Catapult, 2022b [o] ORE Catapult, 2021b	

Types of floating foundation

In contrast with fixed foundation wind turbines, which are secured directly to the seabed (typically via monopile or jacket foundations), FLOW turbines are installed on floating foundations (otherwise known as substructures or platforms) that are anchored to the seabed via mooring systems. There are currently over 50 different floating foundation designs under development (varying significantly in their technology readiness levels), however, they can generally be grouped into four broad categories (ORE Catapult, 2021a):

- spar buoy
- semi-submersible
- barge
- tension leg platform (TLP)

The choice of foundation design for a FLOW development depends on a number of factors and installation site parameters, such as proximity to the shore, water depth, oceanography considerations, and seabed characteristics. Every foundation design has advantages and disadvantages that should be taken into consideration.

Table 2-4 presents a comparison between the four main floating foundation types, which are illustrated in Figure 2-3. The following subsections provide further details on each type.

Table 2-4. Comparison of FLOW foundation types

Detail	Spar buoy	Semi-submersible	Barge	TLP
Structure configuration [b]	Simpler structure configuration, tall and large size hull	Complex structure configuration, large size structure	Simple design, small draft	Small size structure
Primary stability mechanism [a][b]	Ballast	Buoyancy	Buoyancy	Moorings
Stability comment	Good stability	Less stable	Large flotation system that provides good stability	Good stability, but susceptible to high-frequency dynamic loads
Typical draft (m) [a]	70-100	15-20	7-10	15-25
Typical length / width (m) [a]	10-20	60-80	40-50	20-35
Water depth (m) [a][b]	Over 100	Over 40	Less than 40	Over 40-50
Compatible mooring systems [a][b]	Catenary likely (taut / semi-taut possible), simple mooring system with low cost	Catenary likely (taut / semi-taut possible), simple mooring system with low cost	Catenary likely (taut / semi-taut possible), simple mooring system with low cost	Taut, complex tendon system with high cost
Compatible anchor types [a]	Drag-embedment, suction caisson, driven pile, helical pile	Drag-embedment, suction caisson, gravity, driven pile, helical pile	Drag-embedment	Suction caisson, gravity, driven pile

Detail	Spar buoy	Semi-submersible	Barge	TLP
Installation method [b]	Challenging due to tall hull, heavy lift vessel may be required, high cost	Tug-towing transport and low cost, turbine installed at dockside	Tug-towing transport and low cost, turbine installed in dockside	Tug-towing transport and low cost, turbine installed in dockside
Advantages [a]	• Low sensitivity to wave motion. • Natural stability • Simpler design reduces cost and complexity of manufacturing.	• Smaller draft and natural stability offer flexible wind farm water depth, quayside assembly (shallow water depth), and tow-to-port operations.	• Smaller draft and natural stability offer flexible wind farm water depth quayside assembly (shallow water depth), and tow-to-port operations. • Simpler design for manufacture and assembly (compared to semi-submersible).	• Smaller draft offers flexible wind farm water depth, quayside assembly. • Great stability once installed. • Small mooring footprint.
Disadvantages [a]	• Large draft means limited to deeper wind farm locations and difficult tow-to-port. • Potential solution is to tow structure at an inclined angle and assemble on-site. • Assembly requires deep water facility and expensive offshore heavy lift vessels.	• Heavier, more complex design can increase the cost of fabrication. • Greater sensitivity to wave loading.	• Greater sensitivity to wave loading. • Predominantly concrete designs require higher structural mass to achieve buoyancy.	• Reliance on mooring system for stability Increases cost and complexity of assembly and towing. • Mooring system subject to higher stresses throughout project lifecycle. • Currently the least commercially advanced design.

Sources:
[a] ORE Catapult, 2021a
[b] Empire Engineering, 2021

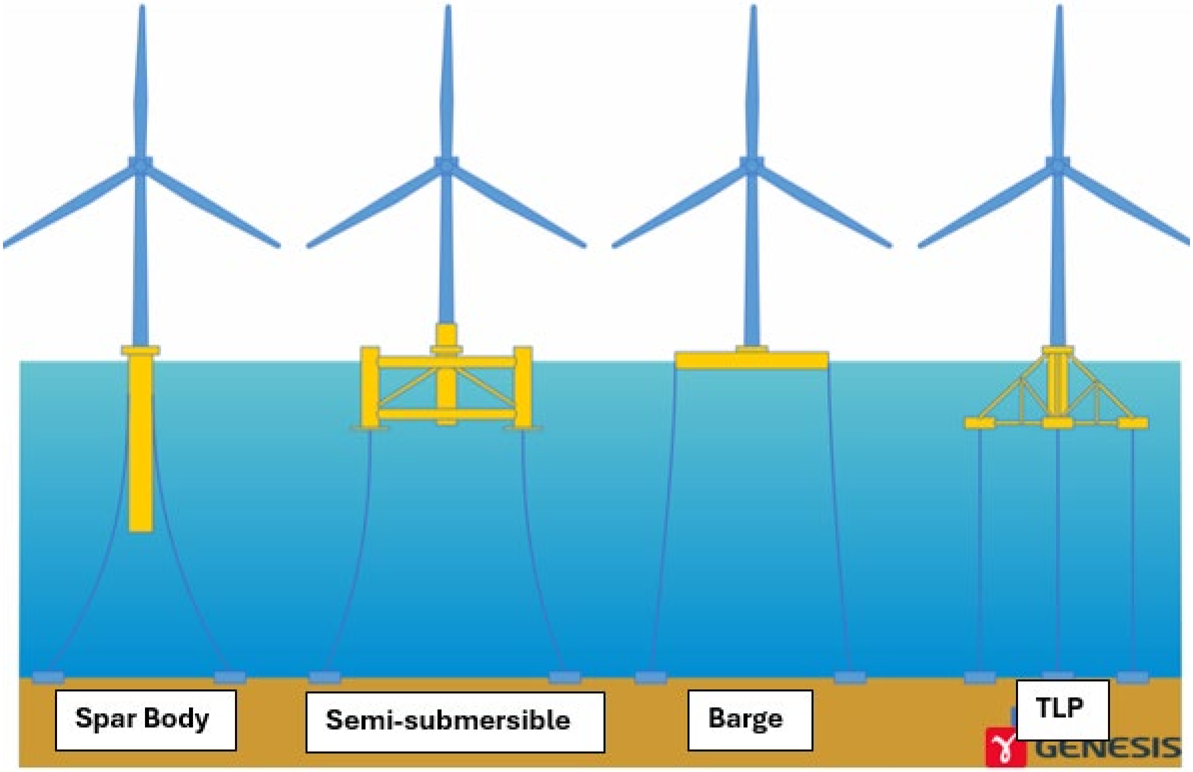


Figure 2-3. FLOW foundation types(L-R, Spar Body, Semi-submersible, Barge, TLP)

Spar buoy

Spar buoy floating foundations are typically of a cylindrical design that resembles the monopile foundations commonly used in fixed foundation offshore wind farms.

Conventional spar buoys have a large draft (up to 100 m in height, with the majority of the substructure submerged below sea level). This is one of the major drawbacks of this foundation type, as they are restricted to wind farm sites with a water depth of over 100 m. Port facilities for assembly, and the route to port for maintenance is also required to consider water depth. In addition, heavy-lift vessels are required for offshore operations. A potential solution is to tow the structure at an inclined angle and assemble on-site (Andersen, 2016; IRENA, 2016).

Spar buoys comprise a weighted mass at the bottom made of concrete or steel (or a mixture of both), a large container of seawater in the middle and an air-filled hull at the top. This is a ballast-stabilised design, whereby seawater, or a combination of concrete and seawater, is used to lower the structure's centre of gravity to below its centre of buoyancy, thereby creating a natural righting motion when the floating foundation is subject to pitch and roll motions from wind or wave action (ORE Catapult, 2021a).

Spar buoys generally use a catenary mooring configuration, as due to their natural stability, the principal function of its mooring system is to provide station keeping. Despite this, taut, or semi-taut moorings can also be employed to provide greater heave control in certain environmental conditions, or to reduce manufacturing costs through reduced material usage in deeper waters. Drag or suction anchors are usually the anchor type used with spar buoy foundations (IRENA, 2016; Stevens and Rahim, 2014), though other anchor types include the driven pile (Maxwell *et al.,* 2022) and helical pile (Harris, 2019).

The Spar buoy design is less susceptible to wave loading than other floating foundation designs due to its relatively narrow cross-sectional area, small waterplane area and cylindrical form. Additional advantages include the simplicity of its design, which includes relatively few active systems or welds and therefore improves the ease of fabrication (ORE Catapult, 2021a).

The Spar buoy concept has been demonstrated by the Hywind Pilot Park, off the coast of Peterhead in Scotland (Statoil, 2015), and will be demonstrated by Hywind Tampen, which is under construction in the Tampen Area of the North Sea, Norway (Lunde *et al.,* 2021). See Appendix 4 for a summary of FLOW case studies.

Semi-submersible

Semi-submersible floating foundations typically comprise three or four buoyant columns that are connected into a platform formation by horizontal bracings or submerged pontoons.

A key advantage of semi-submersible foundations is that they have a small draft (typically a height of 10 - 20 metres), therefore water depths at the wind farm site can be as shallow as 40 m. This also means that semi-submersible foundations can be constructed onshore or at standard commercial ports with typical quayside water depths, then towed to site using conventional tugs. They can also be towed back to shore for maintenance, reducing the requirement for expensive offshore operations.

A disadvantage of semi-submersible foundations is that they have a high structural mass (and therefore high material usage), as well as a more complicated fabrication compared to other foundation designs, potentially resulting in higher manufacturing costs (Andersen, 2016; IRENA 2016).

Furthermore, the substructure’s greater exposed cross-sectional area at the water level means that semi-submersible designs are more susceptible to wave-induced motion, and there is a higher risk of corrosion effects (ORE Catapult, 2021a).

Stability is primarily achieved through buoyancy tanks contained within the columns, though the columns may also contain either passive or active ballast systems (varying from design to design). Some designs also include a horizontal heave plate to create a drag force that resists heave motions due to wave and wind effects. Due to its inherent stability, as with Spar buoy foundations, catenary mooring configurations are often utilised, although semi-taut or taut mooring configurations can also be used (Stevens and Rahim, 2014).

The semi-submersible concept is the most commonly used floating foundation type for FLOW farms at present. It has been demonstrated by the WindFloat Atlantic project near Portugal (Banister, 2017), as well as Kincardine offshore wind farm near Scotland (Kincardine Offshore Wind Ltd, 2018). In addition, a semi-submersible design has been used for the VolturnUS reference wind turbine, designed by the University of Maine (Allen *et al.,* 2020). See Appendix 4 for a summary of FLOW case studies.

Barge

The barge represents one of the earliest floating foundation design concepts. Though they share a number of characteristics with semi-submersible substructures, barges are a simpler structure with a large waterplane area and buoyancy compartments distributed throughout the platform. Barges are primarily buoyancy-stabilised and can therefore utilise catenary mooring systems to prevent drifting (Barooni *et al.,* 2022).

Advantages of barges are that they have the lowest draft of the four typologies (typically less than 10 metres in height) and thereby offer greater flexibility, both in terms of the choice of the assembly facility, and the range of wind farm locations, as barges can technically be installed in shallow water sites (less than 40 metres). Barges are also fairly simple to manufacture and install (ORE Catapult, 2021a).

A principal drawback of the barge design is that its large waterplane area makes it more susceptible to wave loading, resulting in significant stress on the turbine tower and blades (Vijay *et al.,* 2016; Maxwell *et al.,* 2022). Furthermore, barge designs, which are currently predominantly concrete, generally require a higher structural mass in order to achieve buoyancy (ORE Catapult, 2021a).

Of the four main FLOW foundation typologies, barge platforms are currently the least common design.

One example of a project utilising the barge type floating foundation is a Japanese demonstrator wind turbine; BW Ideol’s “Hibiki”, which has been in operation at Kitakyushu City since 2018. This is the most advanced barge design at the time of writing. This type of floating structure is distinguished by a rectangular annulated-shaped floating substructure with a pool at its centre (known as the moon pool), which helps counteract wave induced loading and provide further stability (BW Ideol, 2023). See Appendix 4 for a summary of FLOW case studies.

Tension leg platforms

A typical TLP configuration includes a buoyant central column upon which the turbine is installed, with arms or a surrounding lattice frame that connect to the mooring lines. The key distinguishing characteristic of the TLP when compared to the other types of floating foundation is that it derives its stability from its moorings. The mooring system generally runs vertically, or at a slight incline directly to the seabed. A TLPs buoyancy tank (or tanks) exert a buoyancy force that exceeds the weight of the platform, establishing a continuous tension between the platform and its anchors (usually suction anchors, though can also include gravity (Horwath *et al*., 2020) and driven pile anchors (Maxwell *et al.,* 2022).

A key advantage of TLPs is that once installed, the tension in the mooring system provides excellent stability, which can resist pitch, roll, sway and yaw motions from wind and wave loading. Stability is enhanced further by the TLPs small water plane area. In addition, the taut mooring configuration means that the TLP has the smallest mooring footprint on the seabed, when compared to the other foundation types. The draft is also fairly small (as with semi-submersible foundation types) and thus TLPs can be constructed and installed in shallower water (around 50 m) (IRENA, 2016). The smaller dimensions of TLPs also mean they have a lower mass and therefore lower material requirements (ORE Catapult, 2021a).

Disadvantages of the TLP design are that a special purpose vessel may be required for installation, as the structures are not inherently self-stable during transport. TLPs are not an ideal foundation choice for areas subject to seismic activity. Installation of tensioned mooring lines is costly, and the system is liable to total failure if a single mooring line is damaged (Andersen, 2016).

Whilst there is a wealth of experience of TLP applications in the oil and gas sector, it is currently the least commercially advanced FLOW foundation concept. GICON and Glosten are the first-movers of the TLP floating foundation design. The GICON-SOF prototype has been in development by GICON in Dresden, Germany since 2009 and fabrication of first full-scale prototype took place in 2014. To begin with, the TLP floating foundation design was based on a latticed structure, however, in 2015 a gravity foundation design was introduced (GICON, 2023). The PelaStar TLP was first engineered by Glosten in 2006, by adapting established TLP technology from the oil and gas industry. In 2019, Glosten received funding from the United States Department of Energy’s “ARPA-E ATLANTIS” program to develop designs for General Electric’s Haliade X 12 MW offshore wind turbine. Glosten is developing 15 MW PelaStar designs for the United States northeast coast, United States west coast, and Scotland, however, development is ongoing and there are no operational turbines as of yet (Glosten, 2014). See Appendix 4 for a summary of FLOW case studies.

Novel floating foundation designs

In recent years, researchers have proposed novel floating platforms that take advantage of the strengths of existing concepts and combine them to achieve designs that have the potential to be more cost-effective.

Fully submersible platforms combine the advantages of semi-submersible and spar buoy foundations. This concept is similar to a semi-submersible one, but the middle parts of the columns are inclined outwards, while the upper and lower parts remain upright to connect to the centre column via a set of cross braces and pontoons. This alteration lowers the platform’s centre of gravity, which is the primary source of stability in spar buoy foundations, while simultaneously increasing the moment of inertia from which semi-submersible platforms achieve stability. The dynamic response analysis of fully submersible platforms indicates that this type of floating platform has a relatively better overall dynamic performance, and the cost is 10 – 15 % lower than that of a semi-submersible platform (Zhang *et al*., 2022; Barooni *et al*., 2022).

Catamarans are frequently utilised in the maritime transportation and leisure industries; however, it has recently been suggested that converting a catamaran into a FLOW turbine support platform could be worthwhile. Catamarans are well-known for their high levels of stability and vast usable deck space, both of which would be advantageous for offshore renewable energy systems. To achieve stability, a catamaran relies on its beam (width) and demi-hull buoyancy. Stability increases with increasing beam width and length. To date, using catamarans for FLOW has been tested only at small scales and is subject to continuous research (Barooni *et al.,* 2022).

The technology of multi-turbine platform design is also currently in development, which can accommodate multiple turbines on a single platform. This concept results in a reduction of installation and mooring costs (Bashetty and Ozcelik, 2020). Coordinated by ESTEYCO, the TELWIND project is a 3-year project (beginning in 2016) co-financed by the European Commission under the H2020 program for Research and Development. TELWIND is a novel multi-body floating platform with a wide cylindrical platform and a cylindrical ballast body suspended by six tendons. The spar of TELWIND is composed of a telescopic tower and two independent concrete bodies connected by suspension tendons. The upper concrete body maintains buoyancy, while the lower concrete body serves as the ballasting body. The telescopic tower allows for wet towing of the pre-assembled system, as folding in the tower provides a more stable configuration for the structure. This floating platform is designed to withstand harsh metocean conditions (Zhang *et al.,* 2022; Barooni *et al.,* 2022). See Appendix 4 for a summary of FLOW case studies.

Types of mooring configurations

Floating foundations require mooring lines to anchor them to the seabed and maintain position over the lifetime of the development. Each floating foundation is stabilised by three to nine mooring lines anchored to the seabed (Maxwell *et al*., 2022).

For a number of mooring configurations, the mooring lines will experience some drift, leading each turbine to also drift within a certain radius of its station (Simos *et al*., 2018). It is important to consider the mooring system type when evaluating the environmental impacts of FLOW on a site, as different mooring systems have different physical footprints (i.e., the geographic space that the system occupies) and ecological footprints (i.e., the system's impact in the water column and on the seabed) both during and post-installation (James and Costa Ros, 2015).

At present, the three main types of mooring configurations are:

- catenary
- taut
- semi-taut

The materials most commonly used for mooring lines are steel chain, steel wires/cables, and synthetic/polyester rope (Monfort, 2017; ORE Catapult, 2022a). Selection of the appropriate mooring line material depends on the stiffness, weight, minimum breaking loads and mooring configuration (Monfort, 2017).

A comparison of the three main mooring configurations is presented in Table 2-5, which includes a summary of available information on a number of parameters relevant for the assessment of environmental impacts of each mooring line type. The mooring configurations are illustrated in Figure 2-4. The following subsections provide further details on each type.

Table 2-5. Comparison of FLOW mooring line configurations

Detail	Catenary	Semi-taut	Taut
Number of mooring lines per turbine [a]	3-9	3-9	3-9
Mooring configuration seabed footprint (Quantitative values unavailable)	High [note 1] Expected to have the longest length of mooring line on the seabed.	Medium [note 1] Expected to have some length of mooring line on the seabed, in between catenary and taut.	Low [note 1] Expected to have no length of mooring line on the seabed.
Mooring line length (m) [b][e][f]	Four times longer than the depth of the water column	Dependent upon mooring line angle (typically 30-45°) and the depth of the water column	Dependent upon mooring line angle (typically 30-45°) and the depth of the water column
Mooring line material [i]	Upper segment of lighter and more flexible line (such as large-diameter synthetic rope), lower segment of heavy chain	Synthetic fibres, chains, or wire moorings	Synthetic or wire ropes that have a higher elasticity in comparison to steel chains
Scour protection requirements	Information unavailable	Information unavailable	Information unavailable
Compatible floating foundation types [c]	Spar buoy, semi-submersible, barge	Spar buoy, semi-submersible, barge	Most likely TLP, but spar buoy, semi-submersible, barge possible
Compatible anchor types: examples of where used to date [g]	Suction caisson, drag embedment, driven pile, gravity anchor, helical	Suction caisson	Suction caisson, gravity anchor, driven pile, torpedo
Advantages [d][f][g][j][l]	• Familiar mooring system due to long term use in oil and gas. • Suited for deployment over deep waters.	• Flexible enough to accommodate for wave action without the added pressure of mooring chains resting on the seabed. • Smaller footprint than catenary mooring systems. • Lower cost of mooring line than catenary mooring systems.	• Small seabed footprint (2-3 times less than catenary systems). • Reduced cost of mooring lines due to shorter length. • Seabed disturbance limited to anchor footprint.

Detail	Catenary	Semi-taut	Taut
		• Suited for deployment over deep waters.	• Suited for deployment over deep waters. • Capable of withstanding large vertical loads. • Flexible assembly [h]. • Lowest risk of marine megafauna entanglement (primary, secondary, and tertiary).
Disadvantages [d][g][j][k][l]	• Portion of mooring line resting on seabed can become overlaid with sediment making restoration more challenging. • Continuous operational phase seabed disturbance from mooring line movement. • High cost as mooring lines have to be long. • Highest animal entanglement risk (including secondary entanglement on fishing gear caught in lines).	• Although shorter than catenary mooring systems, a portion of the mooring line remains on the seabed. • Continuous operational phase seabed disturbance from mooring line movement, though over a smaller area compared to the catenary configuration. • Greater cost of mooring line than taut mooring systems. • Greater risk of entanglement than taut mooring systems.	• Challenging installation process.

[note 1] In the absence of quantitative values of seabed footprints, each mooring line type has been comparatively ranked low, medium, or high in terms of estimated seabed footprint from available literature. At the time of writing, Crown Estate was commissioning work by Arup Group and it is hoped that this work could provide further information in future. In addition, future FLOW trial and demonstration sites should aim to record specific information on mooring line dimensions and scour.

Sources:
[a] Maxwell *et al* (2022).
[b] Barter *et al* (2020).
[c] Kincardine Offshore Wind Ltd, 2020).
[d] Bach-Gansmo *et al* (2020).
[e] ABC Moorings (2023).
[f] Wang (2022).
[g] Xodus Group Ltd / SMRU Consulting (2022).
[h] Golightly (2017).
[i] Lin *et al* (2019).
[j] Ikhennicheu *et al* (2020)
[k] James and Costa Ros (2015)
[l] Benjamins *et al* (2014)

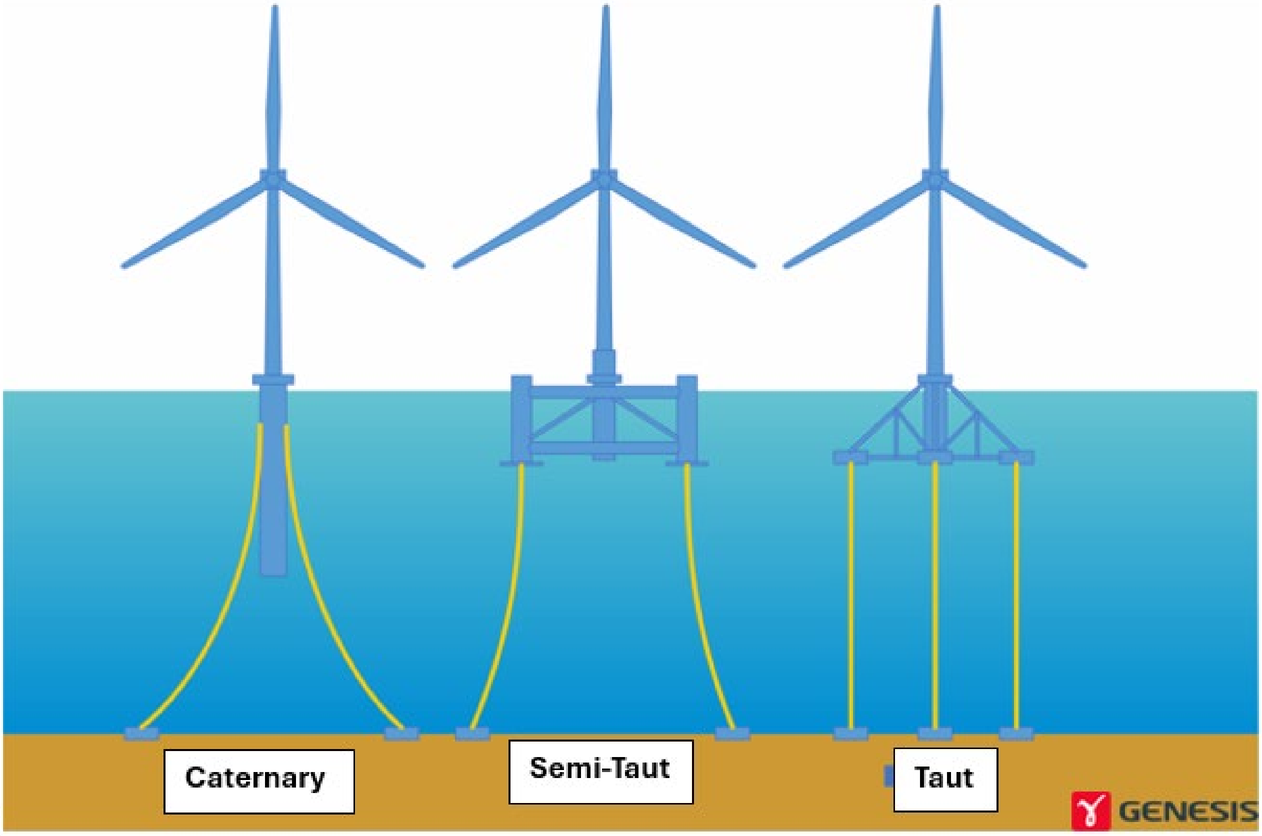


Figure 2-4. FLOW mooring configurations (L-R, Caternary, Semi-Taut, Taut)

Catenary

A catenary mooring system is the most common mooring system employed in shallow waters. Catenary mooring lines are most commonly used with the spar, semi-submersible, and barge floating foundation types. As described above, the reason for this is that the primary function of the catenary mooring system is to provide station keeping, as opposed to providing stability.

In this configuration, the mooring lines form a catenary shape, i.e., the curve that an idealised hanging chain or cable assumes under its own weight when supported only at its ends. Each line may be divided into an upper segment of lighter and more flexible line (such as large-diameter synthetic rope) that connects to the floating foundation and is suspended in the water column, and a lower segment of heavy chain that weighs down the mooring line horizontally to the seabed (Monfort, 2017). Catenary mooring lines are designed to be four times longer than the depth of the water column to account for wave action (Barter *et al*., 2020). A significant proportion of chain therefore rests on the seabed and may be lifted up and down through surface wave action moving the floating foundation and turbine. This can lead to sediment abrasion and trenching, particularly where the chain touches the seabed (Low *et al*., 2018; Thethi and Moros, 2001). The catenary mooring system has the largest relative physical and ecological footprint of the three mooring system types (James and Costa Ros, 2015).

Examples of FLOW developments that use catenary mooring lines are Hywind Pilot Park, off the coast of Peterhead in Scotland (Statoil, 2015; Lin *et al*., 2019); and Kincardine offshore wind farm near Scotland (Kincardine Offshore Wind Ltd, 2018). See Appendix 4 for a summary of FLOW case studies.

Semi-taut

Semi-taut mooring systems can be used with semi-submersible, spar buoy and barge floating foundations and represent a “compromise” between the taut and catenary systems in terms of stability and forcing. The most common mooring line materials used for semi-taut systems are synthetic fibres, chains, or wire moorings (Lin *et al*., 2019). The footprint in the water column and on the seabed of the semi-taut mooring system is considered to be medium, i.e., smaller than catenary lines, but greater than that of taut lines. The semi-taut mooring system is a combination of catenary and taut mooring whereby some parts of the line are taut and others, usually the lower portion, including that on the seabed, is catenary (Ikhennicheu *et al.,* 2020). The semi-taut system is flexible enough to accommodate for wave action without the added pressure of mooring chains resting on the seabed that occur with catenary systems (James and Costa Ros, 2015). However, dragging where the chains are on the seabed is a concern with respect to impacts on the seabed and benthic habitats (Sun *et al*., 2020).

An example of a FLOW development which uses semi-taut mooring lines is the FloatGen turbine in France (Aninthaneni, 2021). See Appendix 4 for a summary of FLOW case studies.

Taut

The taut (otherwise known as taut-leg) mooring system is the only configuration suitable for the TLP floating foundation because as described above, TLPs derive their stability from their moorings. However the system can also be used for spar buoys, semi-submersible and barge foundations (Aninthaneni, 2021). This system has taut (i.e., stretched or pulled tight) mooring lines that are typically vertical, or at a slight incline directly to the seabed (e.g., at a 45-degree angle to the seabed) (Monfort, 2017). As the name suggests, the taut mooring system does not allow for much vertical movement, meaning that these systems will experience continuous tension between the platform and its anchors, as well as a significant force acting on the anchors due to any wave action that the floating foundation and turbine experiences. Thus, the optimal line material for taut systems are synthetic or wire ropes that have a higher elasticity in comparison to steel chains (Monfort, 2017). The taut mooring system has the smallest physical and ecological footprint in the water column and on the seabed, however, it does have a more challenging installation process when compared to the catenary or semi-taut mooring lines (James and Costa Ros, 2015).

GICON and Glosten are the first-movers using taut mooring lines, as described previously in the section about TLPs. See Appendix 4 for a summary of FLOW case studies.

Types of anchors

A key component of all FLOW turbine designs is the anchoring system. For spar buoy and semi-submersible floating foundation types, the main function of the anchors is station keeping. The tension developed by TLP anchors provide both station keeping and stability to the floating structure. Different anchor designs are available for any geological seabed condition (Horwath *et al*., 2020). See Table 2-6 for further information on correlation between anchor types and seabed conditions.

FLOW technology borrows designs from the offshore oil and gas industry. Mooring and anchoring techniques have been used in the oil and gas sector for many years, however, FLOW brings new challenges. Most of the components and systems utilised in the mooring and anchoring of FLOW turbines are not novel in themselves, however, the application area and operating conditions are different. Mooring spread designs, and floating foundation movement are among the main differences in the use of anchoring for FLOW compared to applications to the oil and gas industry (Weller, 2022).

There are currently several different anchor designs available, however, the four main types currently associated with FLOW are:

- drag-embedment
- suction caissons
- gravity anchor
- driven piles (steel-driven or drilled and grouted)

All of these anchor types, with the exception of driven piles, can be removed during decommissioning. There are also a number of other anchor types being considered for FLOW, for example drop anchor / torpedo pile, vertical load anchor, suction embedded plate anchor, multi-line anchors. These novel anchors are designed to cope with the challenges of anchoring in uneven, rocky seabeds over deeper waters (Golightly, 2017). In addition, a novel multiline anchor concept has also been suggested, in which FLOW turbines share anchors instead of being moored separately. This may have the potential to increase FLOW turbine substructure efficiency and effectively reduce its cost (Fontana, 2019).

The main factors which determine optimal anchor choice for an area include mooring system configuration, soil characteristic, requirements regarding anchor loading and water depths (Castillo, 2020). Regardless of anchor design used, all anchor types will have a direct impact on the seabed and benthic ecosystem to varying degrees (e.g., from installation, trenching, or drift). Some anchors may also cause indirect impacts to the environment such as through noise from installation of pile driven anchors (Maxwell *et al*., 2022). Impacts to the seabed as a result of anchoring are described in Section 4 for the various anchor designs. Buoys will be utilised to provide appropriate marking of anchors as required during construction and operational phases.

The four main anchor types are illustrated in Figure 2-5 and Table 2-6 presents a comparison between them, as well as summarising available information on a number of parameters relevant for the assessment of environmental impacts of each anchor type. Typically, a floating foundation is stabilised by three to nine anchors (Balakrishnan *et al*., 2020; Timmington and Efthimiou, 2022; Xodus Group Ltd, 2013; Statoil, 2015). The following subsections provide further details on each type.

Table 2-6. Comparison of FLOW anchor types (Note: some cells are left deliberately blank)

Detail	Drag-embedment	Suction caisson	Gravity	Driven pile	Helical pile	Torpedo
Number of anchors per turbine [a][b][e]	3-9	3-9	3-9	3-9	3-9	3-9
Seabed footprint [note 1]	High: Quantitative values unavailable	Medium: Quantitative values unavailable	Medium: 25 m^2 for a 3-5 MW turbine	Medium: Quantitative values unavailable	Medium: Quantitative values unavailable	Low: Quantitative values unavailable
Suitable sediment type [c][d][m]	• Suitable for sandy cohesive sediment of adequate soil layering and depth. • Soft material. • No bedrock.	• Suitable for balanced seabed texture with at least an equal depth of non-consolidated clay and/or sands. Not suitable for rocky or coarse-grained seabeds. • Suited for soft clay, stiff clay, sand, stratified profiles. Some types prefer homogeneous soil layers[m].	• Medium to hard sediments, particularly rocky or sandy soils that are stable. • Generally good for sands and stiff clays but is likely favourable for rocky/thin areas[m].	• Cohesive sediment without rocks or boulders. • Suited for soft clay, stiff clay, sand, stratified profiles. Some types prefer homogeneous soil layers[m].	• Clay and sandy sediments.	• Sand, soft to medium clay [p][q]
Seabed penetration depth (m) [k][t][u]	• Dependent upon optimum fluke angle and the softness of the sediment. • Sediment layer 3-5 times fluke.	• Below the mud line – depth dependant on design optimisation. • Thick layer required – Likely	• Can be installed on thin substrate layers [k].	• Below the mud line – depth dependant on design optimisation. • Thick layer required – Likely	• Thick layer required – Likely 15 m or greater [k].	• Typically, 9-15 m [u]. • Anchor tip embedment depth up to x3 anchor length [t].

Detail	Drag-embedment	Suction caisson	Gravity	Driven pile	Helical pile	Torpedo
	length typically required [k].	15 m or greater [k].		15 m or greater [k].		
Scour protection requirements [x]	Concrete mattresses, rock placement, sand/grout filled bags, artificial seaweeds (mats composed of frond, leaf-like line, which mimics natural seaweed).	Concrete mattresses, rock placement, sand/grout filled bags, artificial seaweeds.	Concrete mattresses, rock placement, sand/grout filled bags, artificial seaweeds.	Concrete mattresses, rock placement, sand/grout filled bags, artificial seaweeds.	Concrete mattresses, rock placement, sand/grout filled bags, artificial seaweeds.	Concrete mattresses, rock placement, sand/grout filled bags, artificial seaweeds.
Compatible floating foundation types [c][i][j][k]	Spar buoy, semi-submersible, barge	Spar buoy, semi-submersible, TLP	Mainly TLP, semi-submersible	Spar buoy, semi-submersible, TLP	Spar buoy, semi-submersible	Semi-submersible
Compatible mooring systems [n]	Catenary	Catenary, semi-taut, taut	Catenary, taut	Catenary, taut	Catenary	Taut
Advantages [d][f][g][h] [i][j][l][o][r][t]	• Suited to areas of softer sediment. • Low anchor cost. • Less underwater noise produced during installation than piled anchors.	• Holding capacity independent of load angle. • Engineering and installation can be achieved by one party. • No external load tests required. • Suitable over very deep water. • Less underwater noise produced	• Can exploit areas of hard soils where conditions are not suitable for suction anchors due to soil penetration limitations. • May introduce hard substrate which can become colonised	• They are permanent, • Precisely located, • Piles will not creep, • Well suited to take vertical loading.	• Less noise and vibration than driven piles. • Simple and economic installation. • Faster installation than driven piles.	• Simple installation [h]. • Capable of taking mooring loads from all directions. • Smaller footprint than drag-embedded anchors [o]. • Regarded as one of the most efficient anchors

Detail	Drag-embedment	Suction caisson	Gravity	Driven pile	Helical pile	Torpedo
		during installation than piled anchors.	by invertebrates and fishes. • Less underwater noise produced during installation than piled anchors.			used for taut mooring systems [r]. • Suited to deep waters [t]. • Less underwater noise produced during installation than piled anchors.
Disadvantages [d][v]	• Limited to softer cohesive sediments. • Can be limited penetration in stiff clay and sandy sediments. • Not suited for any vertical loading. • Susceptible to movement.	• Limited to particular seabed sediments including sands and clays.	• Not suitable in areas of softer sediments. • Greater habitat loss for underlying habitats / seabed than other anchor types.	• High cost. • High level of noise pollution. • Potential for resuspension of contaminants.	• Increase in the depth of clayey soil could significantly impact bearing capacity.	• Challenges associated with predicting the embedment depth and the set-up after installation.

[note 1] In the absence of quantitative values of seabed footprints, each anchor type has been comparatively ranked low, medium, or high in terms of estimated seabed footprint from available literature. At the time of writing, Crown Estate was commissioning work by Arup Group and it is hoped that this work could provide further information in future. In addition, future FLOW trial and demonstration sites should aim to record specific information on anchor dimensions and scour.

Sources:

[a] Balakrishnan *et al* (2020).

[b] Timmington & Efthimiou (2022).

[c] Sclavounos *et al* (2010).

[d] Xodus Group Ltd / SMRU Consulting (2022).

[l] Harris (2019).

[m] Porter and Phillips (2020).

[n] Ma *et al* (2021).

[o] Yu *et al* (2018).

[p] Li *et al* (2022).

Detail	Drag-embedment	Suction caisson	Gravity	Driven pile	Helical pile	Torpedo
[e] Xodus Group Ltd (2013) / Statoil (2015). [f] SPT Offshore (2023). [g] Langhamer (2012). [h] Martins (2020). [i] Atkins (2016). [j] Offshore Wind Design AS (2023). [k] Kim (2014). [q] Hossain *et al* (2014). [r] de Aguiar *et al* (2013). [s] Wilde (2009). [t] Cassidy *et al* (2014). [u] Nordvik (2019). [v] Gao *et al* (2015). [w] Seifi *et al* (2023). [x] Highland Wind Limited (2022). [y] Fernandes *et al* (2011).						

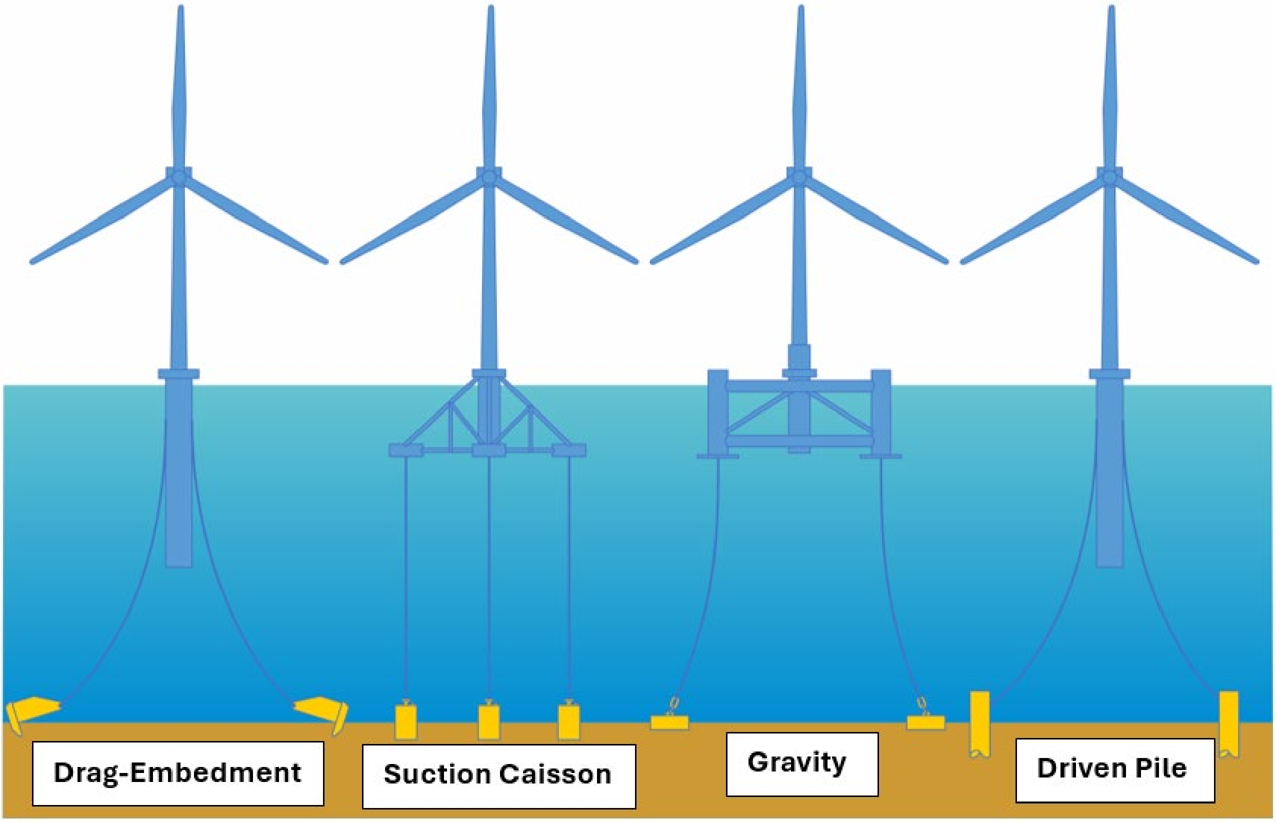


Figure 2-5 FLOW anchor types (L-R, Drag-Embedment, Suction Caisson, Gravity, Driven Pile) (Note that this image was created by Genesis for the purposes of this report)

Drag-embedment

Drag-embedment anchors (e.g., WindFloat Atlantic and Kincardine. See Appendix 4 for a summary of FLOW case studies.) function similarly to vessel anchors and are best suited to sandy sediment of adequate soil layering and depth, and no bedrock. Drag anchors are made of steel and are installed by dragging the anchor through the seabed until it reaches the required depth (Nordvik, 2019). As it penetrates the seabed, it uses soil resistance to hold the anchor in place. Setting the anchor will temporarily disturb the seafloor as the anchor is pulled into and through the sediment. Impacts of anchors on seabed disturbance are discussed further in Section 4. Once in position, drag anchors lie largely or entirely below the seafloor (Horwath *et al*., 2020). These anchors are typically used for spar buoy, semi-submersible, or barge floating foundations utilising catenary mooring lines (Ruinen, 2014). These anchors are simple to install and can be recovered during decommissioning (James and Costa Ros, 2015).

Suction caisson

Suction caisson anchors (e.g., Hywind Scotland Pilot Park (Statoil, 2015) and Hywind Tampen uses shared suction caisson anchors (Lunde *et al.,* 2021). See Appendix 4 for a summary of FLOW case studies.) are embedded into the seabed by negative pressure inside the caisson. These anchors require a balanced seabed texture with at least an equal depth of non-consolidated clay and/or sands. Suction caisson anchors can be utilised over deeper waters though are not suitable for rocky or coarse-grained seabeds. The technology, installation and decommissioning processes of this anchor type is well defined from oil and gas platforms. Anchors can be recovered during decommissioning by pumping water back into the caisson, where the pressure then lifts the anchor out of the seabed (Golightly, 2017). Suction caisson anchors can be installed at precise locations and exhibit a small installation footprint (Chung, 2012).

Gravity

Gravity anchors (otherwise known as deadweight anchors) are buried to a depth depending on their weight, geometry, and the soil characteristics. The holding power (ability to hold the turbine in place) is proportional to the weight of the anchor. Among the anchor types, gravity anchors, made of concrete or steel, have the greatest mass and the largest footprint on the seabed (Horwath *et al*., 2020). Gravity anchors are suitable for a variety of seabeds; particularly rocky or sandy soils that are stable enough to support the heavy anchor and are best suited in shallower waters. Gravity anchors are generally used in hard soils where conditions are not suitable for suction anchors due to soil penetration limitations. Sclavounos *et al* (2010) analysed the use of gravity anchors to support 3-5 MW turbines equipped with a TLP and found the anchor footprint to be 25 m^2 (per anchor). Gravity anchors can be repurposed after decommissioning.

Driven pile

Driven piles are large and hollow metal cylinders, which can be installed by vibration, driving, drilling and grouting them vertically into the seabed. These anchors are permanent and so cannot be removed during decommissioning. The anchoring site must consist of cohesive sediment without rocks or boulders (Maxwell *et al*., 2022). Driven piles utilise the same technology as that used to attach fixed turbine monopile foundations to the seabed, although the piles are smaller. They can achieve a very high vertical load capacity and can be precisely located.

Torpedo

Torpedo anchors are installed by allowing the anchor to free fall through the water column and penetrate the seabed to the targeted embedment depth upon impact (Raaj *et al.,* 2022). Given their simple application this type of anchor can provide both temporal and economic advantages during mooring installation (Martins, 2020). These anchors are capable of withstanding horizontal loads but currently perform poorly with vertical loads, leading to their limited application in FLOW thus far (Raaj *et al.,* 2022). Despite this, technological developments are continuing to advance. Successful use of these anchors in the oil and gas industry has been demonstrated in Brazil where there are estimated to be over 2,000 installed (Martins, 2020).

Helical pile

Another relatively recent anchor concept is the use of helical pile anchors. A helical pile is a steel foundation pile with a central shaft with one or more helical bearing plates. Helical piles were historically used in shallow offshore applications and have the potential to be cost effective as anchors to FLOW applications (Harris, 2019).

Helical pile foundations can be used as anchors for FLOW systems with catenary mooring lines in clay and sandy soils. The use of a spar buoy platform and multiline system decreases the required helical pile size compared to a semi-submersible platform and a single-line mooring system. Helical piles designed for use in sand sediments are smaller in size compared to helical piles used in clay sediments, due to greater strength of the sand. For efficiency, in terms of capacity per unit weight, single and groups of helical piles are more efficient than suction caissons, using less steel to produce the same capacity. For catenary mooring line systems, the helix of a vertically installed helical pile does not contribute to lateral load resistance (Harris, 2019).

Helical piles are installed into soil using rotation, which requires torque to overcome frictional resistance at the soil-steel interface. Smaller surface area thus reduces the installation torque required. Methods of installation include use of a hydraulic torque drive that rotates the lead section into the ground (Harris, 2019).

The installation is very quiet compared to other anchor types, such as driven piles, which send pressure waves through the ground during installation. For sites with noise sensitivity, using helical piles would be advantageous over driven piles. Helical piles can also be removed by torqueing in the opposite direction, which makes decommissioning structures with this anchor method simple and potentially quicker than other methods (Harris, 2019).

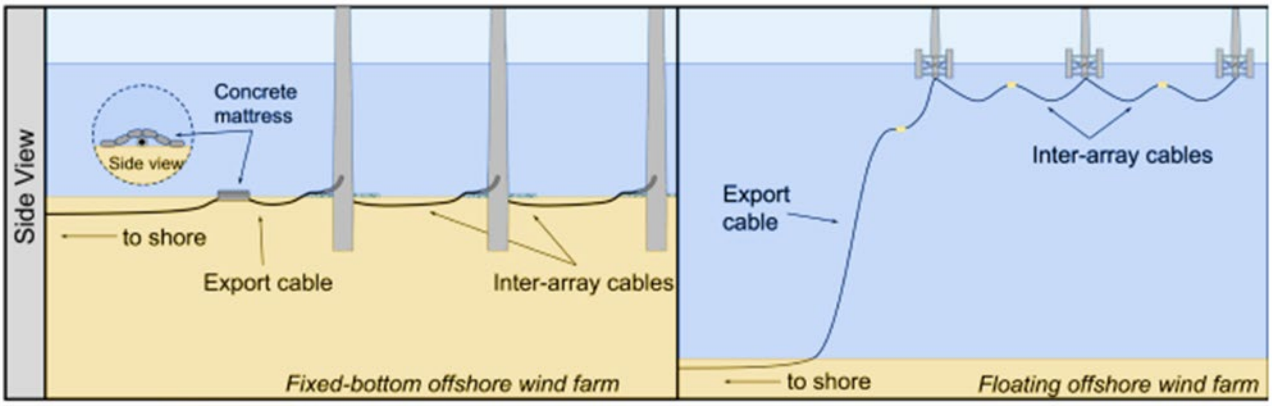
Disadvantages of helical piles are that the slim shaft and relatively small downward force applied during installation mean that helical piles are unable to penetrate bedrock without pre-drilling. Similarly, helical piles can face refusal in soils with high boulder content. In addition, there has been minimal research to date for deep water installation methods of helical piles, which would be necessary for successful application to FLOW developments (Harris, 2019).

Inter-array cables

As the electrical export cables that connect an offshore wind farm to the onshore power grid are typically the same (buried and protected within the seabed) for both fixed and floating foundation turbines, the impacts of export cables are out with the scope of this report and thus only the inter-array cables are described in this section. Note, as the end section of the export cable is suspended in the water column for FLOW, this dynamic section of the export cable should be considered in future works on FLOW developments.

Similarly, offshore substations (the systems that collect and export the power generated by turbines) are out with the scope, as these structures are the same for both floating and fixed offshore wind farms.

Inter-array cables are electrical cables that connect individual wind turbines to each other. To connect floating turbines together (and to export power to shore), the use of dynamic power cables is required between the floating foundation and the seabed, as opposed to the static cables used for fixed foundation (ORE Catapult, 2022b). Figure 2-6 illustrates the power transmission system of a FLOW farm (Rentschler, *et al.,* 2020) and Figure 2-7 highlights the differences between electrical cable use in fixed foundation and FLOW farms (U.S. Offshore Wind Synthesis of Environmental Effects Research (SEER), 2022d).



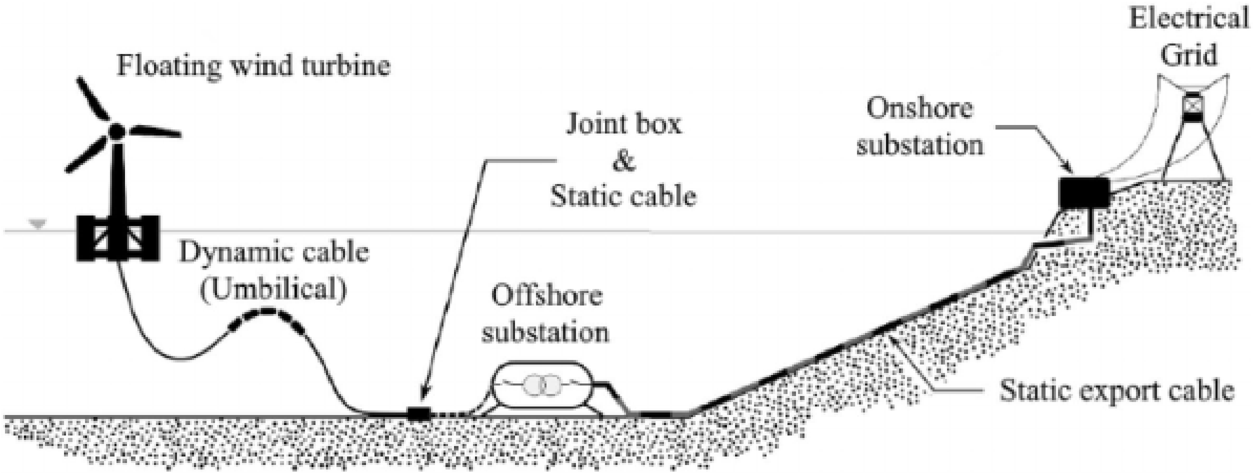


Figure 2-6. Power transmission system of a floating offshore wind farm (Krügel, 2017; Rentschler, *et al.,* 2020)

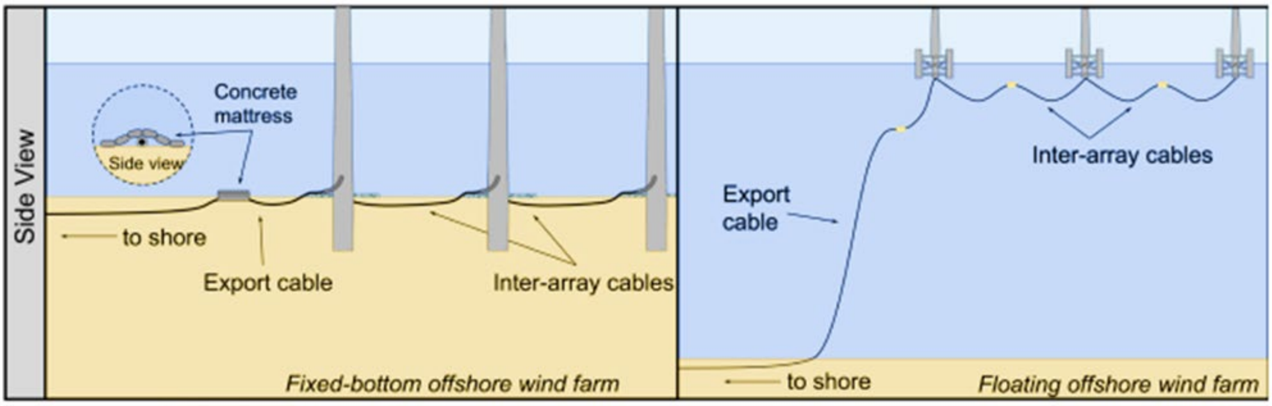


Figure 2-7. An illustration of how electrical cables are used at fixed-bottom and FLOW farms (SEER, 2022d)

The dynamic array cables for FLOW are suspended freely in the water column, as it is necessary that they are designed to compensate for the movement of the floating foundation and the forces of the water column. The presence of dynamic inter-array cables in the water column presents a key difference between FLOW and fixed foundation offshore wind.

Dynamic cable systems can be located in a particularly harsh part of the marine environment and are subject to complex static and dynamic mechanical, thermal and electrical loading, in addition to abrasion and other environmental impacts and interactions. The relatively shallow water of many UK FLOW sites (60 – 120 m) means dynamic loading on dynamic inter-array cable systems is increased (ORE Catapult, 2022d).

Table 2-7 summarises available information on a number of parameters relevant for the assessment of environmental impacts of inter-array cable designs. However, whilst the general principles of the design and specification of these systems are well understood, the specifics of the system design process, representative testing and qualification approaches are complex and a number of knowledge gaps exist (ORE Catapult, 2022d).

Dynamic cables are complex systems, with significant variation in the scope, scale, function and complexity of the different system components and technologies. There are many possible configurations in which the dynamic power cable can be attached to the floating foundation (ORE Catapult, 2022b). The two main dynamic inter-array cable configuration designs are; the catenary configuration (free hanging, extending to the seafloor under its own weight), or the “lazy wave” configuration (buoyancy elements added to the intermediate part of the cable such that the cables do not touch the seafloor) (Rentschler *et al*., 2020). In FLOW projects, tethered lazy wave configurations are commonly used as they can better accommodate the large motions from the floating foundation (ORE Catapult, 2022b). In addition, the lazy wave configuration is better suited to deeper water (Rentschler *et al*., 2020). There are many variations to the lazy wave configuration, such as optimised lazy wave, high lazy wave, or lazy “s” (stretched). The quantity of buoyancy elements required varies with water depth and cable size. Should catenary cable configurations be utilised then the requirement for buoyancy modules to create the lazy wave shape would be eliminated for these systems (ORE Catapult, 2022b).

An example of dynamic inter-array cable design using the lazy wave configuration is the TwinHub FLOW demonstration project, which uses buoyancy and sealed ballast modules attached to the midpoint of the cable. This allows the configuration of the cable to be extended and shaped in response to the movements of the floating platform and decouples the floater motions from the fixed end of the static cable (Hexicon, 2022). The Kincardine offshore wind farm also has unburied inter-array cables held in a lazy wave profile (Kincardine Offshore Wind Ltd., 2018).

Dynamic inter-array cables are stabilised by bend stiffeners, intermediate buoys, sinkers, touchdown protection or other devices / configurations to stabilise (Taninoki *et al.,* 2017). Bend stiffener connectors are found at the interface of the inter-array dynamic cable with the floating turbine substructure. They have traditionally been used in oil and gas applications; however floating wind brings additional challenges. Notably, a significant increase in the number of connectors required, as well as many more connect and disconnect cycles than would be expected in oil and gas (ORE Catapult, 2022d).

The depth of the dynamic array cable in the water column depends on the specific design of an offshore wind farm. Inter-array cables are often buried in fixed foundation offshore wind installations. In fixed wind, rock placement may also be used as a protection method where the rock size is chosen to be small enough to avoid cable damage and large enough to give suitable long-term protection (ORE Catapult, 2022b). In some cases of FLOW, the inter-array cables may also be buried or weighted where they reach the seabed, between the floating substructures they connect (Maxwell *et al*., 2022). Where the inter-array cable touches down on the seabed, specially designed protection sleeves known as Touchdown Abrasion Protection Sleeves are used around the cable's touchdown point to protect the outer layer of the cable (ORE Catapult, 2022b).

Whether buried or surface laid, the inter-array cables between the turbines represent a sizable physical and ecological footprint, particularly for a commercial-scale project (Maxwell *et al*., 2022).

There are two basic seabed layouts that can be used when designing the power-collector arrays for offshore wind farms – strings and loops. String-based array cable layouts form a 'tree' structure and loop-based structures form closed loops (Figure 2-8).

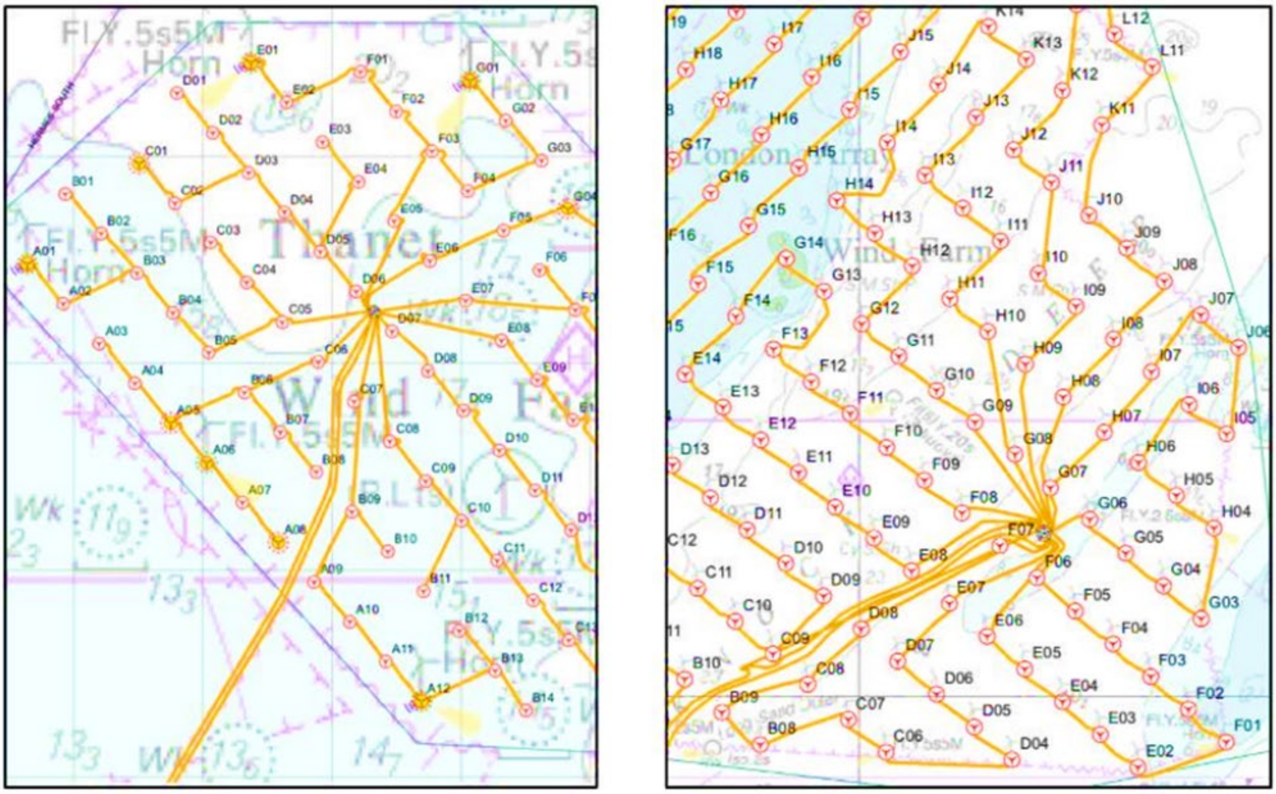


Figure 2-8. Comparison of string and loop inter-array cable layout on the seabed. Left – string; Right - loop (PLOCAN, 2021)

Both configurations have their own advantages and disadvantages. Loop-based array cable layouts have greater resilience: an array cable fault has a reduced impact on power output and no impact on the continuity of auxiliary power supplies for the turbine. The downside is that loops tend to be more expensive since additional cables are required. String-based array cable layouts, in contrast, offer lower capital costs but are less resilient if a fault occurs (PLOCAN, 2021).

The greater resilience of loop-based array cable layouts is advantageous for FLOW dynamic cables, which are subject to additional stresses and thus are potentially at greater risk of failure. Secondly, many FLOW farm concepts envisage that turbines may need to be disconnected and towed back to port for major maintenance activities. This could have a severe impact in a string-based array, while the greater resilience of loop-based approaches would help mitigate this impact (PLOCAN, 2021).

For this reason, it is likely that loop-based array cables may be used for FLOW, which would cause increased disturbance to the seabed in comparison to string-based design.

Table 2-7. Comparison of FLOW inter-array cable configuration and layout designs

	Configuration		Layout	
Detail	**Catenary configuration**	**Lazy wave configuration**	**String-based seabed layout**	**Loop-based seabed layout**
Description	Free hanging, extending to the seafloor under its own weight	Buoyancy elements on the intermediate part of the cable such that the cables do not touch the seafloor	'Tree' structure where turbines are connected to a substation by strings of turbines	Closed loop where turbine strings are coupled in loops using redundant minimum-capacity cables between strings, that avoid disconnected turbines in case of cable failure.
Number of inter-array cables in a wind farm [d]	Based on number of turbines	Based on number of turbines	Based on number of turbines, but lower number of cables than loop-based layout [d].	Based on number of turbines, but higher number of cables than string-based layout [d].
Cable size / length [f][d]	• Based on wind farm layout and voltage, water depth dependent [f]. • Shorter dynamic cable lengths than lazy wave configuration (e.g., around 1.3 times water depth in the dynamic portion) [f].	• Based on wind farm layout and voltage, water depth dependent [f]. • Longer dynamic cable lengths than catenary (e.g., around 2 times water depth) [f].	• Based on wind farm layout and voltage, water depth dependent [f]. • Shorter cable length than loop-based layouts [d].	• Based on wind farm layout and voltage, water depth dependent [f]. • Longer cable length than string-based layouts [d].
Depth in water column	• Inter-array cables extend from the floating foundation structure, down to the seabed. • Depth in water column is thus based on draft of the floating foundation type,	• Inter-array cables extend from the floating foundation structure, down to the seabed. • Depth in water column is thus based on draft of the floating foundation type,	• Inter-array cables extend from the floating foundation structure, down to the seabed. • Depth in water column is thus based on draft of the floating foundation type,	• Inter-array cables extend from the floating foundation structure, down to the seabed. • Depth in water column is thus based on draft of the floating foundation type,

	Configuration		Layout	
Detail	**Catenary configuration**	**Lazy wave configuration**	**String-based seabed layout**	**Loop-based seabed layout**
	which can range from 7 m (barge) to 100 m (spar).	which can range from 7 m (barge) to 100 m (spar).	which can range from 7 m (barge) to 100 m (spar).	which can range from 7 m (barge) to 100 m (spar).
Cable material [f]	Copper	Copper	Copper	Copper
Voltage (kV) [a][b][f]	33 – 66 (potentially up to 132)	33 – 66 (potentially up to 132)	33 – 66 (potentially up to 132)	33 – 66 (potentially up to 132)
Seabed footprint [note 1] [d][e]	High [note 1] [d] Quantitative values unavailable	Low [note 1] [d] Quantitative values unavailable	Low [note 1] [e] Quantitative values unavailable	High [note 1] [e] Quantitative values unavailable
Installation method [f]	Installation contractors and cable lay vessels will be required for cable pre-laying (with pre-trenching or simultaneous trenching for buried cables), as well as cable hook up to the floating platform. Installation aids and accessories such as winches may be required.	Installation contractors and cable lay vessels will be required for cable pre-laying (with pre-trenching or simultaneous trenching for buried cables), as well as cable hook up to the floating platform. Installation aids and accessories such as winches may be required.	Installation contractors and cable lay vessels will be required for cable pre-laying (with pre-trenching or simultaneous trenching for buried cables), as well as cable hook up to the floating platform. Installation aids and accessories such as winches may be required.	Installation contractors and cable lay vessels will be required for cable pre-laying (with pre-trenching or simultaneous trenching for buried cables), as well as cable hook up to the floating platform. Installation aids and accessories such as winches may be required.
Burial status [f][b]	Unburied to 0.5 m burial [f]	Unburied to 0.5 m burial [f] FLOW cables generally not planned to be trenched, unless required for physical stabilisation on the seabed. Exceptions to this may be the cables which have significant length outside of the anchor pattern between	Unburied to 0.5 m burial [f]	Unburied to 0.5 m burial [f]

Detail	Configuration		Layout	
	Catenary configuration	**Lazy wave configuration**	**String-based seabed layout**	**Loop-based seabed layout**
		turbines. Maximum of 10 % of total cable length likely to be buried [b].		
Cable protection requirements [c]	Tethers and anchor systems, bend stiffeners, abrasion protection, touch down protection (Touchdown Abrasion Protective Sleeves), bend restrictors [c].	Tethers and anchor systems, bend stiffeners, abrasion protection, touch down protection (Touchdown Abrasion Protective Sleeves), bend restrictors [c].	Information unavailable	Information unavailable
Scour protection [b]	Information unavailable	None considered [b]	Information unavailable	Information unavailable
Advantages [c][d][e]	• Shorter cable length required [f].	• Can better accommodate the large motions from the floating foundation [c]. • Better suited to deeper water [d].	• Lower capital costs due to shorter cable length [e].	• Greater resilience to inter-array cable faults, as electricity can still be exported following a cable outage [e].
Disadvantages [c][d][e][f]	• Less able to accommodate the large motions from the floating foundation [c]. • In deep water above 100 m, the catenary shape is not feasible due to the critical tension at the hang-off [d].	• Longer cable length required [f]. • Feasible for water depths greater than 200 m as the lazy wave configuration cuts tension almost by half of catenary configuration [d].	• Less resilient if a fault occurs and are particularly vulnerable if an array cable near the substation should fail [e].	• More expensive as additional cables are required [e].

[note 1] In the absence of quantitative values of seabed footprints, the two mooring configurations have been assessed.
Sources:
[a] Vattenfall and RSK, 2021
[b] Kincardine Offshore Wind Ltd., 2018
[c] ORE Catapult, 2022b

	Configuration		Layout	
Detail	Catenary configuration	Lazy wave configuration	String-based seabed layout	Loop-based seabed layout
[d] Rentschler *et al.,* 2020 [e] PLOCAN, 2021. [f] ORE Catapult, 2021b				

3. Identification of environmental receptors

Several environmental receptors are considered in this report including benthic communities (species living on or in the seabed), pelagic communities (those inhabiting the water column i.e., plankton, zooplankton, fish, and marine mammals), and avian communities (seabirds and sea ducks). In addition to ecological communities, key physical characteristics (such as bathymetry and metocean conditions), as well as socio-economic receptors (i.e., other users of the sea) have also been described.

This section aims to address Objective 2 in part, by identifying those environmental receptors that may be impacted by potential FLOW sources of impact and pressure pathways, and therefore require assessment in Section 4. Consideration has been given to which receptors may be unique to FLOW projects or be impacted in a different way to fixed foundation offshore wind.

Bathymetry

When considering the development of a FLOW farm, it is important to understand bathymetry in an area. As described previously, FLOW can operate in water depths up to 1,000 m, whereas fixed foundation turbines are limited to depths of 60 to 80 m (Paya and Du, 2020). At the shallower depths, fixed foundation wind turbines are expected to be more economical than FLOW foundations (Horwath *et al*., 2020). Though some types of FLOW foundation (semi-submersible, barge, and TLP) could be installed in water depths as low as 30 m, the current cost of floating foundations is two to three times that of fixed foundations, such that it is not economically feasible for shallow water depths where fixed foundations can be installed.

The costs of the overall floating system (foundation and mooring system) will increase with water depth (Crown Estate, 2023).

The Celtic Sea is a low-gradient shelf sea, which stretches to the edge of the European continental shelf (Somerfield *et al.,* 2019). It is bordered to the north by Ireland, by England and Wales to the east. The western extremity of the Celtic Sea borders the southeast side of Brittany. In general, the Celtic Sea has relatively deep water, with large tidal ridges found on the mid and outer shelf of the Celtic seabed (Somerfield *et al.,* 2019). The deep water is primarily the reason that the wind resource in the area has not been utilised much to date. The bathymetry of the Celtic Sea is shown in Figure 3-1. Areas in light blue highlight depths shallower than 60 m, or deeper than 200 m, which indicates their assumed unsuitability for FLOW.

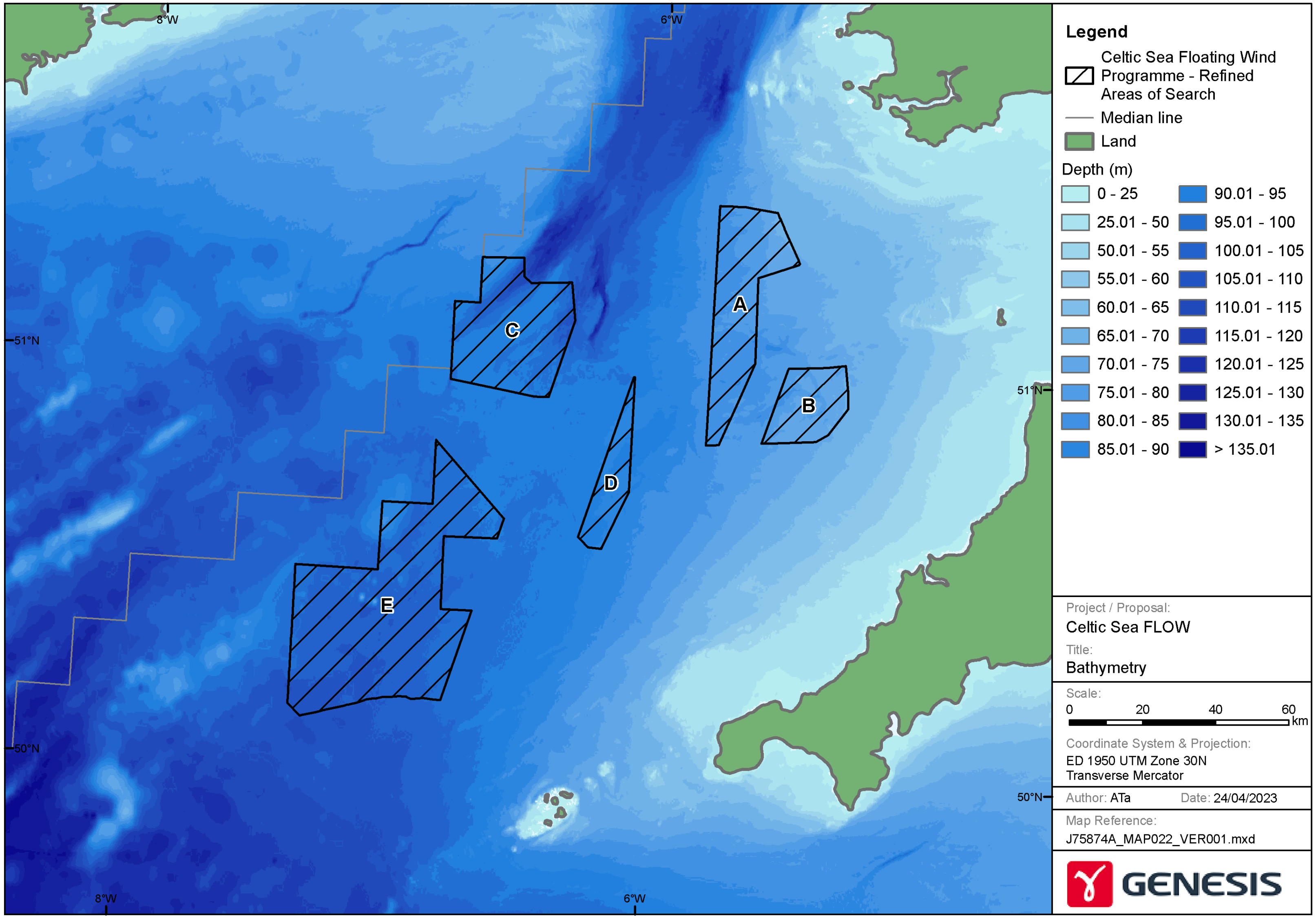


Figure 3-1. Bathymetry in the Celtic Sea showing Celtic Sea Floating Wind Programme areas of search (ORE Catapult, 2020)

Metocean conditions

Metocean conditions refer to the combined wind, wave, current and climate conditions as found at a certain location. The type of floating foundation selected for a FLOW farm site depends on the Metocean conditions, and FLOW concepts can be deemed unsuitable for a site if metocean conditions are particularly challenging. As metocean conditions become more onerous, floating foundations and mooring and anchoring systems have to accommodate higher extreme loads, becoming more complex and expensive (Crown Estate, 2023). For example, significantly high wave height can induce high dynamic response of the floating foundation that may exceed the limit of motion, acceleration and heel angle of the turbine. One aspect is that high pitch motions can induce unacceptable loads on one side, and loss of efficiency on the other side. In addition, strong currents could lead to floating foundation offset, which, together with dynamic motions, can make the dynamic cable design impossible to work. A site with low average wave height would be desirable, however, usually this does not coincide with sites offering the desired high wind speed (James and Costa Ros., 2015).

Blue Gem Wind, the joint venture between TotalEnergies and Simply Blue Group has recently deployed a floating Light Detection and Ranging (LiDAR) system to the proposed Valorous project site in the Celtic Sea. The purpose of this is to provide weather data at the site for a number of key parameters such as wind, wave and current data. The weather data from the LiDAR is available for public use on the Blue Gem Wind website. Table 3-1 summarises the available data at the time of writing. Some of these parameters are discussed in more detail in the following subsections.

Table 3-1. Weather data from the Valorous project site in the Celtic Sea (Last updated 15/03/2023 11:35AM; Blue Gem Wind, 2023)

Parameter	LiDAR values reported at the Valorous site
Wave height	2.01 m
Wave period	10.20 seconds
Mean wave direction	229.70 ° southwest
Surface wind direction	158.60 ° south southeast
Surface wind speed	10.16 m/s
Air temperature	8.94 °C
Humidity	89.20 %
Barometric pressure	1011.66 mbar
Sea surface temperature	9.49 °C
Surface current speed	0.36 m/s
Surface current direction	18.50 ° north northeast

Wind speed

Wind speed is an important factor in the success of any FLOW project. Wind speed across the Celtic Sea, and much of the UK, is relatively high, with averages being regularly above 9 m/s at a height of 100 m. The Celtic Sea specifically has average wind speeds of approximately 9.5 m/s, which is suitable for high yields, indicating that wind energy will be commercially viable in the region. As described in the Bathymetry section above, this resource has not been utilised primarily to date due to the area's relatively deep water, which increases project costs, making offshore wind previously un-economical. However, due to falling costs of offshore wind technology and advancement of FLOW developments, there is now the potential to harness the wind resource in the Celtic Sea. The wind rose in Figure 3-2 demonstrates that the highest wind speeds occur in the west and southwest (Saha *et al.,* 2010).

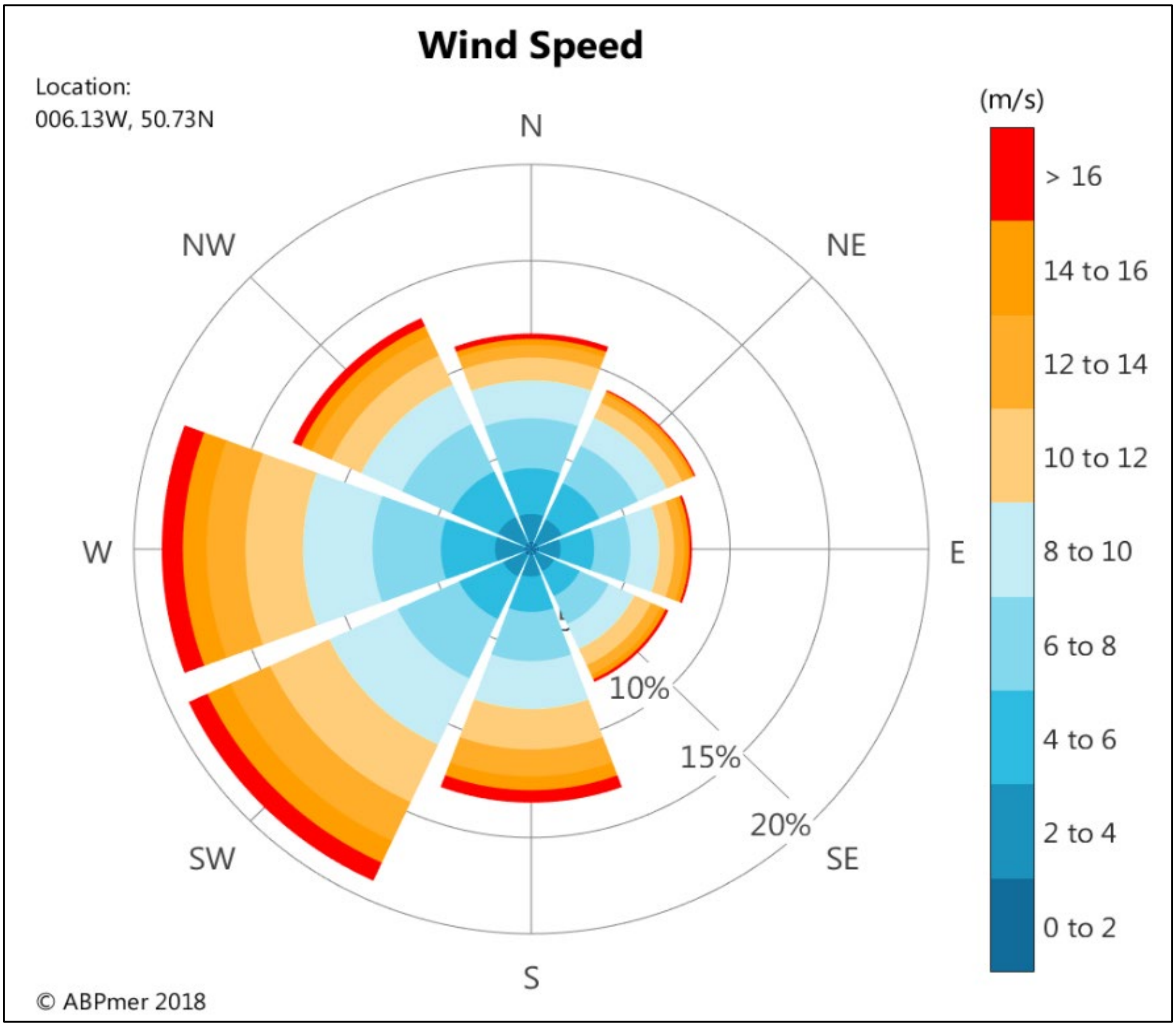


Figure 3-2. Wind rose for the Celtic Sea (Specifically, Refined Area of Search D) (Saha *et al.,* 2010)

Wind speed throughout the Celtic Sea is illustrated in Figure 3-3. It can be seen in that the further from shore, the higher average wind speeds will be. Wind speeds are greatest in the southwest of the region, however, the wind resource across the whole of the region presents excellent opportunity for wind power. Site selection is therefore not so reliant on wind speed in this area as all locations have good resource (ORE Catapult, 2020).

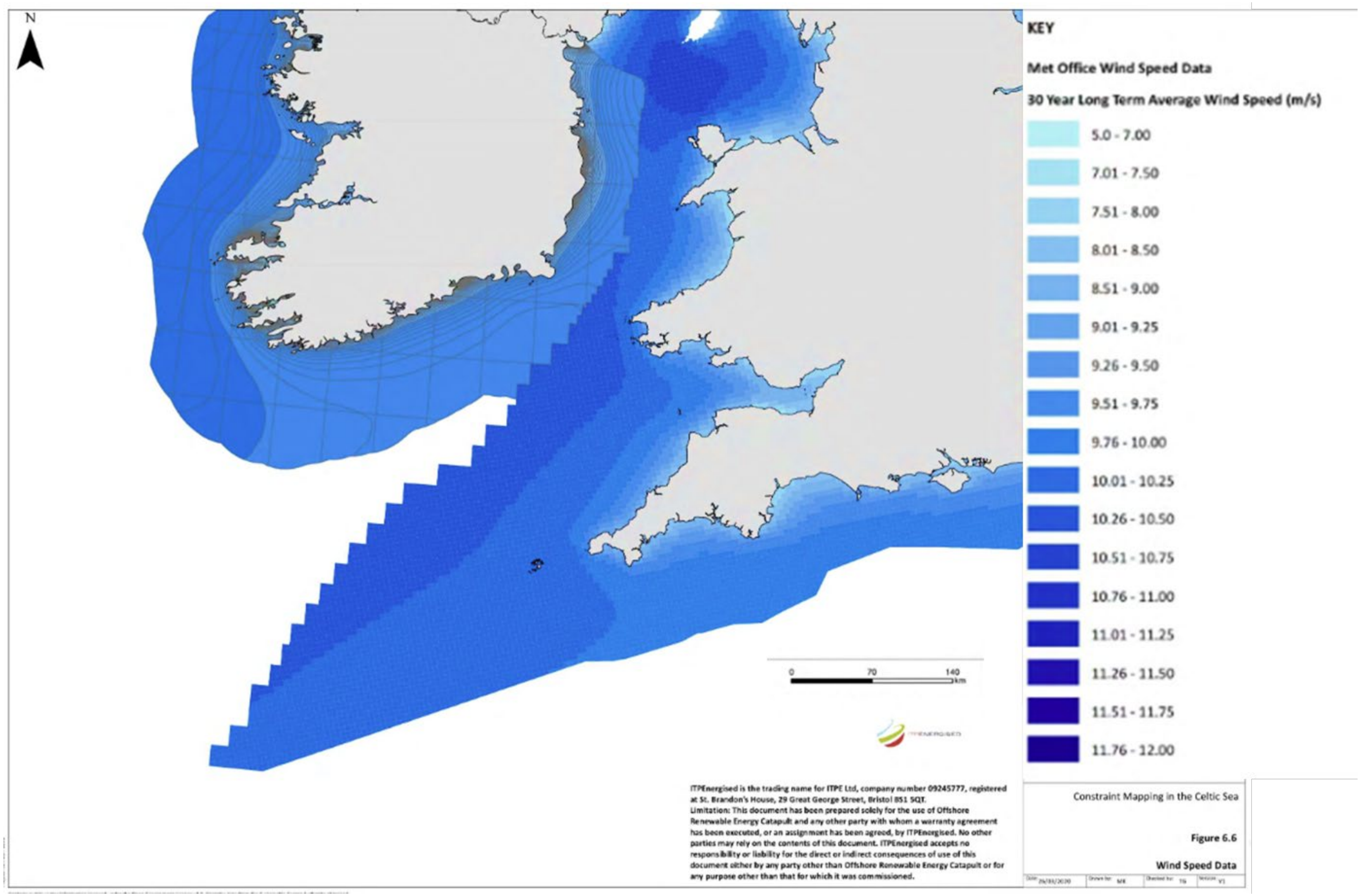


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Figure 3-3. Wind resource in the Celtic Sea for the 30 year long term average wind speed (m/s) (ORE Catapult, 2020)

Wave power

The average wave power (kW/m) in the Celtic Sea is illustrated in Figure 3-4, illustrating that wave power increases with increasing distance from shore (ORE Catapult, 2020). Almost all regions of the Celtic Sea are subject to significant waves, therefore this is unlikely to form a deciding factor in which floating foundation type could be used for a specific FLOW farm location. Annual average wave power was the selected data source over wave height, as this was considered to give a better representation of areas of high wave activity (ORE Catapult, 2020).

The wave rose in Figure 3-5 illustrates the significant wave height and suggests that predominant wave direction in the Celtic Sea originates from the west (ABPmer, 2013).

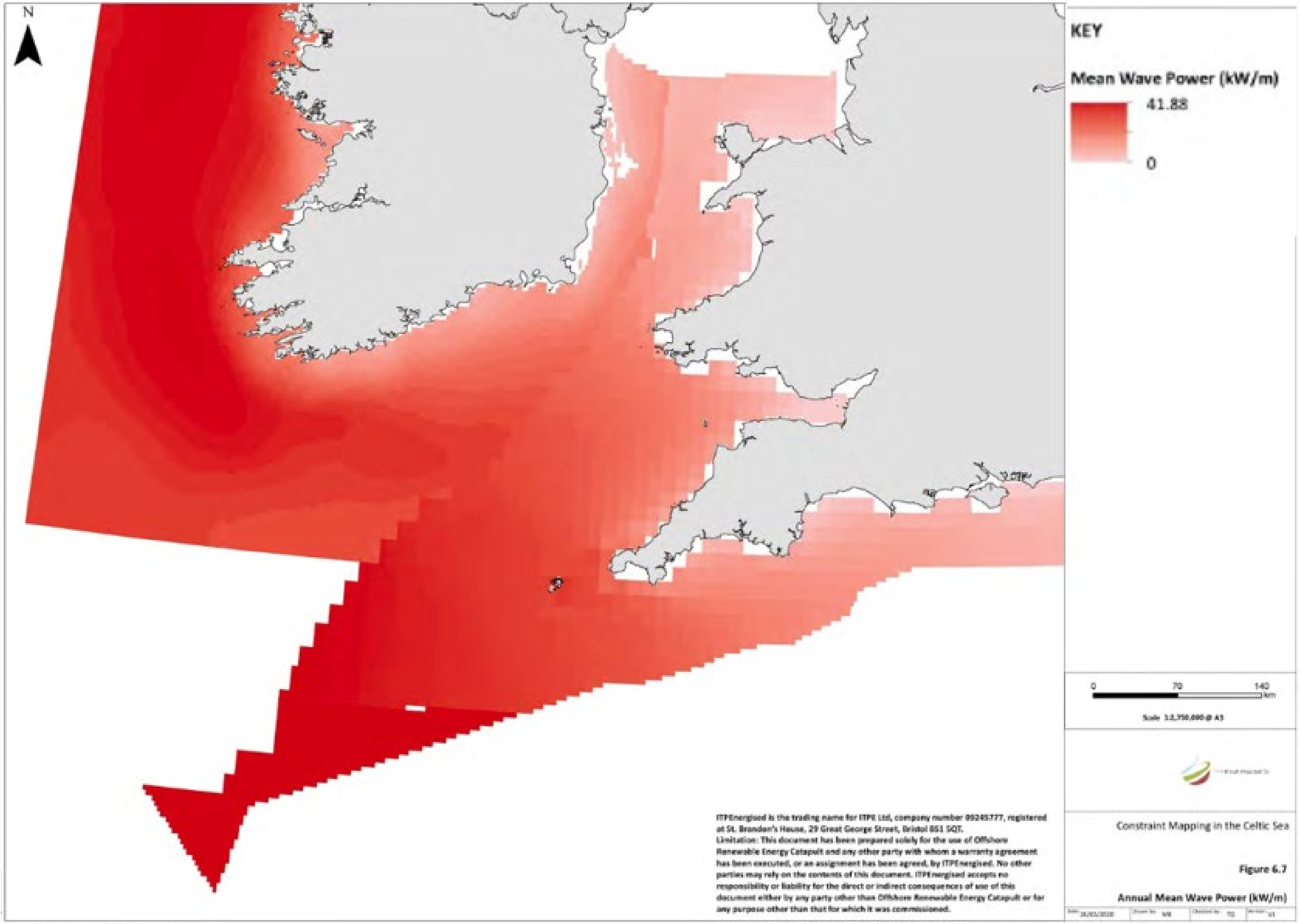

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Figure 3-4. Annual mean wave power (kW/m) in the Celtic Sea (ORE Catapult, 2020)

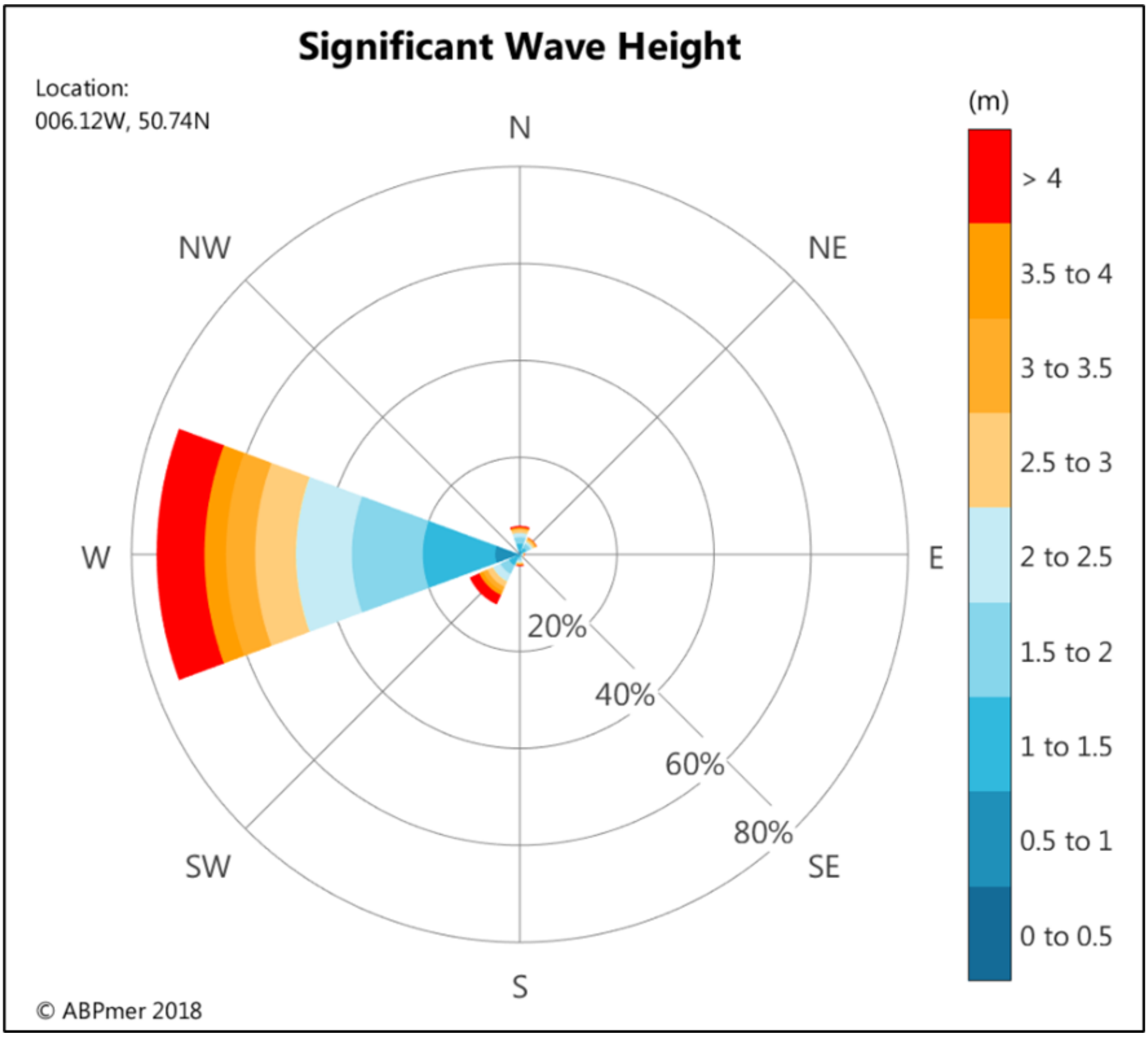

Figure 3-5. Wave rose for the Celtic Sea (Specifically, Refined Area of Search D) (ABPmer, 2013)

Current

The current force per square meter is illustrated for the Celtic Sea in Figure 3-6. It is evident that high currents are produced where the tide is forced between bodies of land and or around headlands i.e., the regions around the Bristol Channel, Pembrokeshire and Holyhead can be seen to have the highest tidal speeds (ORE Catapult, 2020).

As current and wave power increase, greater force will be experienced by offshore structures. This can impact the windows within which FLOW turbines can be constructed or accessed for operational & maintenance purposes, especially in winter months when wave power increases, with greater height, stronger currents induced by high tidal ranges, and challenging weather patterns (ORE Catapult, 2020).

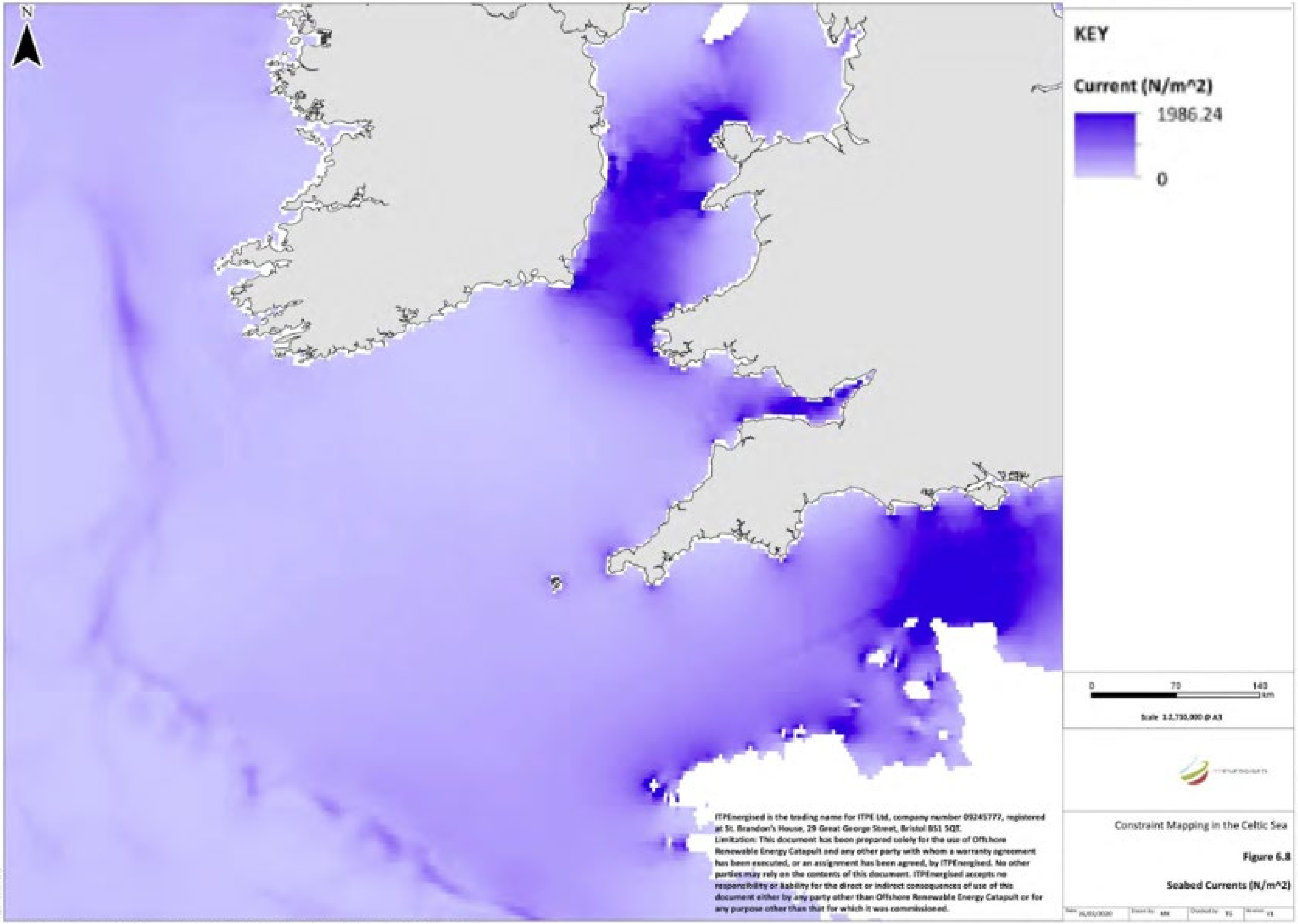

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Figure 3-6. Seabed current force per square meter (N/m^2) in the Celtic Sea (ORE Catapult, 2020)

Tidal fronts and upwelling

Many pelagic biodiversity hotspots are related to tidal fronts. It has been suggested that oceanic front distributions would provide a cost-effective initial comparison of candidate sites for offshore wind farms, to estimate their importance to marine life (Miller and Christodoulou., 2014).

The Celtic Sea is considered to have a dynamic regime known as “seasonally stratified shelf seas”, which is the same dynamic regime as the central North Sea and central Irish Sea. The dynamics associated with this regime include two-layer thermal stratification in summer; fully mixed in winter (strongly depending on local conditions); stratifying agent of summer surface warming; de-stratifying agent of autumn cooling, tidal energy, wind stress; thermocline in summer inhibits vertical exchange between bottom and surface layers; after spring bloom, surface waters are nutrient-depleted and bottom waters are nutrient-rich (van Berkel *et al.,* 2020).

Data layers are publicly available on the potential location of tidal fronts and upwelling, as part of a report aiming to support the identification and designation of MCZs to ensure that they are based on the best available science (Brown, Hull, and Warken., 2012). One element of the project was the production of secondary information to help support the site selection processes, e.g., benthic productivity, biodiversity, knowledge of invasive species locations and the amount of energy reaching the seabed. In identifying the current distribution of species and habitats of conservation importance; the project reviewed approaches which will have allowed marine biodiversity hotspots and important areas for benthic productivity (e.g., nutrient cycling) to be identified; and areas where important geological features are found. This includes information on the potential location of tidal fronts and areas of upwelling (Brown, Hull, and Warken., 2012).

Sediments

Seabed sediments comprising mineral and organic particles occur commonly in the form of mud, sand or gravel and are dispersed by processes driven by wind, tides and density driven currents. It is important to understand sediment type when considering the development of FLOW in an area, as different anchor types are suited to different types of sediment (discussed in Section 2). In addition, the severity of seabed disturbance impacts (as discussed in Section 4) can vary depending on sediment type (such as increased risk of scour in softer sediments). Therefore, sediment type may form a constraint when choosing location or anchor type for a specific FLOW farm development. In addition, sediment forms an environmental receptor as sediment habitats are often features of MPAs and they have the potential to be impacted by FLOW anchors and mooring lines, and associated scour protection.

The Celtic Sea presents an accessible shelf habitat, with a variety of sediment types covering a range of shelf sediments (Hicks *et al*., 2017). In the offshore waters, the seabed is dominated by sediment habitats formed mainly of sand, or mixtures of sand and gravel sediments (BEIS, 2022). Gravel occurs in the east and south of the area, grading to more muddy habitats in the north, and tends to be less perturbed by natural disturbance than that found in shallower coastal waters. The Celtic Sea’s inner shelf is characterised as “featureless” with surface sediments consisting largely of reworked mobile sediments, which were deposited in Pleistocene and early Holocene transgressions, along with biogenic carbonate (Somerfield *et al.,* 2019). These are mostly fine and coarse sands with lesser amounts of gravel and mud (Somerfield *et al*., 2019). The central Celtic Sea, “Celtic Deep”, is characterised by muddy sea sediments (Ward *et al.*, 2015).

Figure 3-7 illustrates the European Nature Information System (EUNIS) sediment types within the Celtic Sea as a whole, and in the context of the Refined Areas of Search. According to the EUNIS habitat classification, four sediment types occur within the Refined Areas of Search: offshore circalittoral sand, offshore circalittoral course sediment, offshore circalittoral mud, and offshore circalittoral mixed sediment (EEA, 2022). Table 3-2 describes each of these sediment types in more detail.

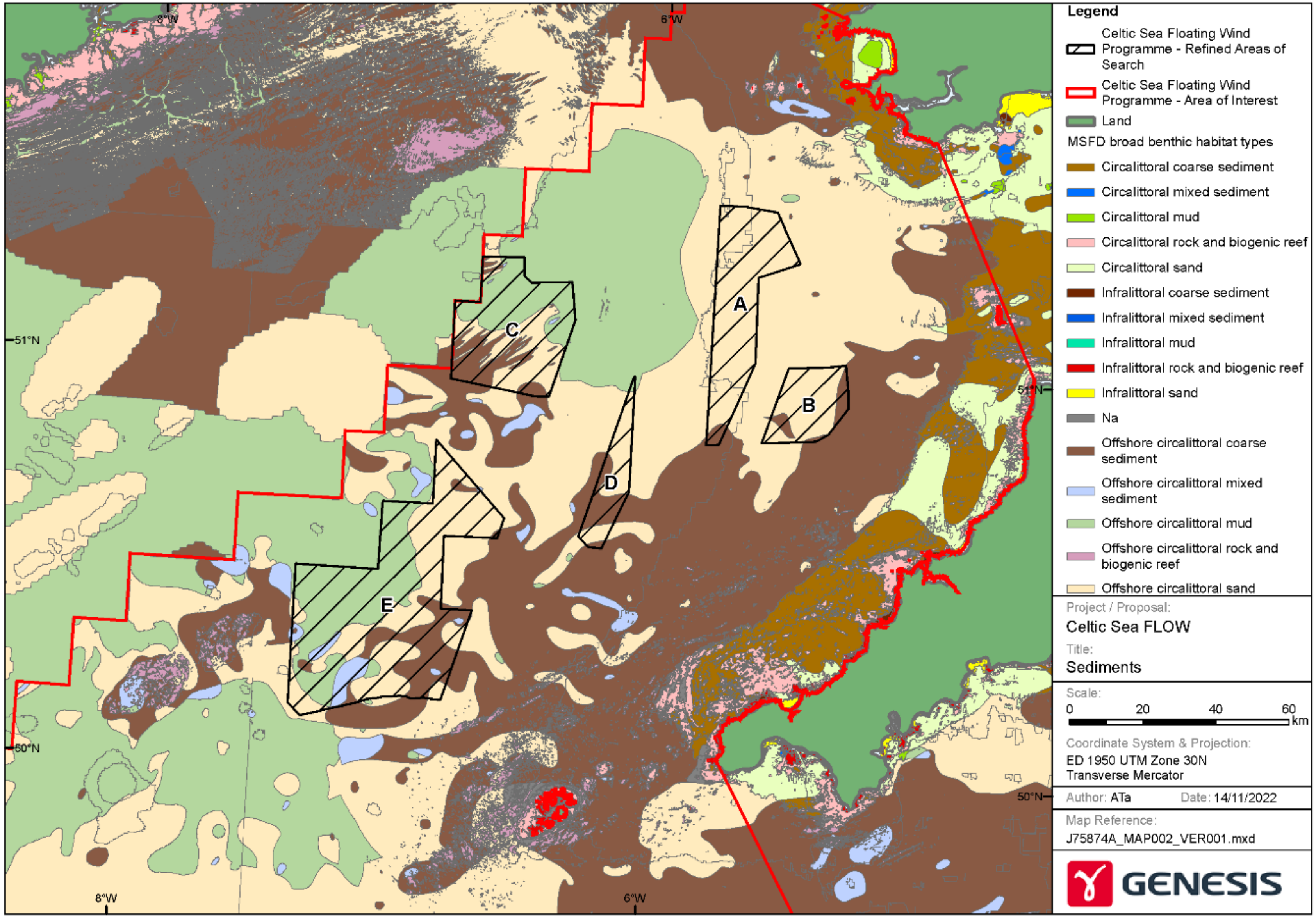


Figure 3-7. EUNIS habitat types within the Refined Areas of Search (EEA, 2022)

Table 3-2. Sediment types within the Refined Areas of Search (EEA, 2022)

Sediment type and EUNIS identification number	Description	Refined Area of Search
A4.33 Offshore circalittoral rock and biogenic reef	Occurs on wave-sheltered circalittoral bedrock and boulders subject to mainly weak/very weak tidal streams. The biotopes identified within this habitat type are often dominated by encrusting red algae, brachiopods (*Neocrania anomala*) and ascidians (*Ciona intestinalis* and *Ascidia mentula*).	A
A5.15 offshore circalittoral coarse sediment	Offshore (deep) circalittoral habitats with coarse sands and gravel or shell. This habitat may cover large areas of the offshore continental shelf although there is relatively little quantitative data available. Such habitats are quite diverse compared to shallower versions of this habitat.	A, B, C, D, E,
A5.45 offshore circalittoral mixed sediment	Offshore (deep) circalittoral habitats with slightly muddy mixed gravelly sand and stones or shell. This habitat may cover large areas of the offshore continental shelf although there is relatively little data available. Such habitats are often highly diverse.	C, E
A5.37 offshore circalittoral mud	In mud and cohesive sandy mud in the offshore circalittoral zone, typically in depths below 50-70 m, a variety of faunal communities may develop, depending upon the level of silt/clay and organic matter in the sediment.	C, D, E
A5.27 offshore circalittoral sand	Offshore (deep) circalittoral habitats with fine sands or non-cohesive muddy sands. Very little data is available on these habitats however they are likely to be more stable than their shallower counterparts.	A, B, C, D, E

Benthic species

A FLOW development will directly and indirectly impact benthic species. Therefore, it is important to understand the species present before the impacts of FLOW can be determined.

Benthic habitat is the combination of physical, chemical, and biological conditions that together create a home for a variety of invertebrate organisms that are located on or in the seafloor. Bacteria, plants, and animals which live on or within seabed sediments are collectively referred to as the benthic species or benthos (SEER, 2022a). Organisms living on the surface of the seabed are known as epifauna. Organisms that burrow themselves into the seafloor are called benthic infauna and include clams, worms, and small crustaceans. Semi-infaunal animals, including sea pens and some bivalves, lie partially buried in the seabed. Benthic organisms that live in mud and sand in deeper water, generally experience fewer natural disturbances (Kenny, *et al.*, 2018).

Species are at direct risk of displacement, smothering, and habitat loss / change from anchor installation and the action of mooring lines on the seabed, as well as behavioural disturbance from electromagnetic fields (EMFs) emitted by inter-array cables (Dannheim *et al.,* 2020).

Indirectly, local benthic community composition could continue to change after construction, as a result of a change in commercial fishing activities in the area (Dannheim *et al.,* 2020). The impacts of FLOW on benthic communities are discussed fully in Section 4.

Benthic communities have a strong correlation with habitat (or substrate/sediment) type. Table 3-3 presents a detailed breakdown of Celtic Sea benthic species grouped by their community or preferred seabed type.

Table 3-3. Benthic species found in the Celtic Sea (BEIS, 2022; JNCC, 2022b)

Community or seabed type	Species type	Species examples
Deep Venus community	Polychaetes	• *Glycera lapidum* • *Aonides paucibranchiata* • *Laonice bahusiensis* • *Mediomastus fragilis* • *Hilbigneris gracilis* • *Pseudomystides limbata* • *Protomystides bidentata*
	Syllid species & bivalves	• *Timoclea ovata* • *Glycymeris glycymeris* • *Spisula elliptica* • *Goodallia triangularis*
Boreal deep mud association	Brittlestars	• *Amphiura chiajei* • *Amphiura filiformis*
	Bivalves	• *Nucula sulcate* • *Nucula tenuis* • *Thyasira flexuosa* • *Abra nitida*
	Polychaetes	• *Myriochele heeri* • *Lagis koreni* • *Amphicteis gunneri.*
Tide swept mobile clean sands with a sparse infauna of opportunistic polychaetes and crustacea, to deeper circalittoral gravels, coarse sands, medium sands and shell gravels	Polychaetes	• *Mediomastus fragilis* • *Lumbrineris* • *Sabellaria spinulosa* • *Glycera*
	Urchin	• *Echinocyamus pusillus*
	Venerid Bivalves	• *Kurtiella bidentata* • *Spisula* • *Timoclea ovata* • *Tellina*

Community or seabed type	Species type	Species examples
Cohesive sands and muddy sands dominated	Other	• *Amphiura filiformis* • *Kurtiella bidentata*
Stable, compacted fine sands	Other	• *Tellina fabula* • *Abra alba* • *Kurtiella bidentata* • *Spiophanes bombyx* • *Chaetozone* • *Magelona* • *Bathyporeia tenuipes*
Well-sorted medium and fine sands	Other	• *Nephtys cirrosa,* • *Bathyporeia*
Rocky reef	Bryozoan	• *Pentapora fascialis*
	Devonshire Cup Corals	• *Caryophyllia smithii*
	Jewel Anemones	• *Corynactis viridis*
	Sponge	• *Caryophyllia smithii*
	Squat Lobster	• *Munida*
	Other	• Cup sponges • Erect branching sponges • Featherstars (crinoids) • Brittlestars (ophiuroids) • Worms • Cockles • Urchins • Sea cucumbers
Subtidal mud (Jones Bank)	Other	• Burrowing fireworks anemones • Brittlestars • Luminous sea pens
Celtic Deep / fine mud	Other	• Sea pens • Burrowing megafauna communities
Deep, low stress water	Dead Man’s Fingers	• *Alcyonium digitatum* • *Eunicella verrucosa*
	Jewel Anemones	• *Corynactis viridi*
	Devonshire Cup Corals	• *Caryophyllia smithii.*
Granite or slate bedrock reefs (exposed and sheltered)	British Stony Coral	• *Caryophyllia smithii* • *Balanophyllia regia* • *Caryophyllia inornate* • *Hoplangia durotrix* • *Leptopsammia pruvoti*

Fish and shellfish

More than 330 fish species are thought to inhabit the shelf seas of the UKCS (BEIS, 2022).

Fish species in the Celtic Sea are influenced by the Atlantic Ocean and pelagic species from warmer waters are occasionally reported in the area (Stebbing *et al.,* 2002). The abundance of offshore species in the Celtic Sea increases with depth and species including megrim (*Lepidorhombus whiffiagonis*), boarfish (*Capros aper*), blue whiting (*Micromesistius poutassou*), hake (*Merluccius merluccius*) and long rough dab (*Hippoglossoides platessoides*) are frequent (Warnes & Jones, 1995). The Celtic Sea and Bristol Channel possess several key spawning and nursery grounds. Figure 3-8 and Figure 3-9 illustrate the fish nursery grounds and spawning areas (respectively) in the Celtic Sea. It can be seen from the maps that the majority of the Celtic Sea waters are spawning and nursery grounds for many different fish species (ORE Catapult, 2020). One particular example is Carmarthen Bay to the north of the Celtic Sea; where a number of juvenile rays and flatfish mature (Ellis *et al.,* 2012).

In the following sections fish species have been divided into subsections in line with where they tend to be situated in the water column, as this is likely to influence how they are impacted by pressures associated with FLOW developments.

Demersal

Demersal species (e.g., cod, haddock, sandeels, sole and whiting) typically live on or near the seabed, (Nichol and Somerton, 2002; Hobson *et al.,* 2007). Many are known to passively move (e.g., drifting eggs and larvae) and / or actively migrate (e.g., juveniles and adults) between areas during their lifecycle. During construction of a FLOW development demersal species are likely to be most impacted by features such as anchors and mooring lines, which can disturb the seabed (Maxwell *et al.,* 2022).

Cod are abundant in the Celtic Sea and are believed to migrate inshore over winter, following summer feeding over deeper waters (Pawson, 1995). Another species found to be abundant in inshore waters is Whiting, which spawn in similar locations to cod. Reef areas provide spawning grounds for pollack and saithe, which are locally abundant in the area. Haddock tends to predominate the northern areas of the Celtic Sea, while hake occupy deeper areas (BEIS, 2022).

Sole and lemon sole are also common in the Celtic Sea, with the Bristol Channel forming the area with the highest sole abundance. However, plaice and common dab form the most commercially important species. These flatfish species all spawn in the area at different times. Sole tend to spawn from March to May, lemon sole from April to September and plaice from December to May. Once mature, these species usually relocate to deeper waters (BEIS, 2022).

The Celtic Sea is also home to bass, which are abundant in inshore areas, spawning there in spring. Estuaries in the area also provide important nursery grounds for juvenile bass.

Pelagic

Pelagic species (e.g., herring, mackerel, blue whiting, and sprat) are typically found in the water column. Despite this, they sometimes depend on benthic habitats for foraging and reproduction (Overholtz and Friedland, 2002), as well as making extensive seasonal movements or migrations. Given their location in the water column the impacts of FLOW developments on pelagic species are likely to derive from features such as mooring lines and dynamic inter-array cables. However, Taormina *et al* (2018) emphasise that further research is required to gain a better understanding of attraction or avoidance of pelagic species to these features.

Mackerel are abundant at the shelf edge of the Celtic Sea, migrating to feeding grounds in Cornwall in the winter (Ellis & Heessen 2015). Herring are particularly abundant in the Bristol Channel (Dickey-Collas *et al*. 2015), with limited spring spawning occurring towards Cornwall and Pembrokeshire (Coull *et al.,* 1998). Along the southern coast of Cornwall, horse mackerel is very abundant throughout the year (Ellis, 2015). Argentines (e.g., *Argentina silus*) are present in the area, particularly in the Bristol Channel, while summer spawning sprat migrate inshore over winter (Heessen, 2015). The ocean sunfish (*Mola mola*) can also be observed along the Pembrokeshire coast in the summer months (BEIS, 2022).

Diadromous

Diadromous fish migrate between freshwater and marine habitats to complete their life cycle, a complexity that makes them vulnerable to the adverse effects of current and past human activities on land and in the oceans (Jones, 2006). Although there is limited research, the main impacts of FLOW developments on diadromous species is likely to derive from EMFs from the inter array cables and platforms, as well as noise impacts during construction. These impacts have potential to impact upon the migration of these species (Gill *et al.,* 2012).

Salmon and sea trout frequent the rivers along the south coast of Wales, as well as the Bristol Channel, which is also a key area for lampreys and shads (Heessen & Daan 2015). The Severn, Wye, Usk and Tywi, of the Bristol Channel, flow into the Celtic Sea and are the last UK rivers known to host spawning twaite shad, which are protected under Schedule 5 of the Wildlife and Countryside Act 1981. The Tamar Estuary, in the western English Channel, possess one of the two only known spawning populations of the allis shad (Maitland & Hatton-Ellis, 2003). It has been estimated that the biomass of silver eel successfully reaching the sea to spawn in 2016 was 9 % for the River Severn management unit and just 0.6 % for the southwest of England (BEIS, 2022).

Elasmobranchs

Elasmobranchs including sharks, rays, skates, and sawfish are most likely to be impacted by FLOW developments through EMFs from cables and platforms, which can impact upon survival, migration and reproductive success (Normandeau *et al.,* 2011). Such potential impacts are of particular concern to elasmobranchs given that they are long lived and slow to reproduce (Hutchison *et al.,* 2018).

Several species of ray are present in the Celtic Sea including cuckoo ray (*Leucoraja naevus*), smalleyed ray (*Raja microocellata*), and spotted ray (*Aetobatus narinari*) (Ellis *et al*., 2015). Thornback rays can also be found spawning in the shallow bays around this area. Additionally, starry smooth hounds, lesser and greater spotted dogfish and spurdogs may also be present. The Celtic Sea also plays host to seasonal visits from mako sharks (*Isurus oxyrinchus*), thresher sharks (*Alopias vulpinus*) and blue sharks (*Prionace glauca*), on occasion. Further to this, there are high catches of porbeagle sharks in the Bristol Channel, suggesting this area may act as a nursery for the species (Bendall *et al*., 2013).

The Celtic Sea, and in particular Cornish coast, is also an area frequented by basking sharks, with numerous sightings reported in the summer months (Solandt & Chassin 2014). A satellite tagging study by Witt *et al* (2014) found that the Celtic Sea acts as an important migration corridor for basking sharks moving between southwest England, the Isle of Man and the Scottish Hebrides. Basking Sharks are protected under Schedule 5 of the Wildlife and Countryside Act 1981.

Shellfish

Shellfish including various species of molluscs, crustaceans, and echinoderms are found throughout UK waters including the Celtic Sea. Similar to demersal species, many shellfish occupy the seabed where their sessile nature leaves them susceptible to impacts from direct contact and drag of anchors and mooring lines. Several shellfish species are also filter feeders and so suspended sediments associated with anchors and mooring lines could impact feeding (Wilber & Clarke, 2001). In addition to this, research into the effect of EMFs on crabs has demonstrated negative impacts which may have unfavourable consequences on foraging and finding a mate (Scott *et al.,* 2021).

Abundant populations of lobsters, green crabs, brown crabs, and velvet crabs are all present in the Celtic Sea. *Nephrops* can be found offshore from the southern coast of Ireland. The Severn Estuary also forms an important area for cockles, whelks and razor clams. Figure 3-10 illustrates the location of shellfish waters in the Celtic Sea (ORE Catapult, 2020).

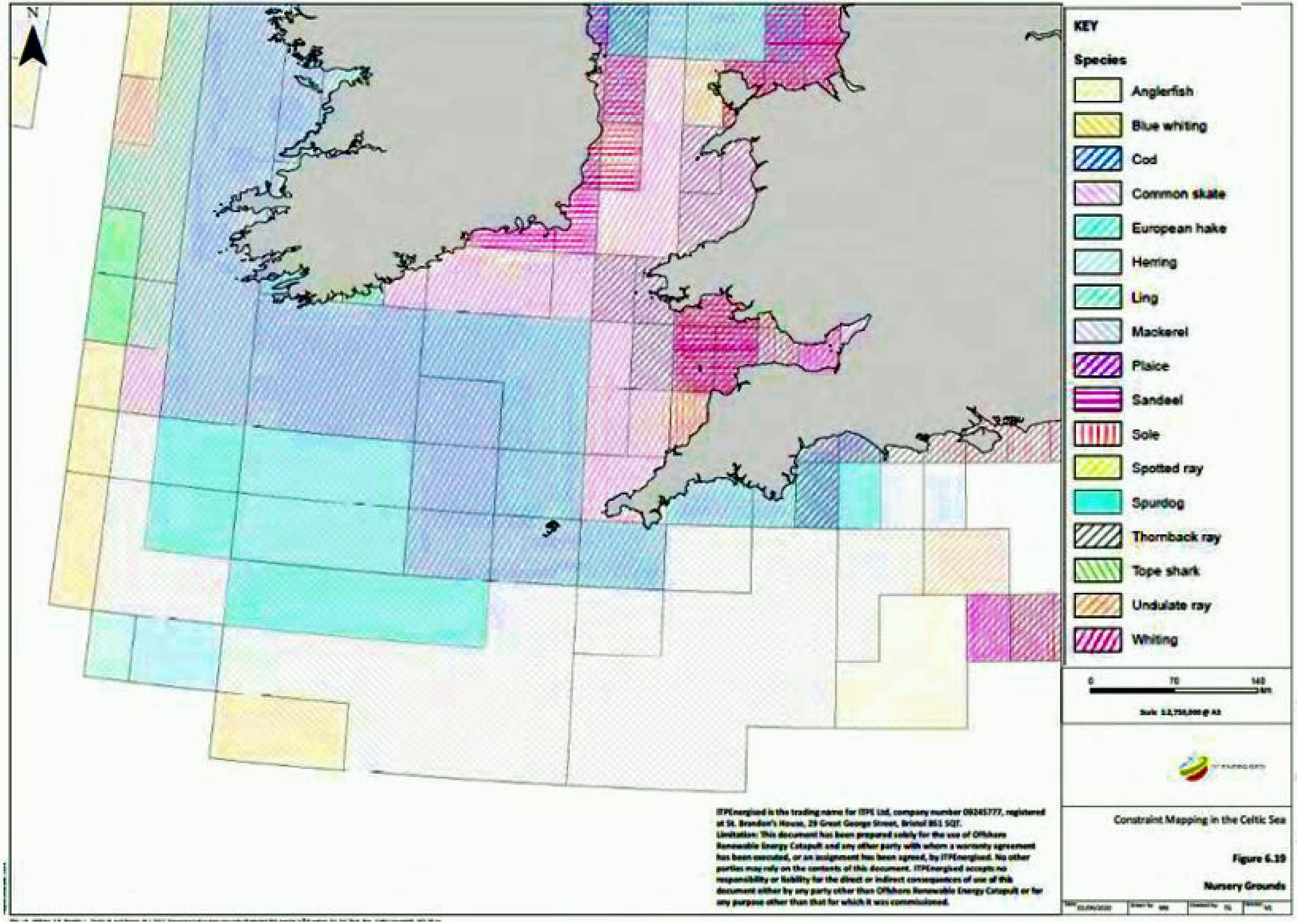


Figure 3-8. Nursery grounds of fish species in the Celtic Sea (ORE Catapult, 2020)

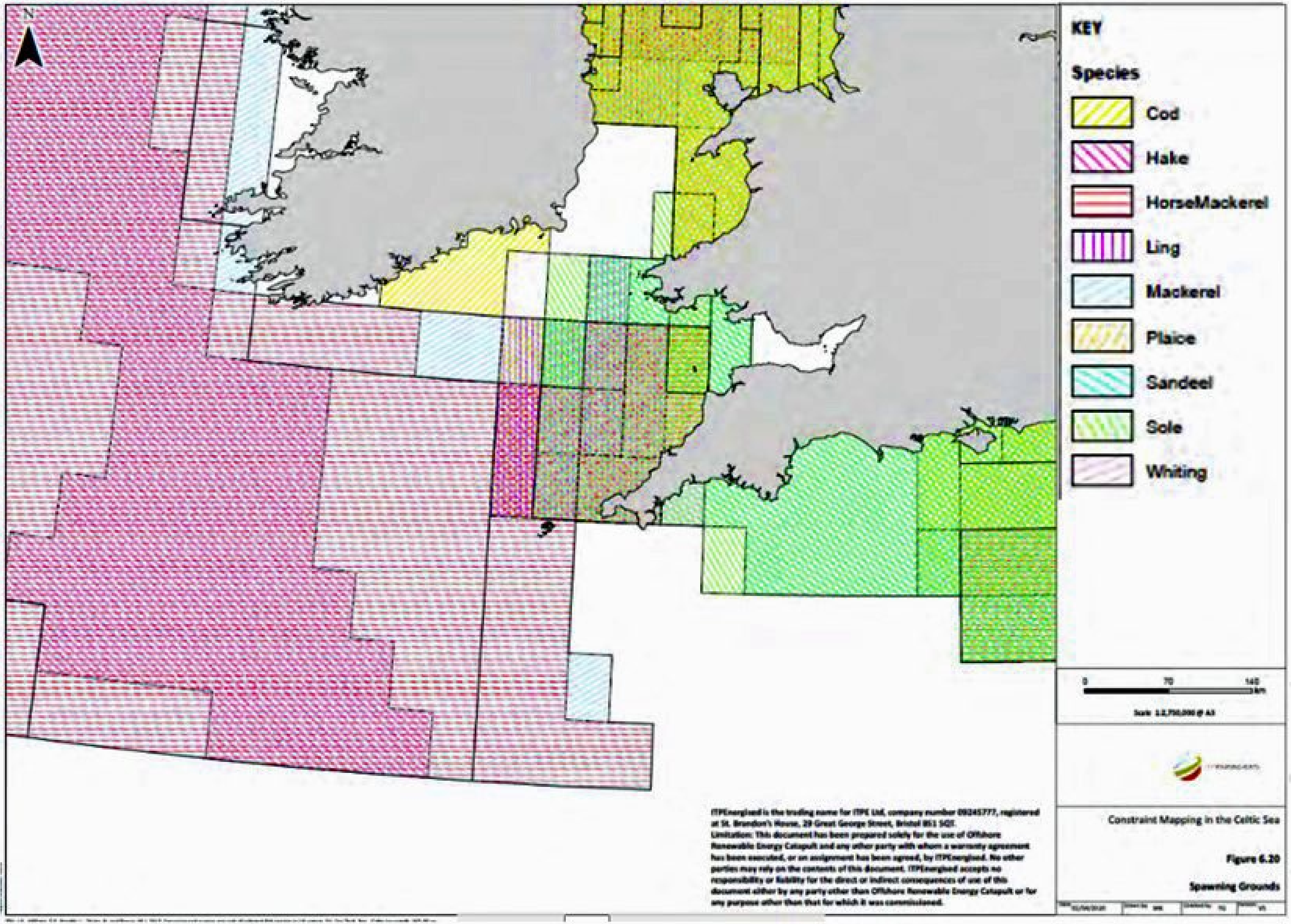


Figure 3-9. Spawning areas of fish species in the Celtic Sea (ORE Catapult, 2020)

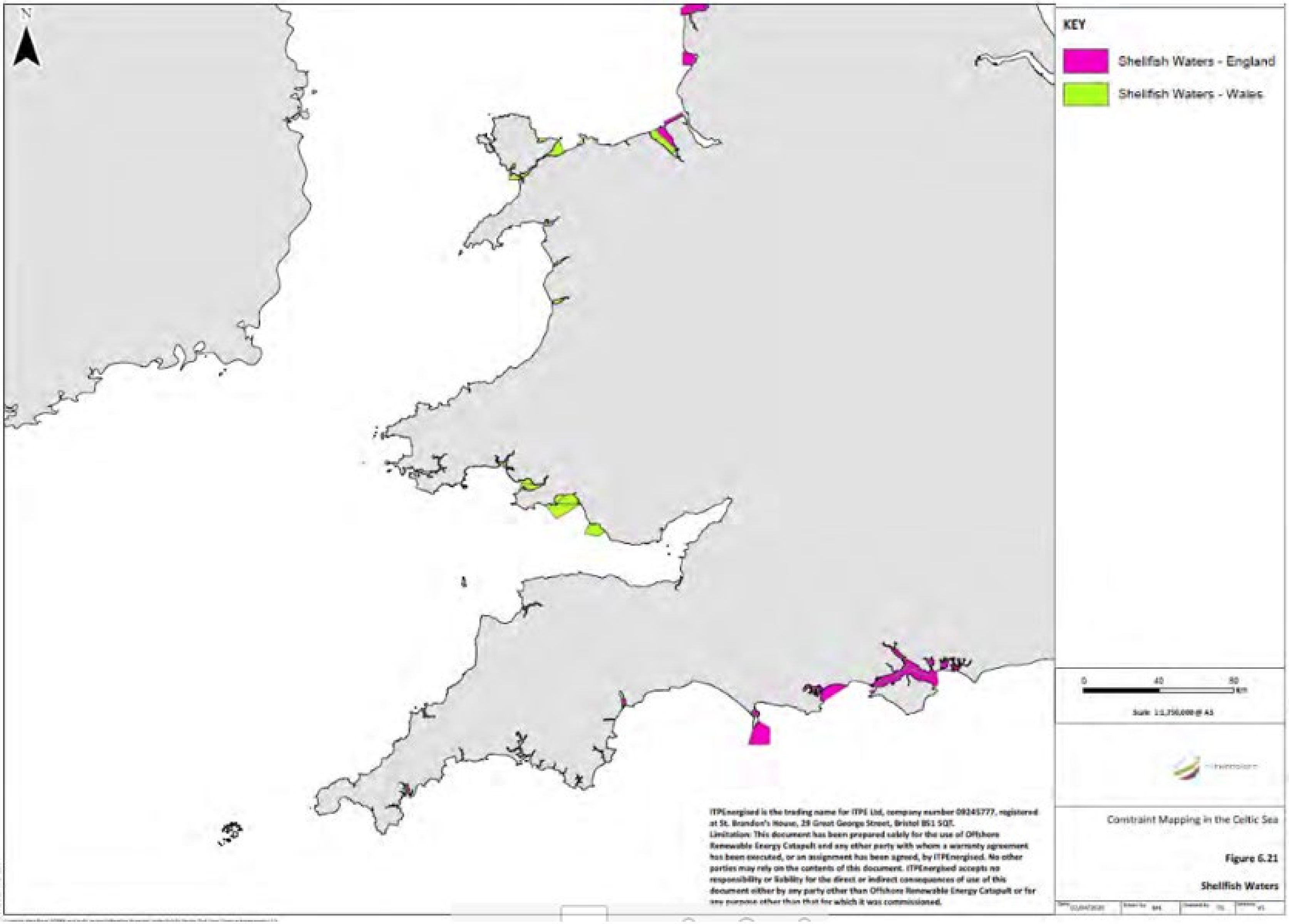


Figure 3-10. Shellfish waters in the Celtic Sea (ORE Catapult, 2020)

Marine mammals

Cetaceans

Cetaceans are an entirely aquatic order of mammals comprising the whales, the dolphins, and the porpoises. In UK waters, a total of 28 cetacean species have been recorded from sightings and strandings data, 11 of which are known to occur regularly, while 17 are considered rare (UK Marine Monitoring and Assessment Strategy Community (UKMMAS), 2010; BEIS, 2022). Of the regular species there are several whose abundance and distribution are considerably well known, these include:

- harbour porpoise (*Phocoena phocoena*)
- bottlenose dolphin (*Tursiops truncatus*)
- white beaked dolphin (*Lagenorhyncus albirostris*)
- minke whale (*Balaenoptera acutorostrata*)
- fin whale (*Balaenoptera physalus*)

There is less data relating to the remaining six regularly occurring species:

- Atlantic white-sided dolphin (*Lagenorhyncus acutus*)
- short-beaked common dolphin (*Delphinus delphi*)
- Risso’s dolphin (*Grampus griseus*)
- killer whale (*Orcinus orca*)
- long-finned pilot whale (*Globicephala melas*)
- sperm whale (*Physeter macrocephalus*)

All cetaceans are legally protected throughout Europe under the Habitats Directive, and specifically in the UK under the Wildlife and Countryside Act 1981. All cetacean species found in UK waters have European Protected Species (EPS) status, along with several other marine mammals. Bottlenose dolphin and harbour porpoise are also listed under Annex II of the Habitats Directive.

Cetaceans are sensitive to a number of impacts caused by FLOW development, such as potential entanglement with mooring lines (primary, secondary, and tertiary entanglement; as defined in Section 4), vessel-cetacean collision, hearing impairment or behavioural changes as a result of underwater noise (during construction and operation), and possible behavioural changes due to electromagnetic changes.

The UK Offshore Energy Strategic Environmental Assessment (OESEA4) states that short-beaked common dolphin, minke whale, harbour porpoise and bottlenose dolphin frequent the Western English Channel and Celtic Sea area (BEIS, 2022). It is further noted that Risso’s dolphins and long-finned pilot whales are also regularly encountered in this area.

The distribution of cetacean species in UK waters has been compiled by the JNCC in the Atlas of Cetacean Distribution in North-West European Waters (Reid *et al.,* 2003), incorporating *c.* 2,500 days of observation carried out from 1979-1997. The Atlas was updated for Welsh waters to include data from 1990-2009 (Baines & Evans, 2012). This data suggest that nine cetacean species occur in the Celtic Sea (Figure 3-11). Short-beaked dolphin are evidently the most commonly sighted species, with up to 5 individuals identified per hour in Area D of the Refined Areas of Search (Reid *et al.,* 2003).

There are currently regional surveys for benthic habitats and highly mobile species distribution (including birds and marine mammals) as part of the POSEIDON (Planning Offshore Wind Strategic Environmental Impact Decisions) project, led by Natural England. This four-year project will establish a robust evidence base made accessible through new mapping tools and improve the knowledge of environmental risks across UK waters, providing tools for future offshore wind planning. The project is part of the Offshore Wind Evidence and Change Programme (OWEC), led by The Crown Estate which aims to facilitate the sustainable and coordinated expansion of offshore wind to help meet the UK's commitments to low carbon energy transition whilst supporting clean, healthy, productive, and biologically diverse seas. The latest and most comprehensive data on marine mammals from current POSEIDON survey effort should be used to inform future FLOW development assessments. The outputs of POSEIDON will include a tool, which will be developed to model spatial distribution and sensitivity to offshore wind farms (Crown Estate, 2022d; UK Government, 2023c).

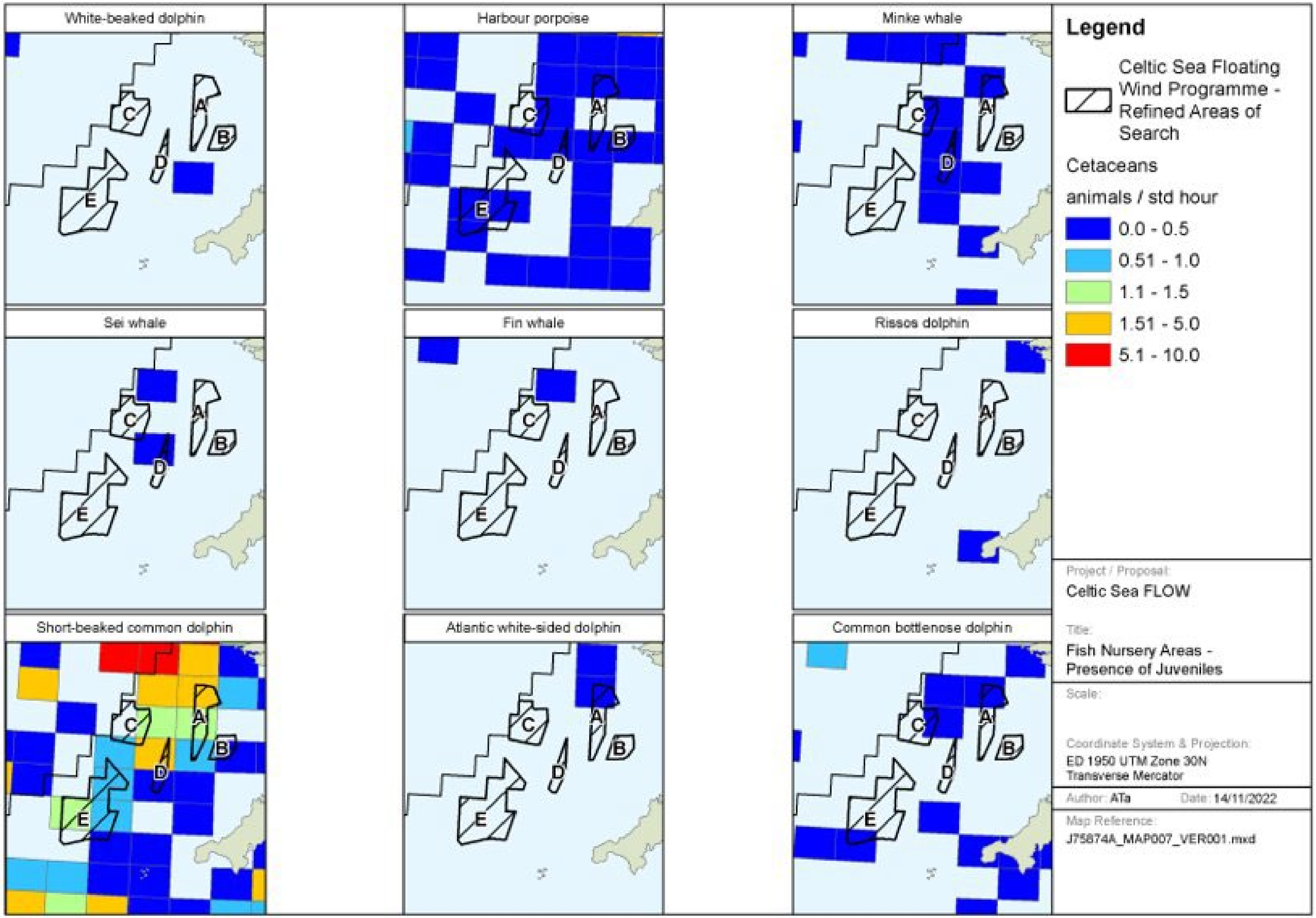


Figure 3-11. Annual distribution of cetacean species (animals/std hour) around the Refined Areas of Search (Reid *et al.,* 2003)

Table 3-4 presents the monthly sightings of cetaceans in the Celtic Sea, demonstrating that several species are present throughout the majority of the year (Reid *et al.,* 2003).

Table 3-4. Seasonal occurrence of cetaceans in the water around the Refined Areas of Search as noted by Reid *et al* (2003)

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Atlantic white-sided dolphin	A	A	A	A	A	A	A	A	P	A	A	A
Common bottlenose dolphin	P	P	P	P	P	P	P	P	P	P	P	P
Short-beaked common dolphin	P	P	P	P	P	P	P	P	P	P	P	P
White-beaked dolphin	A	A	A	A	A	A	P	A	A	A	A	A
Risso's dolphin	A	A	A	A	A	P	P	P	P	P	A	A
Harbour porpoise	P	P	P	P	P	P	P	P	P	P	P	P
Minke whale	P	P	P	P	P	P	P	P	P	A	P	P
Key: P - Present A - Absent												

Strong seasonal shifts in the distribution of short-beaked common dolphins have been observed, with winter movements onto the Celtic Shelf and into the western English Channel (Northridge *et al.,* 2004), resulting in a 10-fold increase in density in this area at that time (Hammond *et al.,* 2008). Reid *et al* (2003) also observed large numbers of short-beaked common dolphins throughout the year off the southwestern coast of Wales.

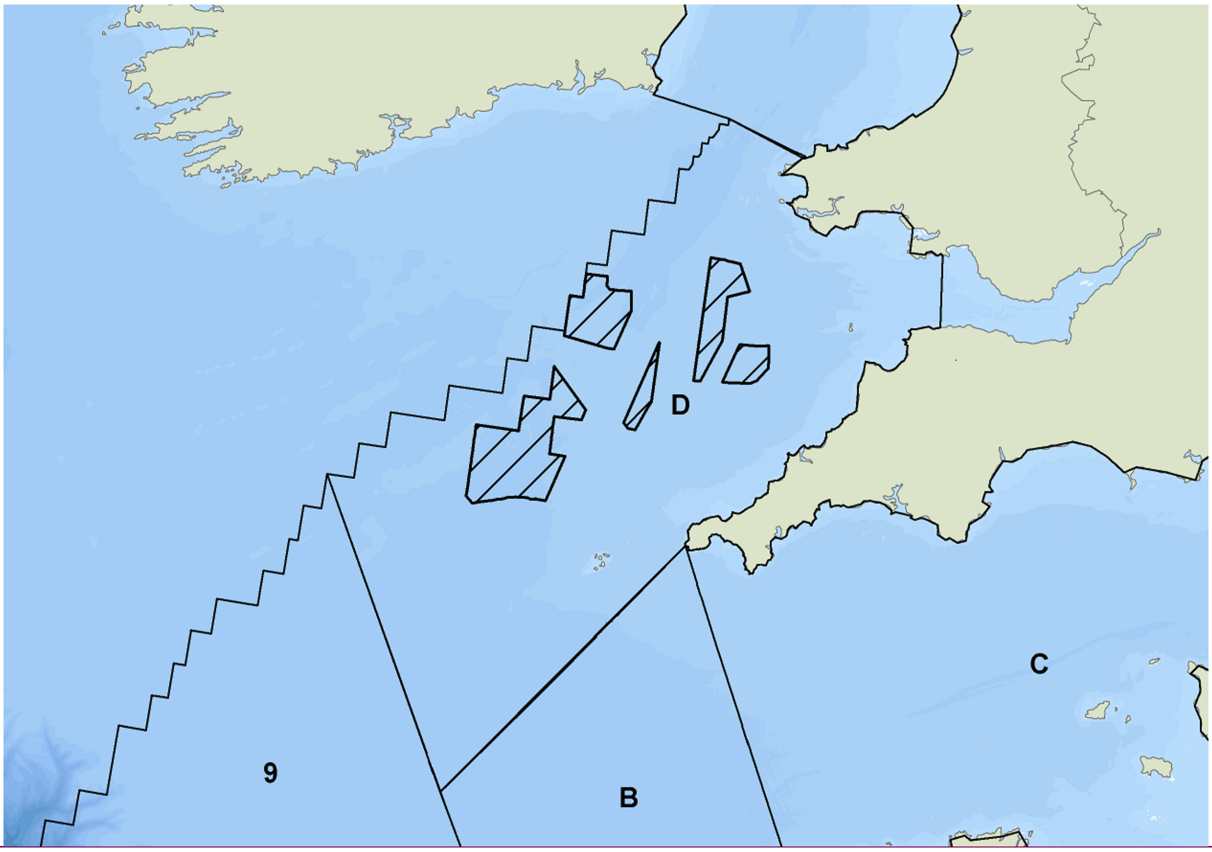
Harbour porpoise are abundant across the Celtic Sea, with the majority of sightings occurring off the southwest coast of Wales, outer Bristol Channel coast, and west of Cornwall (BEIS, 2022). Dedicated shore watches by Evans *et al.,* (2015) have also revealed several harbour porpoise hotspots in this region, including at the Gower Peninsula on the southern coast of Wales, and the south side of the outer Bristol Channel.

A series of Small Cetacean Abundance in the North Sea (SCANS) surveys have been conducted to obtain an estimate of cetacean abundance in the Celtic Sea and adjacent waters. The results from the most recent survey (SCANS-III) are presented in Hammond *et al.,* (2021). Aerial and shipboard surveys were carried out during the summer of 2016 to collect data on the abundance of harbour porpoise, bottlenose dolphin, Risso's dolphin, white-beaked dolphin, white-sided dolphin, common dolphin, striped dolphin, pilot whale, all beaked whale species combined, sperm whale, minke whale and fin whale.

The Refined Areas of Search are located within SCANS-III Block 'D'. Aerial survey estimates of animal abundance and densities (animals per km^2) within this area are summarised in Table 3-5. The data confirm that some of those species identified by Reid *et al.,* (2003), frequent Block D; minke whale, harbour porpoise and bottlenose dolphin (Hammond *et al.,* 2021).

Table 3-5. Cetacean abundance in SCANS-III Survey Block "D" (includes map of Refined Areas of Search)

SCANS-III Block D	Species	Animal abundance [a]	Density (animals/ km^2) [a]	Celtic and Irish Seas (CIS) Management Unit (MU) population [b]
Map included below	Unidentified Common or Striped Dolphin	31,800	0.655	No data
	Striped Dolphin	262	0.005	No data
	Harbour Porpoise	5,734	0.118	62,517
	Common Dolphin	18,187	0.374	102,656
	Bottlenose Dolphin	2,938	0.061	10,947
	Minke Whale	543	0.011	20,118



Sources:
[a] Hammond *et al.,* (2021)
[b] IAMMWG (2022)

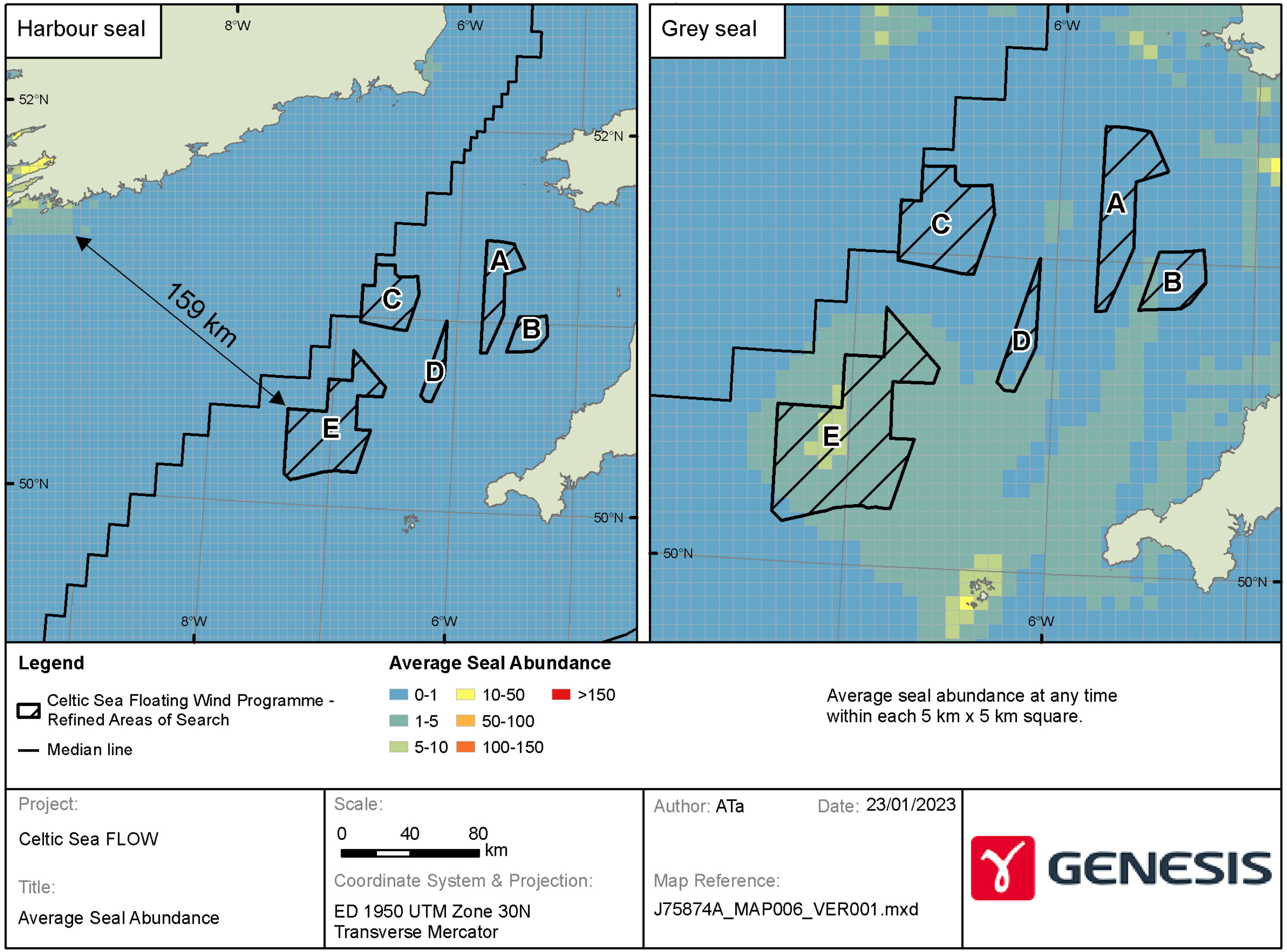
Pinnipeds

Two species of pinniped commonly known as seals live and breed in the UK, namely the grey seal (*Halichoerus grypus*) and the harbour seal (*Phoca vitulina*), and both are listed under Annex II of the Habitats Directive (BEIS, 2022). Research from tagging studies, in the UK, has shown that both harbour and grey seals adjust their behaviour to utilise wind turbine structures and cables for foraging (Russell *et al.,* 2014; Russell *et al.,* 2016). Harbour seals have been shown to only show avoidance to pile driving activities involved with offshore wind farms (Russel *et al.,* 2016).

Approximately 32 % of European harbour seals are found in the UK. The proportion has declined from approximately 40 % in 2002 due to the more rapid recovery and higher sustained rates of increase in the Wadden Sea population, on the north coast of the Netherlands (Special Committee on Seals, 2021).

The UK provides breeding grounds to 36% of the world's grey seal population. Two large colonies of grey seal are known to be present at Skomer and Ramsey off southwest Wales, however studies of marine usage by grey seals has generally shown low activity levels across most of the Celtic Sea (BEIS, 2022).

Distribution maps based on telemetry data (1991-2012) and count data (1988-2012) indicate that harbour seals are unlikely to occur in the Refined Areas of Search, or in the Celtic Sea generally (Figure 3-12). The nearest area where harbour seals have been observed is 159 km northwest of Area E, off the southeast coast of Ireland. An average grey seal abundance of 1-5 individuals has been observed in portions Area B, D and E of the Crown Estate Refined Areas of Search. The centre of Area E presents the highest average abundance of 5-10 individuals (Russell *et al.*, 2017).



Project: Celtic Sea FLOW

Title: Average Seal Abundance

Coordinate System & Projection: ED 1950 UTM Zone 30N Transverse Mercator

Author: ATa

Date: 23/01/2023

Map Reference: J75874A_MAP006_VER001.mxd

GENESIS

Figure 3-12. Harbour seal and grey seal distribution in relation to the Refined Areas of Search for the Celtic Sea Floating Wind Programme (Russell *et al*, 2017)

Reptiles

Turtles

The leatherback sea turtle (*Dermochelys coriacea*) is the only species of sea turtle that occurs regularly in Irish waters. Leatherback turtles can maintain their body temperature to as much as 18 degrees above that of their surrounding waters, which allows them to be the most widely distributed of the sea turtles (ORCA Ireland, 2023; WWF, 2020).

Leatherback sea turtles migrate long distances across oceans. Results from tagging studies have shown that the North Atlantic is a stronghold for leatherbacks outside of their nesting periods. It is clear that this area plays an important role in the feeding ecology of these leatherbacks and possibly many others (ORCA Ireland, 2023).

During 2003-2005 (June-October), (Houghton *et al.* 2006b) carried out aerial surveys throughout the Irish and Celtic Seas to determine the abundance (order of magnitude) of leatherback sea turtles. During the surveys, four live and one dead leatherback turtle were observed from the air, equating to 0.25 leatherbacks per 1,000 km of track flown (or 0.06 leatherbacks per 100 km^2) (Doyle, 2007).

Birds

There are 25 species of seabirds which regularly breed in the UK and Ireland, as well as several other waterbird species (Table 3-6). Procellariidae (e.g., petrel and shearwater) include the most pelagic of all seabirds, meaning they travel to or beyond the continental shelf to forage in deeper waters (Scottish Government, 2023).

Waterbirds are a loosely defined category of birds that tend to occupy inshore marine environments including sea ducks, divers, herons, waders, geese, and swans (e.g., red-throated diver and common scoter). These birds are a major feature of the coastal habitats of the UK, with resident, migratory and over-wintering populations present (BEIS, 2022).

The UK is located on the course of some of the major migratory flyways of the east Atlantic, with many species not only overwintering in the area, but also using the UK as a stopover during spring and autumn migrations. Birds do not use fixed migratory corridors, rather a broad front, which often covers the whole of the UK. The estuaries, bays and other coastal areas of the UK are of great importance to wintering and passage wildfowl, as well as for breeding waders and other waterbirds (BEIS, 2022).

Table 3-6. Seabird and waterbird species breeding and overwintering in the UK and Ireland

Family	Species
Seabirds	
Procellariidae	• Northern fulmar (*Fulmarus glacialis*)

Family	Species
	• Manx shearwater (*Puffinus puffinus*) • European storm petrel (*Hydrobates pelagicus*) • Leach's storm-petrel (*Oceanodroma leucorhoa*)
Phalacrocoracidae	• Great cormorant (*Phalacrocorax carbo*) • European shag (*Phalacrocorax aristotelis*)
Sulidae	• Northern gannet (*Morus bassanus*)
Stercorariidae	• Great skua (*Stercorarius skua*) • Arctic skua (*Stercorarius parasiticus*)
Laridae	• Herring gull (*Larus argentatus*) • Common gull (*Larus canus*) • Black-headed gull (*Larus ridibundus*) • Lesser black-backed gull (*Larus fuscus*) • Great black-backed gull (*Larus marinus*) • Mediterranean gull (*Larus melanocephalus*) • Black-legged kittiwake (*Rissa tridactyla*) • Little gull (*Hydrocoloeus minutus*)
Sternidae	• Sandwich tern (*Sterna sandvicensis*) • Roseate tern (*Sterna dougallii*) • Common tern (*Sterna hirundo*) • Arctic tern (*Sterna paradisaea*) • Little tern (*Sterna albifrons*)
Alcidae	• Common guillemot (*Uria aalge*) • Razorbill (*Alca torda*) • Black guillemot (*Cepphus grylle*) • Puffin (*Fratercula arctica*)
Waterbirds	
Anatidae	• Mute swan (*Cygnus olor*) [note 1] • Greylag goose (*Anser anser*) [note 1] • Canada goose (*Branta canadensis*) [note 1] • Egyptian goose (*Alopochen aegyptiacus*) [note 1] • Shelduck (*Tadorna tadorna*) [note 1] • Mandarin (*Aix galericulata*) [note 1]

Family	Species
	• Wigeon (*Anas penelope*) [note 1] • Gadwall (*Anas strepera*) [note 1] • Teal (*Anas crecca*) [note 1] • Mallard (*Anas platyrhynchos*) [note 1] • Pintail (*Anas acuta*) [note 1] • Garganey (*Anas querquedula*) • Shoveler (*Anas clypeata*) [note 1] • Pochard (*Aythya farina*) [note 1] • Tufted duck (*Aythya fuligula*) [note 1] • Eider (*Somateria mollissima*) [note 1] • Common scoter (*Melanitta nigra*) [note 1] • Goldeneye (*Bucephala clangula*) [note 1] • Red-breasted merganser (*Mergus serrator*) [note 1] • Goosander (*Mergus merganser*) [note 1] • Ruddy duck (*Oxyura jamaicensis*) [note 1] • Whooper swan (*Cygnus cygnus*) [note 2] • Bewick's swan (*Cygnus columbianus bewickii)* [note 2] • Taiga bean goose (*Anser fabalis*) [note 2] • Tundra bean goose (*Anser serrirostris*) [note 2] • Pink-footed goose (*Anser brachyrhynchus*) [note 2] • European Greenland white-fronted goose (*Anser albifrons flavirostris*) [note 2] • Barnacle goose (*Branta leucopsis*) (Svalbard and Greenland) [note 3] • Dark-bellied Brent goose (*Branta bernicla bernicla*) [note 2] • Light bellied Brent goose (*Branta bernicla hrota*) [note 2] • Scaup (*Aythya marila*) [note 2] • Long-tailed duck (*Clangula hyemalis*) [note 2] • Velvet scoter (*Melanitta fusca*) [note 2] • Smew (*Mergus albellus*) [note 2]
Gaviidae	• Red-throated diver (*Gavia stellata*) [note 1] • Black-throated diver (*Gavia arctica*) [note 1] • Great northern diver (*Gavia immer*) [note 2]

Family	Species
Podicipedidae	• Little grebe (*Tachybaptus ruficollis*) [note 1] • Great crested grebe (*Podiceps cristatus*) [note 1] • Slavonian grebe (*Podiceps auritus*) [note 1] • Black-necked grebe (*Podiceps nigricollis*) • Red-necked grebe (*Podiceps grisegena*) [note 2]
Ardeidae	• Bittern (*Botaurus stellaris*) [note 1] • Little egret (*Egretta garzetta*) [note 1] • Grey heron (*Ardea cinerea*) [note 1]
Rallidae	• Coot (*Fulica atra*) [note 1]
Haematopodidae	• Oystercatcher (*Haematopus ostralegus*) [note 1]
Recurvirostridae	• Avocet (*Recurvirostra avosetta*) [note 1]
Charadriidae	• Little ringed plover (*Charadrius dubius*) [note 1] • Ringed plover (*Charadrius hiaticula*) • Golden plover (*Pluvialis apricaria*) [note 1] • Lapwing (*Vanellus vanellus*) [note 1] • Grey plover (*Pluvialis squatarola*) [note 2]
Scolopacidae	• Dunlin (*Calidris alpina*) [note 1] • Ruff (*Philomachus pugnax*) [note 1] • Snipe (*Gallinago gallinago)* [note 1] • Black-tailed godwit (*Limosa limosa)* [note 1] • Whimbrel (*Numenius phaeopus*) [note 1] • Curlew (*Numenius arquata*) [note 1] • Common sandpiper (*Actitis hypoleucos*) [note 1] • Greenshank (*Tringa nebularia*) [note 1] • Redshank (*Tringa totanus*) [note 1] • Red-necked phalarope (*Phalaropus lobatus*) [note 1] • Knot (*Calidris canutus*) [note 2] • Sanderling (*Calidris alba*) [note 2] • Little stint (*Calidris minuta*) [note 2] • Curlew sandpiper (*Calidris ferruginea*) [note 2] • Purple sandpiper (*Calidris maritima)* [note 2]

Family	Species
	• Jack snipe (*Lymnocryptes minimus)* [note 2] • Bar-tailed godwit (*Limosa lapponica*) [note 2] • Green sandpiper (*Tringa ochropus*) [note 2] • Wood sandpiper (*Tringa glareola*) [note 2] • Spotted redshank (*Tringa erythropus*) [note 2]

[note 1] Waterbirds included here are typically associated with estuarine, coastal**,** and marine habitats, but also freshwater/terrestrial habitats during breeding, therefore not every member of the Family is listed.

[note 2] Waterbird species which also regularly overwinter/stage in the UK (JNCC, 2023; Hume, 2002).

[note 3] There are two distinct populations of barnacle goose known to winter in the UK, the Svalbard population which winter at the Solway Firth, Lindisfarne**,** and Loch of Strathbeg, and the Greenland population which principally winters in the Western Isles. There is also an increasing naturalised barnacle goose population which breeds in the UK (JNCC, 2021; Frost *et al*., 2021; BTO, 2022).

The North Sea is an internationally important area for breeding and feeding seabirds. Using seabird density maps from European Seabirds at Sea (ESAS) data collected over 30 years, Table 3-7 identifies a number of bird species (and their predicted maximum monthly abundance) known to occur in the Celtic Sea (Kober *et al.,* 2010).

The data indicate that a number of seabird species are likely to occur in the area over the summer breeding season and winter months. For all species combined, up to 125 seabirds are predicted to occur per km^2 during the breeding season (April to October), whilst during the winter months (November to March) a maximum of 65 seabirds are predicted to occur per km^2.

The fifth Birds of Conservation Concern review, in association with the International Union for Conservation of Nature (IUCN) Red List of Threatened Species (IUCN, 2023), was released in 2021. This review categorised the conservation concern of UK bird species against an indicative criterion of “Green”, “Amber” and “Red”. The assessment incorporated the historical decline, recent trends in population and range, population size, localisation, and international importance of each species, as well as its global and European threat status. In total, 20 species of seabirds are known to visit the Refined Areas of Search, with 25 % designated “Red” conservation concern status, 60 % “Amber” and 15 % “Green” (Stanbury *et al.,* 2021; Table 3-7).

Table 3-7 Predicted density (maximum number of individuals per km^2) and IUCN List of Threatened Species category of seabirds in the Celtic Sea (Kober *et al.*, 2010; IUCN, 2023). Some cells have been deliberately left empty.

<table>
<tr><th>Species</th><th>IUCN red list</th><th>Season</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th></tr>
<tr><td rowspan="2">Northern fulmar [note 1]</td><td rowspan="2">AMBER</td><td>Breeding</td><td></td><td></td><td colspan="5">1.0 – 5.0</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Winter</td><td colspan="2">5.0 – 10.0</td><td></td><td></td><td></td><td></td><td></td><td colspan="5">5.0 – 10.0</td></tr>
<tr><td>Great shearwater</td><td>GREEN</td><td>Summer</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="4">1.0 – 5.0</td><td></td><td></td></tr>
<tr><td>Sooty shearwater</td><td>GREEN</td><td>Summer</td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="5">≤1.0</td><td></td></tr>
<tr><td rowspan="2">Manx shearwater [note 1]</td><td rowspan="2">AMBER</td><td>Breeding</td><td></td><td></td><td></td><td></td><td colspan="5">>20.0</td><td></td><td></td><td></td></tr>
<tr><td>Additional</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">≤1.0</td><td></td></tr>
<tr><td>European storm petrel</td><td>AMBER</td><td>Breeding</td><td></td><td></td><td></td><td></td><td></td><td colspan="5">5.0 – 10.0</td><td></td><td></td></tr>
<tr><td rowspan="2">Northern gannet [note 1]</td><td rowspan="2">AMBER</td><td>Breeding</td><td></td><td></td><td></td><td></td><td colspan="5">5.0 – 10.0</td><td></td><td></td><td></td></tr>
<tr><td>Winter</td><td colspan="4">5.0 – 10.0</td><td></td><td></td><td></td><td></td><td></td><td colspan="3">5.0 – 10.0</td></tr>
<tr><td rowspan="2">Great cormorant [note 1]</td><td rowspan="2">GREEN</td><td>Breeding</td><td></td><td></td><td></td><td colspan="5">≤1.0</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Winter</td><td colspan="3">≤1.0</td><td></td><td></td><td></td><td></td><td></td><td colspan="4">≤1.0</td></tr>
<tr><td rowspan="2">European shag [note 1]</td><td rowspan="2">RED</td><td>Breeding</td><td></td><td></td><td colspan="7">1.0 – 5.0</td><td></td><td></td><td></td></tr>
<tr><td>Winter</td><td colspan="2">≤1.0</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="3">≤1.0</td></tr>
<tr><td rowspan="2">Arctic skua</td><td rowspan="2">RED</td><td>Breeding</td><td></td><td></td><td></td><td></td><td colspan="4">≤1.0</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Additional</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="3">≤1.0</td><td></td></tr>
<tr><td rowspan="2">Great skua [note 1]</td><td rowspan="2">AMBER</td><td>Breeding</td><td></td><td></td><td></td><td></td><td colspan="4">≤1.0</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Winter</td><td colspan="4">≤1.0</td><td></td><td></td><td></td><td></td><td colspan="4">≤1.0</td></tr>
<tr><td rowspan="2">Black legged kittiwake [note 1]</td><td rowspan="2">RED</td><td>Breeding</td><td></td><td></td><td></td><td></td><td colspan="5">1.0 – 5.0</td><td></td><td></td><td></td></tr>
<tr><td>Winter</td><td colspan="4">5.0 – 10.0</td><td></td><td></td><td></td><td></td><td></td><td colspan="3">5.0 – 10.0</td></tr>
<tr><td rowspan="2">Great black-backed gull</td><td rowspan="2">AMBER</td><td>Breeding</td><td></td><td></td><td></td><td colspan="5">≤1.0</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Winter</td><td colspan="3">≤1.0</td><td></td><td></td><td></td><td></td><td></td><td colspan="4">≤1.0</td></tr>
<tr><td>Common gull</td><td>AMBER</td><td>Winter</td><td colspan="4">≤1.0</td><td></td><td></td><td></td><td></td><td colspan="4">≤1.0</td></tr>
<tr><td rowspan="2">Lesser black-backed gull [note 1]</td><td rowspan="2">AMBER</td><td>Breeding</td><td></td><td></td><td></td><td></td><td colspan="4">10.0 – 20.0</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Winter</td><td colspan="4">>20.0</td><td></td><td></td><td></td><td></td><td colspan="4">>20.0</td></tr>
<tr><td rowspan="2">Herring gull</td><td rowspan="2">RED</td><td>Breeding</td><td></td><td></td><td></td><td colspan="5">5.0 – 10.0</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Winter</td><td colspan="3">>20.0</td><td></td><td></td><td></td><td></td><td></td><td colspan="4">>20.0</td></tr>
<tr><td>Common tern</td><td>AMBER</td><td>Breeding</td><td></td><td></td><td></td><td></td><td colspan="4">≤1.0</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Arctic tern</td><td>AMBER</td><td>Breeding</td><td></td><td></td><td></td><td></td><td colspan="4">≤1.0</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Common guillemot</td><td>AMBER</td><td>Breeding</td><td></td><td></td><td></td><td></td><td colspan="2">10.0 – 20.0</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Species	IUCN red list	Season	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
[note 1]		Additional								>20.0				
		Winter	5.0 – 10.0									5.0 – 10.0		
Razorbill	AMBER	Breeding					≤1.0							
		Additional								1.0 – 5.0				
		Winter	1.0 – 5.0									1.0 – 5.0		
Atlantic puffin [note 1]	RED	Breeding				1.0 – 5.0								
		Winter	5.0 – 10.0							5.0 – 10.0				
ALL species combined		Breeding				>20.0								
		Summer							>20.0					
		Winter	>20.0										>20.0	

Key	Not recorded	≤1.0	1.0 – 5.0	5.0 – 10.0	10.0 – 20.0	>20.0

[note 1] Migratory species to the UK/Celtic Sea Refined Areas of Search.

The protected areas in the vicinity of the Refined Areas of Search afford protection for the following seabirds:

- Atlantic puffin (*Fratercula arctica*)
- red-throated diver (*Gavia stellata*)
- European storm-petrel (*Hydrobates pelagicus*)
- lesser black-backed gull (*Larus fuscus*)
- little gull (*Larus minutus*)
- black (common) scoter (*Melanitta nigra*)
- manx shearwater (*Puffinus puffinus*)
- little tern (*Sterna albifrons*)
- common tern (*Sterna hirundo*)

In order to assess the potential impacts of FLOW on seabird species, risk of collision with wind turbines is assessed in Section 4 (Masden *et al.,* 2016). As part of this, it is important to understand bird flight heights. All of the seabirds known to occur in Celtic Sea FLOW area (Table 3-6), apart from the great shearwater, have been identified by Martin (2022) to be vulnerable to collision and displacement resulting from FLOW turbines.

Species-specific flight heights have been indicated for seabirds in the Refined Areas of Search in Table 3-8 (APEM-Marine Scotland, 2022). Species which have been identified to fly below a height of 20-25 m may also spend considerable time flying close to the sea surface within 5 m.

Table 3-8. Flight heights of seabird species in the Refined Areas of Search

Flight height	Species
Below 25 m [note 1]	Northern fulmar [note 5], Northern gannet [note 5], black legged kittiwake [note 5]
Below 20 m [note 2]	Northern fulmar [note 5], manx shearwater [note 5], Northern gannet [note 5], great cormorant, European shag, Arctic skua, great skua, black legged kittiwake [note 5], great black-backed gull, common gull, lesser black-backed gull, herring gull, common tern, Arctic tern, common guillemot, razorbill, Atlantic puffin
Below 10 m [note 3]	Great shearwater, sooty shearwater [note 5], manx shearwater [note 5], European storm petrel [note 5]
Below 5 m [note 4]	Sooty shearwater [note 5], European storm petrel [note 5].

[note 1] Species identified to generally fly below 25 m above sea level (APEM-Marine Scotland, 2022).
[note 2] Species identified to generally fly below 20 m above sea level (Johnston *et al.,* 2014).
[note 3] Species identified to generally fly below 10 m above sea level (Paton *et al.,* 2010).
[note 4] Species identified to generally fly within 5 m of the sea level (Deakin *et al.,* 2022).
[note 5] Species in more than one category.

The preliminary Crown Estate design envelope states that the minimum rotor surface clearance of the Celtic Sea FLOW turbines will be 22 m (Table 2-3). Table 3-8 therefore demonstrates that there will be potential for seabird collisions with the turbines as several species fly around this height. These impacts are discussed further in Section 4.

Johnston *et al* (2014) used pre-construction monitoring data from offshore wind farm sites across Europe to estimate continuous flight height distributions for 25 seabird species (Table 3-8). The findings from this study were found to be consistent with that of others (e.g., Krijgs-veld *et al.,* 2011), stating that the majority of flights were within 20 m of the sea surface for all bird species considered.

Vessel-based observations suggest European storm petrels generally fly within 2 m of the sea surface, but occasionally up to 5 m (Flood & Thomas, 2007). They may fly lower in strong winds to shelter in wave troughs, as observed in the oceanitid and Northern storm petrels (Ainley *et al.,* 2015).

Sooty shearwaters are considered to have low collision risk as they generally fly very close to the sea surface, often below 5 m, and therefore below turbine blade height (usually assumed to be 20–150 m above sea level), however this is based on very small sample sizes (Paton *et al.,* 2010; Cook *et al.,* 2012; Deakin *et al*., 2022). It is also assumed that sooty and manx shearwaters fly at similar heights (Furness and Wade, 2012). Like manx shearwaters, sooty shearwaters may fly higher in stronger winds (Spear and Ainley, 1997; Ainley *et al.,* 2015).

APEM-Marine Scotland (2022) used novel LiDAR technology to assess the flight heights of some of the most common seabird species found along the UK coastline. Results found that flight heights of fulmar, gannet and kittiwake are generally below 25 m above sea surface level. The flight heights recorded in the study were in line with previous research of those seabird species, suggesting that they are commonly found in flight just above the sea surface (Johnston, *et al.,* 2014).

The foraging ranges of seabird species within the Celtic Sea are presented in Table 3-9. The species with the greatest foraging range is the great shearwater, foraging to a distance of 9,257 ± 3,249 km, whilst Arctic skua demonstrate the smallest foraging range of 2 ± 0.7 km (Schoombie *et al.,* 2018; Woodward *et al*., 2019).

Table 3-9. Mean maximum foraging ranges of breeding seabirds found in the Celtic Sea

Species	Mean maximum foraging range (± 1 SD)
Northern Fulmar	542.3 ± 657.9 [c]
Great Shearwater	9,257 ± 3,249 (during chick-rearing) 6,863 ± 2,521km (during incubation) [a]
Sooty Shearwater	56.6 ± 45.3 km to 393.0 ± 22.1 km [b]
Manx Shearwater	1,346.0 ± 1,018.7 [c]
European Storm Petrel	336.0 [c] [note 1]
Northern Gannet	315.2 ± 194.2 [c]
Great Cormorant	25.6 ± 8.3 [c]
European Shag	13.2 ± 10.5 [c]
Arctic Skua	2 ± 0.7 [c] [note 2]
Great Skua	443.3 ± 487.9 [c]
Black Legged Kittiwake	156.1 ± 144.5 [c]
Great Black-backed Gull	73.0 [c] [note 1]
Common Gull	50.0 [c] [note 1]
Lesser Black-backed Gull	127.0 ± 109.0 [c]
Herring Gull	58.8 ± 26.8 [c]
Common Tern	17.6 ± 9.1 [c]
Arctic Tern	25.7 ± 14.8 [c]

Species	Mean maximum foraging range (± 1 SD)
Common Guillemot	443.3 ± 487.9 [c]
Razorbill	88.7 ± 75.9 [c]
Atlantic Puffin	137.1 [c]

[note 1] No SD available for mean maximum value

[note 2] Mean value with SD – no mean maximum value available

Sources:

[a] Schoombie *et al.,* 2018 [b] Bonnet-Lebrun *et al.,* 2020 [c] Woodward *et al*., 2019

One of the threats to seabirds imposed by FLOW developments is entanglement in materials which may get caught in mooring lines and inter-array cables (Benjamins *et al.,* 2014). It is therefore important to consider the dive depths of seabirds in the vicinity of a development (Table 3-10).

Table 3-10. Dive depths of seabirds present in the Celtic Sea

Bird species	Mean depth (m)	Mean maximum depth (m)
Northern Fulmar [a]	No data	2.6
Great Shearwater [b]	3.3	18.9
Sooty Shearwater [c]	15.9	69.9
European Storm Petrel [d]	1.5	5.1
Northern Gannet [e]	19.7	No data
Great Cormorant [f]	4.7	No data
European Shag [g]	No data	64.9
Black Legged Kittiwake [h]	No data	1
Common Tern [i]	No data	0.5
Arctic Tern [j]	No data	0.5
Common Guillemot [g][k]	17.4	118-132.4
Razorbill [g]	4.1	47.4-88.6
Atlantic Puffin [g]	5.2	38.4

Sources:

[a] Garthe & Furness, 2001
[b] Ronconi *et al.,* 2010
[c] Shaffer *et al.,* 2009
[d] Albores-Barajas *et al.,* 2011
[e] Brierley & Fernandes, 2001
[f] Ropert-Coudert *et al.,* 2006
[g] Browning *et al.,* 2018
[h] Burtt, 1974
[i] Dunn, 1972
[j] Hatch, 2002
[k] Dunn *et al.,* 2019.

The seabird species with the greatest dive depth in the Celtic Sea area is the common guillemot (mean = 17.4 m), while terns exhibit the shallowest surface dives (0.5 m). There is minimal research on the diving depths of manx shearwater, however the closely related wedge-tailed shearwater and Audubon’s shearwater have been found to exhibit dive depths of 14 m (maximum = 66 m) and 15 m (maximum = 35 m) respectively (Burger, 2001). There are also species present in the area which tend not to dive, namely the gulls and skuas. As some floating foundation types have a small draft i.e., the depth to which they protrude into the water column (particularly barges with a draft of 7-10 m), birds with a dive depth greater than this are potentially at risk of entanglement in mooring lines or inter-array cables.

Bats

There is the possibility that bats could be impacted by FLOW, due to disturbance to migration routes and collision risk. The primary legislation protecting bats in the UK is the Conservation of Habitats and Species Regulations (2017) (as amended) in England and Wales, the Conservation (Natural Habitats, &c.) Regulations 1994 (as amended) in Scotland and The Conservation (Natural Habitats, etc.) Regulations (Northern Ireland) 1995 (as amended) in Northern Ireland (Bat Conservation Trust, 2022).

There are seventeen species of bat recorded in Britain and Ireland. The great majority of these species do not undertake large-scale migrations and so do not spend significant time over the sea. The exception to this is Nathusius' pipistrelle (*Pipistrellus nathusii*), which is known to undertake long-distance migrations, including sea crossings (Russ *et al.,* 2001, 2008).

Efforts to understand the migratory movements of *P. nathusii*, including their occurrence in coastal and offshore habitats, have been increasing in recent years. Studies include monitoring of bats from platforms in the German (Hüppop & Hill 2016), Dutch (Lagerveld *et al*. 2014, 2017, 2021) and Belgian (Brabant *et al*. 2020) sectors of the North Sea.

Brabant *et al*., (2020) installed eight acoustic bat detectors at four turbines in the Belgian part of the North Sea. Only species *P. nathusii* was detected, and the study found that bat activity peaked in late September, with the average number of detections at transition piece height (16 m) approximately nine times greater than at nacelle height (93 m).

Lagerveld *et al.,* (2021) also collected acoustic data on the presence of bats at four nearshore locations in the North Sea between 2012 and 2016. In agreement with Brabant *et al.,* (2020), this study also showed that *P. nathusii* migration is strongest in early September.

Given the distribution of records in the UK and along the coast of continental Europe; most of the bat migratory movement is expected to take place across the southern North Sea, English Channel, and perhaps to a lesser extent, central and northern North Sea. There is currently no available information on the occurrence of bats in the Celtic Sea, and the specific migratory routes and stepping-stones used from continental Europe to Britain and from Britain to Ireland are not known (Rodrigues *et al*., 2014; BEIS, 2022).

For this reason, bats have been scoped out of this report and are not discussed further. However, as more information becomes available in future, FLOW developments should consider the impacts that offshore wind turbines may have on bat populations on different geographical scales. Bats and offshore wind are identified as a data gap where further research should be prioritised and the precautionary principle (e.g., proactive curtailment) applied (Bat Conservation Trust, 2022).

Protected areas

A network of Marine Protected Areas (MPAs) are in place to aid the protection of vulnerable and endangered species and habitats through structured legislation and policies. MPAs are defined geographical areas of the marine environment established and managed to achieve long-term nature conservation and sustainable use. The development of a network of MPAs in the marine environment is part of the UK's commitment to protecting its seas and associated benefits to society for future generations (JNCC, 2023).

At present, the UK has a total of 374 designated MPAs, representing 38 % (338,545 km^2) of UK waters (Kemp *et al*., 2023). This figure fulfils international obligations and makes significant contributions to the conservation and recovery of marine ecosystems around the UK.

Offshore seas are defined as the waters between the Territorial Sea limit (12 nm / 22.22 km from the coast) and the Exclusive Economic Zone (EEZ) or UK continental shelf, therefore FLOW developments will likely overlap with offshore MPAs. The UK offshore area contains 76 MPAs covering 36 % of UK offshore waters, with an area measuring 261,543 km^2 (JNCC, 2023; JNCC, 2020).

There are several types of MPA in the UK, which in combination are intended to form an 'ecologically coherent and well-managed network' as a contribution to the effective conservation and sustainable use of the UK's marine environment (JNCC, 2023):

- Special Areas of Conservation (SACs) – designated to protect habitats and species of European importance. Previously designated in the UK under the EU Nature Directives (prior to January 2021) and are now maintained and designated under the Habitats Regulations for England and Wales, Scotland and Northern Ireland.
- Special Protection Areas (SPAs) – classified to protect bird species of European importance and regularly occurring migratory birds. Designated under the Habitats Regulations as of January 2021;
- Marine Conservation Zones (MCZs) (English, Welsh and Northern Irish territorial and offshore waters) and Nature Conservation Marine Protected Areas (NCMPAs) (Scottish territorial and offshore waters) – designated to protect nationally important species, habitats, ecological processes, and features of geological/geomorphological importance. Designated under the UK Marine and Coastal Access Act (2009), Marine Act (Northern Ireland) 2013 (Northern Irish territorial waters), and Marine (Scotland) Act (Scottish territorial waters);
- Sites of Special Scientific Interest (SSSIs) / Areas of Special Scientific Interest (ASSIs) – designated to protect any area of special interest for its flora, fauna, geological or physiographical features. These are coastal (and terrestrial) designations with some sites protecting marine features. ASSIs are designated in Northern Ireland, which are equivalent to SSSIs in England, Scotland and Wales. Designated under the Wildlife and Countryside Act (1981);
- Ramsar sites – wetlands of international importance designated under the Ramsar Convention (1971). These are coastal (and terrestrial) designations with some sites protecting marine features; and
- Highly Protected Marine Areas (HPMAs) – In 2022 the UK government committed to identify, designate, and pilot a new type of MPA – Highly Protected Marine Areas (HPMAs) in English waters, in response to the recommendations of the Benyon Review. The purpose of HPMAs will be biodiversity recovery, protecting all species and habitats and associated ecosystem processes within the site boundary, including the seabed and water column. HPMAs will be designated under the

Marine and Coastal Access Act (2009). In February 2023, the Secretary of State confirmed that that they will designate three HPMA areas by July 2023 (UK Government, 2023b).

Celtic Sea protected features

There are 26 MPAs designated in the offshore area of the Celtic Sea as a whole. Three different types of MPAs (SAC, MCZ and SPA) protect a total of 29 features (JNCC, 2020). None of the Refined Areas of Search overlap with the designated sites, though as can be seen in Figure 3-13, some of the Refined Areas of Search do border different designated sites. The closest Irish MPA is the Saltee Islands SAC, designated for features such as grey seals, reefs and mudflats, and located *c*. 87 km northwest of Refined Area of Search A. A summary of the protected areas and corresponding designated features in the vicinity of the Refined Areas of Search is provided in Table 3-11.

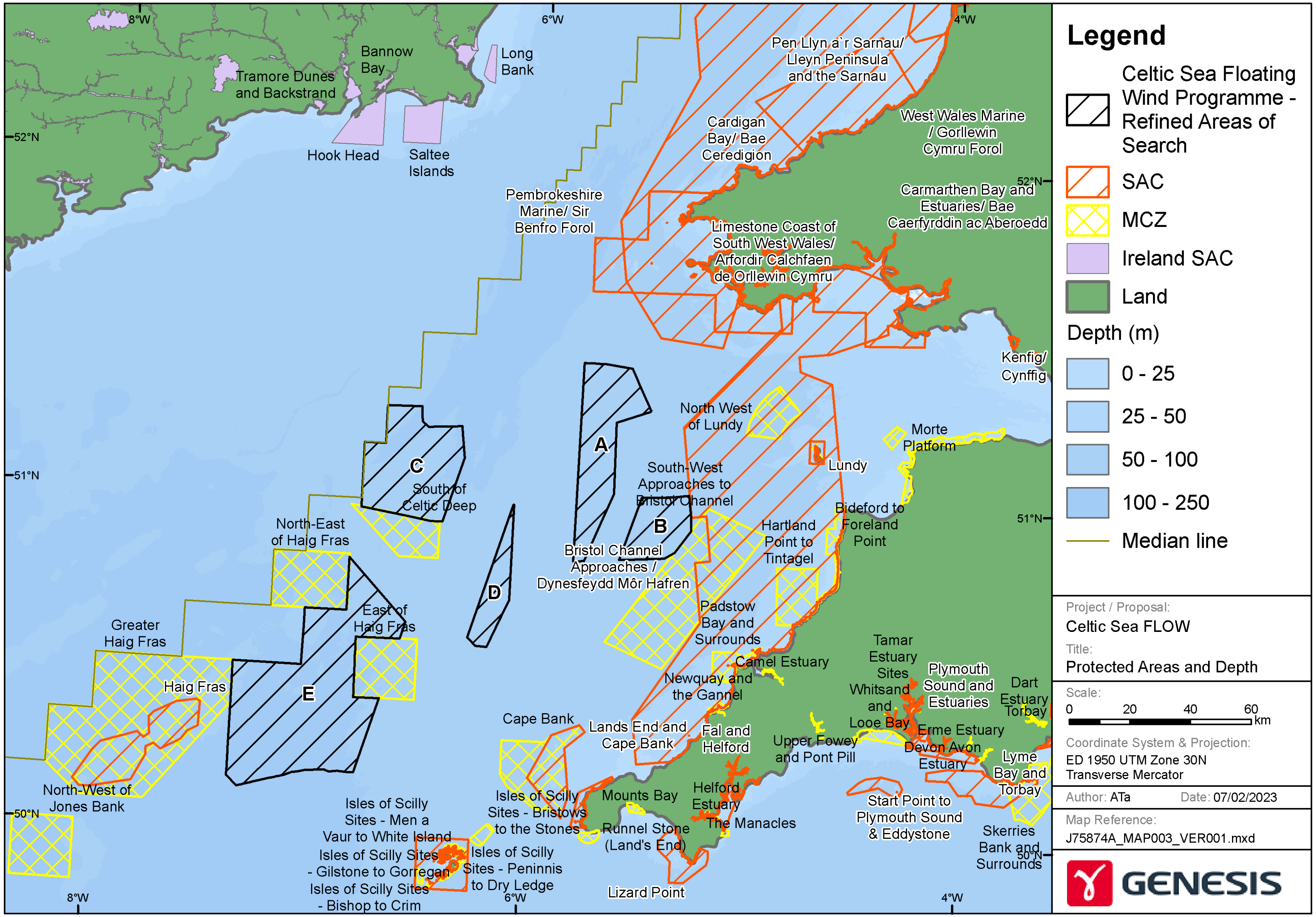


Figure 3-13. Protected areas in the vicinity of the Refined Areas of Search of the Celtic Sea Floating Wind Programme

Table 3-11. Celtic Sea protected features

Protected area	Location (in relation to Refined Areas of Search)	Designated features
South of Celtic Deep MCZ	Borders Refined Area of Search C	Moderate energy circalittoral rock
		Subtidal coarse sediment
		Subtidal mixed sediment
		Subtidal sand
Greater Haig Fras MCZ	Borders Refined Area of Search E	Subtidal coarse sediment
		Subtidal sand
		Subtidal mud
		Subtidal mixed sediment
		Sea-pen and burrowing megafauna communities
North-East of Haig Fras MCZ	Borders Refined Areas of Search E	Subtidal coarse sediment
		Subtidal sand
		Subtidal mud
East of Haig Fras MCZ	Borders Refined Areas of Search E	High energy circalittoral rock
		Moderate energy circalittoral rock
		Subtidal coarse sediment / A5.4: Subtidal mixed sediments mosaic
		Subtidal sand
		Subtidal mud
		Sea-pen and burrowing megafauna communities
		Fan mussel (*Atrina fragilis*)
South-West Approaches to Bristol Channel MCZ	Borders Refined Area of Search B	Subtidal coarse sediment
		Subtidal sand
Bristol Channel Approaches/ Dynesfeydd Môr Hafren SAC	Borders Refined Area of Search B	Harbour porpoise (*Phocoena phocoena*) – Annex II Species
Skomer, Skokholm and the Seas off Pembrokshire SPA	Borders Refined Area of Search A	European storm petrel (*Hydrobates pelagicus*) – Annex I Species (breeding)
		Red-billed chough (*Pyrrhororax pyrrhocorax*) – Annex I Species (breeding)
		Short-eared owl (*Asio flammeus*) – Annex I Species (breeding)
		Manx shearwater (*Puffinus puffinus*)

Protected area	Location (in relation to Refined Areas of Search)	Designated features
		Atlantic puffin (*Fratercula artica*)
		Lesser black-backed gull (*Larus fuscus*)
		Seabird assemblage of international importance – at least 20,000 seabirds in any season

Socio-economic receptors

This section presents information relating to other users of the sea as a receptor, to allow an assessment of whether they are likely to be impacted by FLOW projects.

Commercial fishing

Commercial fishing could pose a constraint on the development of potential FLOW farms due to competition for space, physical conflict between cables and fisheries equipment, and the displacement of important socio-economic activities (and the associated political and public fall out), which may result in a deleterious impact to fishers' incomes (Gray, Haggett, and Bell, 2005).

Within Western UK Seas, the commercial fishing footprint is extensive (ICES, 2023). The most targeted demersal fisheries are hake, caught in gill nets and long lines. Mobile bottom trawls have been deployed in over 44.6 % of the Western UK Sea's spatial extent (ICES, 2023). In western UK Seas otter trawls are dominant, followed closely by static gears (ICES, 2023). The largest footprint on the seabed for each bottom and pelagic gear are the benthic directed fisheries and gillnets, followed by longlines.

West UK midwater trawl fisheries, which trawl at various depths depending on target species, account for the largest catch (by weight), in the Celtic Sea. Types of fish targeted by midwater trawls include blue whiting, mackerel, horse mackerel, herring, boarfish, and sprat (ICES, 2021a). The species most targeted by demersal fishing in the Celtic Sea is hake, using gillnets and longlines. There are also large mixed bottom-trawl fisheries targeting the benthic species such as Norway lobster, and gadoids.

The density of fishing vessels located within the Celtic Sea has been assessed using Automatic Identification System (AIS) (ORE Catapult, 2020). Figure 3-14 shows the number of vessels present per square km ranging from 0 vessels (or no-data) to a maximum of 1,955 vessels, indicating the areas of most intense fishing activity. The map indicates a high density of fishing in Refined Areas of Search A and B, and reduced fishing efforts in Refined Areas of Search C, D and E.

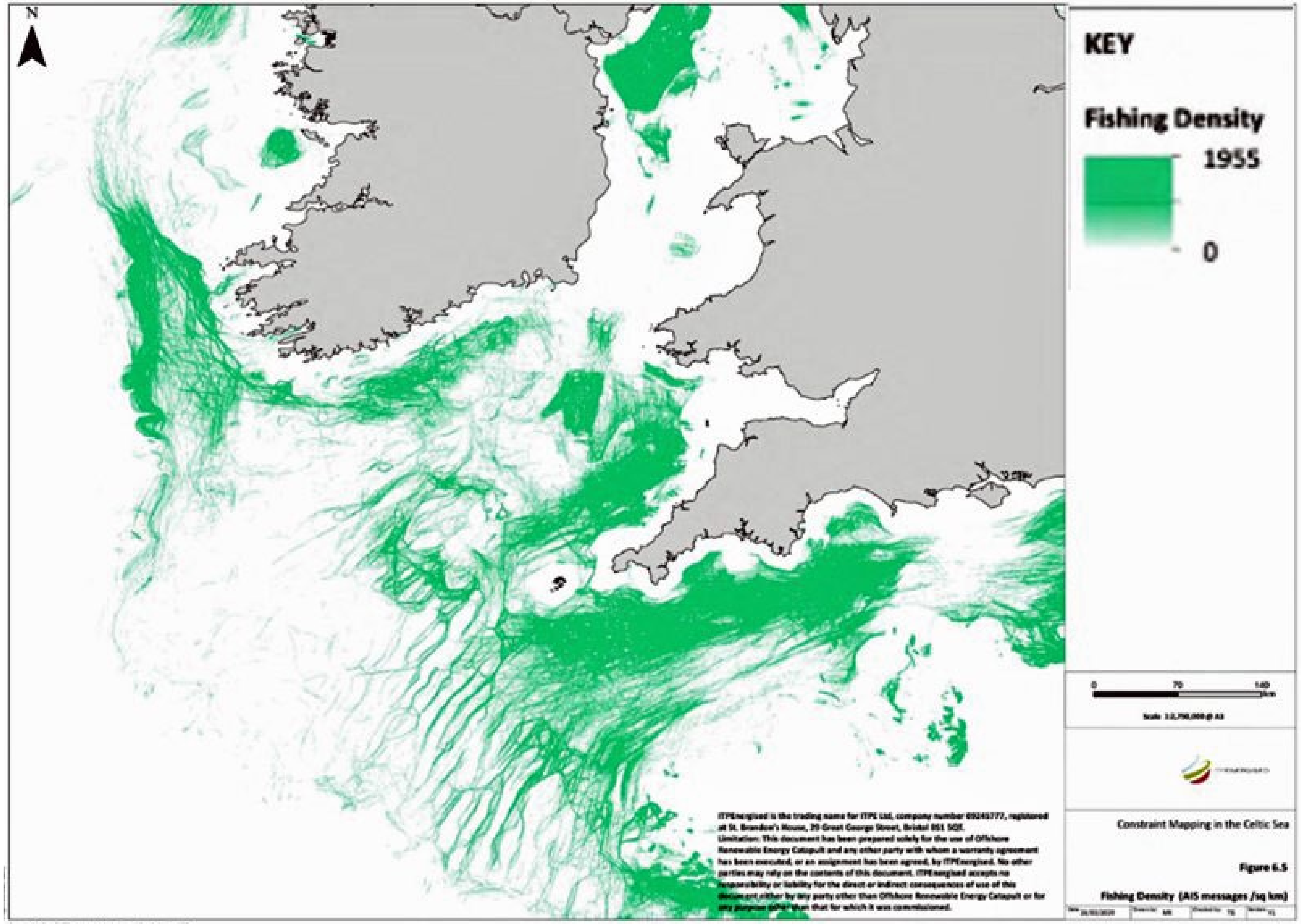


Figure 3-14. Celtic Sea fishing vessel density (between 0-1955) (ORE Catapult, 2020)

The intensity of fishing vessels located within the Celtic Sea has also been assessed by tracking the number of Vessel Monitoring System (VMS) messages received. Figure 3-15 shows the number of vessels present per square km, ranging from five vessels to greater than 300 vessels, indicating the areas of most intense fishing activity. The map indicates a high level of fishing vessel density in northeast Refined Area of Search C, another to the east of Area D and an intermittent area of high fishing vessels southwest of Area E (in the years 2014, 2016, 2018, 2019).

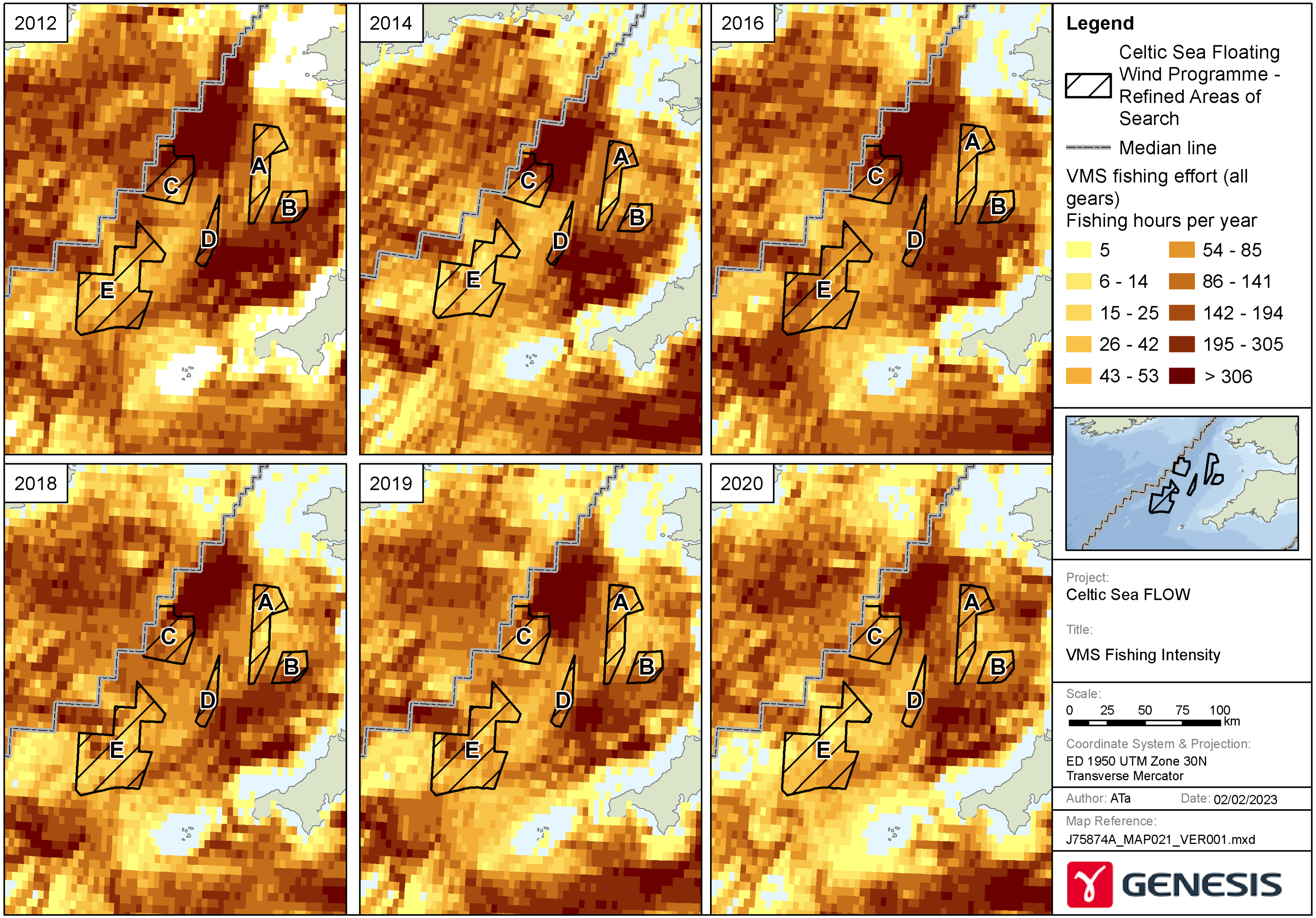


Figure 3-15. Celtic Sea fishing vessel intensity (fishing hours per year) from 2012-2020 (ICES, 2021b)

Shipping

Around 95% of UK import and export tonnage is transported by sea (Department for Transport, 2021). Figure 3-16 shows the 2017 average weekly vessel density around the Refined Areas of Search utilising AIS shipping density data from DEFRA (2017). It is evident that the English Channel forms one of the primary shipping routes, with an average of 100-250 vessels passing per week off the southwest coast of England. Another area of high vessel traffic is around the entrance to the Cleddau estuary, on the southwest coast of Wales, where an average of over 500 vessels pass by per week. Another vessel track with average weekly vessel densities between 10-25 and 25-50 is also present passing south of Area B. Similarly, another two vessel tracks pass east of Areas C and E and west of Area D. Vessel densities along these tracks are lower between 5-10 and 25-50.

The majority of these vessel routes are for commercial purposes involving large vessels. Considerations for developing a FLOW farm in the area include: constrictions on construction, the cost of damages to a vessel or wind farm installations (Bosch *et al.,* 2018).

If shipping is displaced to shipping channels due to the presence of FLOW farms, this could lead to a change in disturbance and displacement impacts to mobile species.

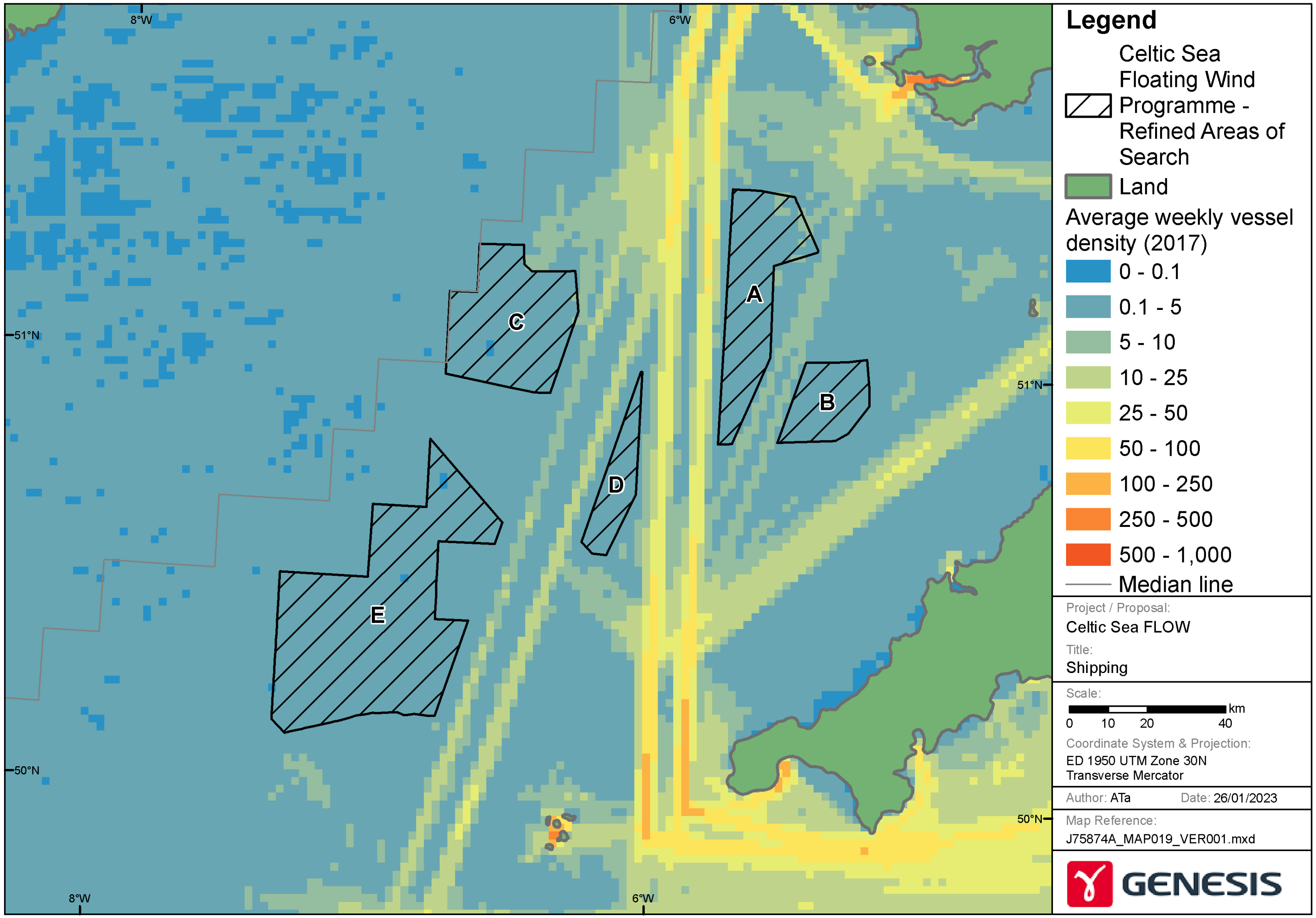


Figure 3-16. Average weekly vessel density in the vicinity of the Refined Areas of Search for the Celtic Sea Floating Wind Programme (DEFRA, 2017)

The intensity of shipping density located within the Celtic Sea has been assessed by the North Sea Transition Authority (NSTA). Figure 3-17 shows the level of shipping density, ranging from ‘negligible’, ‘very low’, ‘low’, ‘moderate’, ‘high’, ‘very high (OGA, 2016). Areas A and B are considered as areas of ‘moderate’ shipping density, which confirm the ORE Catapult (2020) reporting of a marine shipping route down the centre of the English Channel. Area A is characterised by ‘moderate’, ‘very low’ and ‘low’, while Area B is ‘moderate’ and ‘very low’. The map indicates a ‘high’ level of shipping density in Refined Area of Search D. Refined Areas of Search C and E present ‘moderate’, ‘very low’ and ‘negligible’ densities.

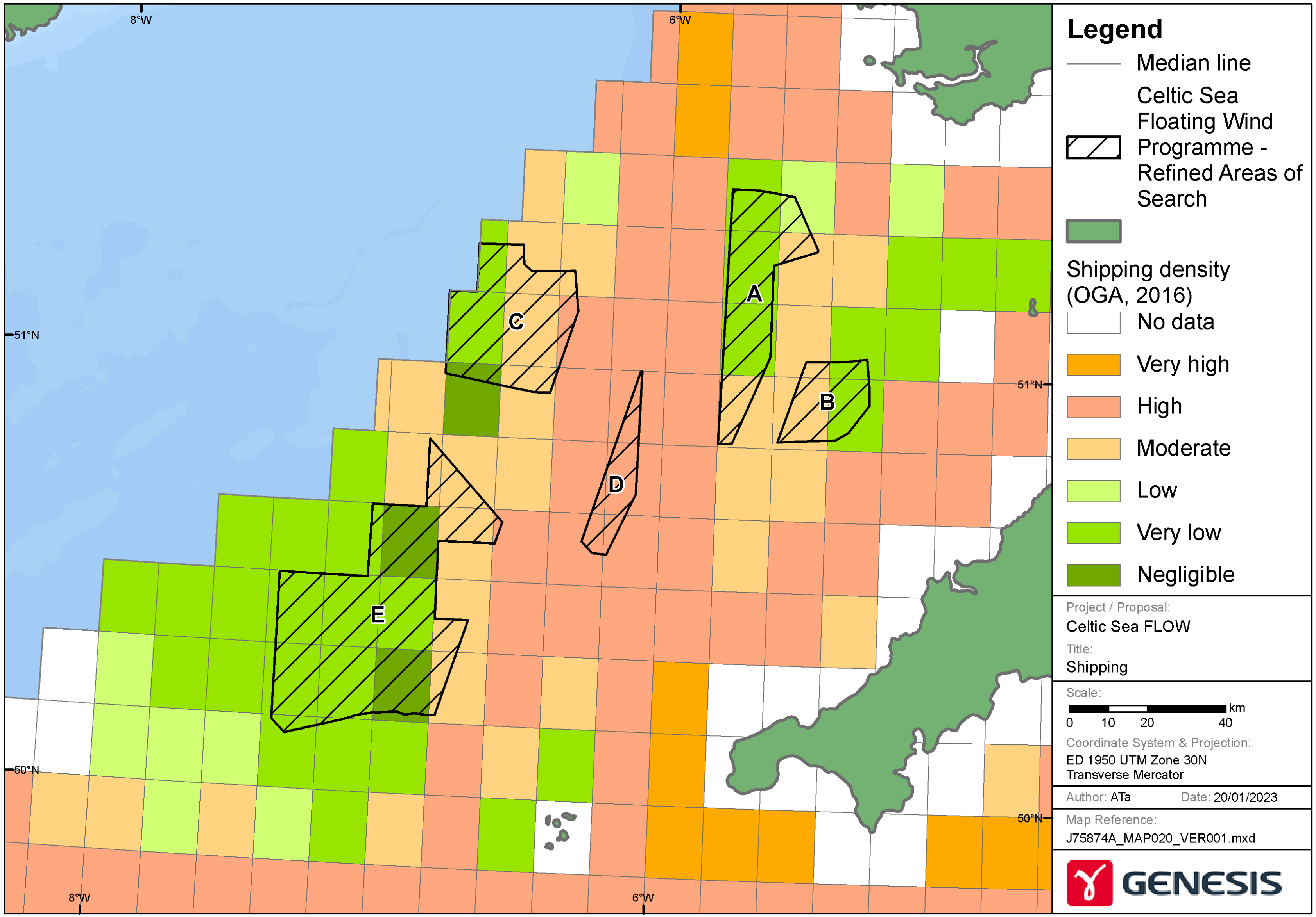


Figure 3-17. Shipping density (between negligible to very high) in the Celtic Sea as categorised by NSTA (NSTA 2016)

Aggregates

The UK has one of the largest construction aggregate dredging industries in the world, providing 24% (10.2 million tonnes) of the UK’s annual consumption of sand and gravel in 2012 (Bide *et al.,* 2014). The largest current demand for sand and gravel is for coarse sand for use in the manufacture of concrete (Bide *et al.,* 2014). These resources face the most restrictions in terms of supply in the immediate future due to high demand by the construction sector and an increasingly restricted supply from onshore resources.

A total of 21 million tonnes of sand and gravel were dredged in the Celtic Sea during 2021, under Crown Estate licencing in England and Wales (Crown Estate, 2023). Within the Refined Area of Search, there are no open functioning aggregates collection sites (Highley *et al.,* 2007).

The only aggregate site in the vicinity of the Refined Areas of Search is the Nobel Banks Aggregate Agreement Site located *c.*11 km off the south coast of Wales (Figure 3-18). Llanelli Sand Dredging Ltd. was granted a 15-year licence to dredge this area for sand in 2006. Under this licence, the maximum quantity of sand which can be dredged annually is 300,000 tonnes (Welsh Assembly Government, 2004).

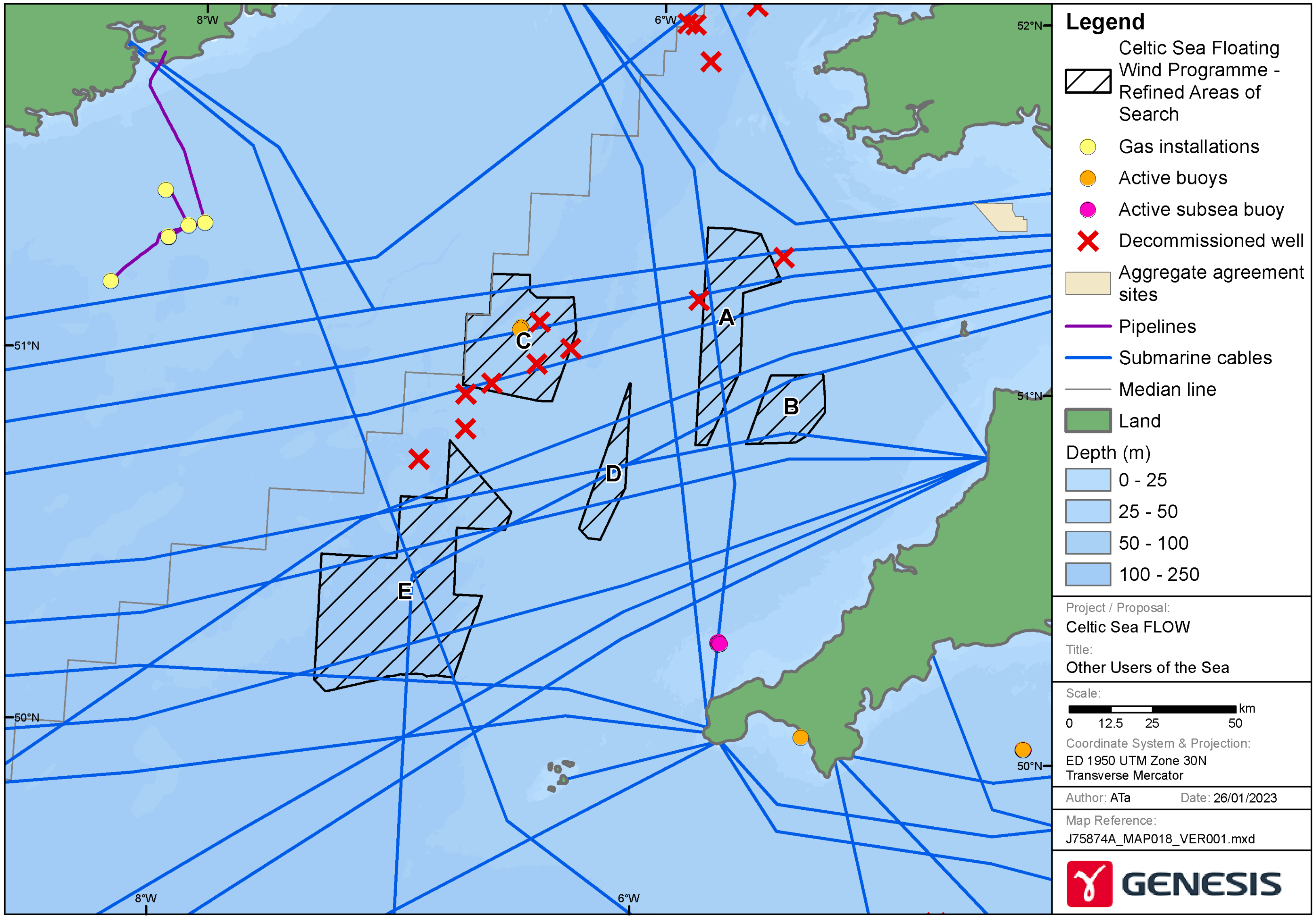


Figure 3-18. Other users (includes gas installations, buoys, decommissioned wells, pipelines, cables) of the Celtic sea in the vicinity of the Refined Areas of Search for the Celtic Sea Floating Wind Programme

Cables

There are over 70 active telecommunication cable systems running across the UK seabed. The presence of an existing telecommunication cable could have a significant impact on the location of potential FLOW farm sites due to the protections outlined under the Submarine Telegraph Act 1885. The Act requires that any person who injures or breaks a legally established submarine cable by culpable negligence should be guilty of an offence for which, under UK law fine, imprisonment, or both (Side, 1999).

In addition, if inter-array cables within a FLOW farm are required to cross existing cables, there may be a requirement for additional scour and cable protection at crossing points, which may therefore have a larger footprint on the seabed and associated impacts to sediments and benthic habitats.

There are a total of eight telecommunication cables running through the Refined Areas of Search (Telegeography, 2023):

- Apollo (13,000 km); passes through Area B, D and E
- Atlantic Crossing-1 (14,301 km); passes through Area E
- EXA Express (4,600 km); passes through Areas A and C
- Tata TGN Atlantic (13,000 km); passes through Areas A and C
- Tata TGN-Western Europe (3,578 km); passes through Areas A, B, D and E
- Yellow/Atlantic Crossing 2 (7,001 km); passes through Areas D and E
- Pan European Crossing (UK-Ireland) (495 km); passes through Area A
- Ireland-France Cable-1 (490 km); passes through Area E

There were no power cables running through the Refined Areas of Search at the time of writing. However, National Grid are currently developing a Holistic Network Design (HND) for a coordinated onshore and offshore power transmission network, which will support the connection of 40 GW of offshore wind by 2030 in the UK. The HND includes the assumption that there will be 1 GW of floating wind from the upcoming Celtic Sea leasing round, as well as including offshore wind projects that secured seabed leases through The Crown Estate’s Offshore Wind Leasing Round 4 and Crown Estate Scotland’s ScotWind Leasing Round. The purpose of the HND is to make sure that the offshore and onshore transmission network enables the growth in offshore wind (and thus supports the achievement of net zero targets) in a way that is efficient for consumers and takes account of the impacts on coastal communities and the environment (National Grid, 2023).

In addition, the Xlinks Morocco-UK Power Project is a future interconnector project, whereby four 3,800 km HVDC cables will transport energy generated by solar and wind energy in the south of Morocco, to the UK energy grid. The proposed cable will come onshore in Devon (XLinks, 2023). The future power cables associated with this project have the potential to be located in the vicinity of the Refined Areas of Search.

Furthermore, cable activities associated with White Cross offshore wind farm, currently in development by Cobra and Flotation Energy (due to be operational in 2026/2027) also have the potential to be located in the vicinity of the Refined Areas of Search. The White Cross wind farm site is located over 52 km off the North Cornwall and North Devon coast (west-north-west of Hartland Point). The offshore export cable will connect the offshore substation platform to shore. Onshore, the grid connection is confirmed as East Yelland (White Cross, 2022).

Aquaculture and shellfish protection areas

In 2018, the UK produced 0.9 million tonnes of farmed fish (including molluscs and crustaceans), with a value of USD 2667.2 million (Organisation for Economic Co-operation and Development (OECD), 2017). Just under 70% of 2020 economic output from aquaculture took place in Scotland and the South-West of England had the second largest output (8%) (Uberoi *et al*., 2022).

Van Hoey *et al* (2021) studied the potential for coexistence between offshore wind farms and aquaculture. During an interview with an aquaculture-based stakeholder it was noted that the closest offshore wind farm to any offshore salmon aquaculture site was more than 100 km away. Salmon form the predominant finfish aquaculture industry in the UK and production is highly concentrated across western Scotland.

In principle, there are no restrictions on any extractive forms of aquaculture in wind farms, and there are thus no compensation mechanisms. In the Netherlands, the government has mandated that aquaculture should coexist with wind energy in the future and has appointed wind farms as aquaculture grounds. However, this could prove to be highly challenging due to the costs associated with longer travel times and the reduced number of working days at sea. Furthermore, due to the high safety risks, offshore wind farm operators require mussel farm employees to take a week's training course, after which they are licensed to navigate through wind farms (Van Hoey *et al.,* 2021).

The only aquaculture sites in the vicinity of the Refined Areas of Search are all for bivalve cultivation and are restricted to coastal and estuarine areas. The sites are therefore considerable distant from all of the Refined Areas of Search.

Military activity

Much of the Celtic Sea is designated for potential military use. These military areas are divided into "danger" and "exercise" zones, as shown in Figure 3-19. Five military areas occur in the Celtic Sea: two Culdrose practice areas, a series of exercise zones on the south coast, various danger zones, and a larger area of exercise zones west of Cornwall. The majority of the military zones are unlikely to impact the Refined Areas of Search, however Area E, D and E may interact with the North West Military Exercise Zone. FLOW wind developments will have to work closely with military bases to ensure coexistence of military surveillance systems and wind turbines. This may involve mitigation measures currently being investigated (MoD, 2022).

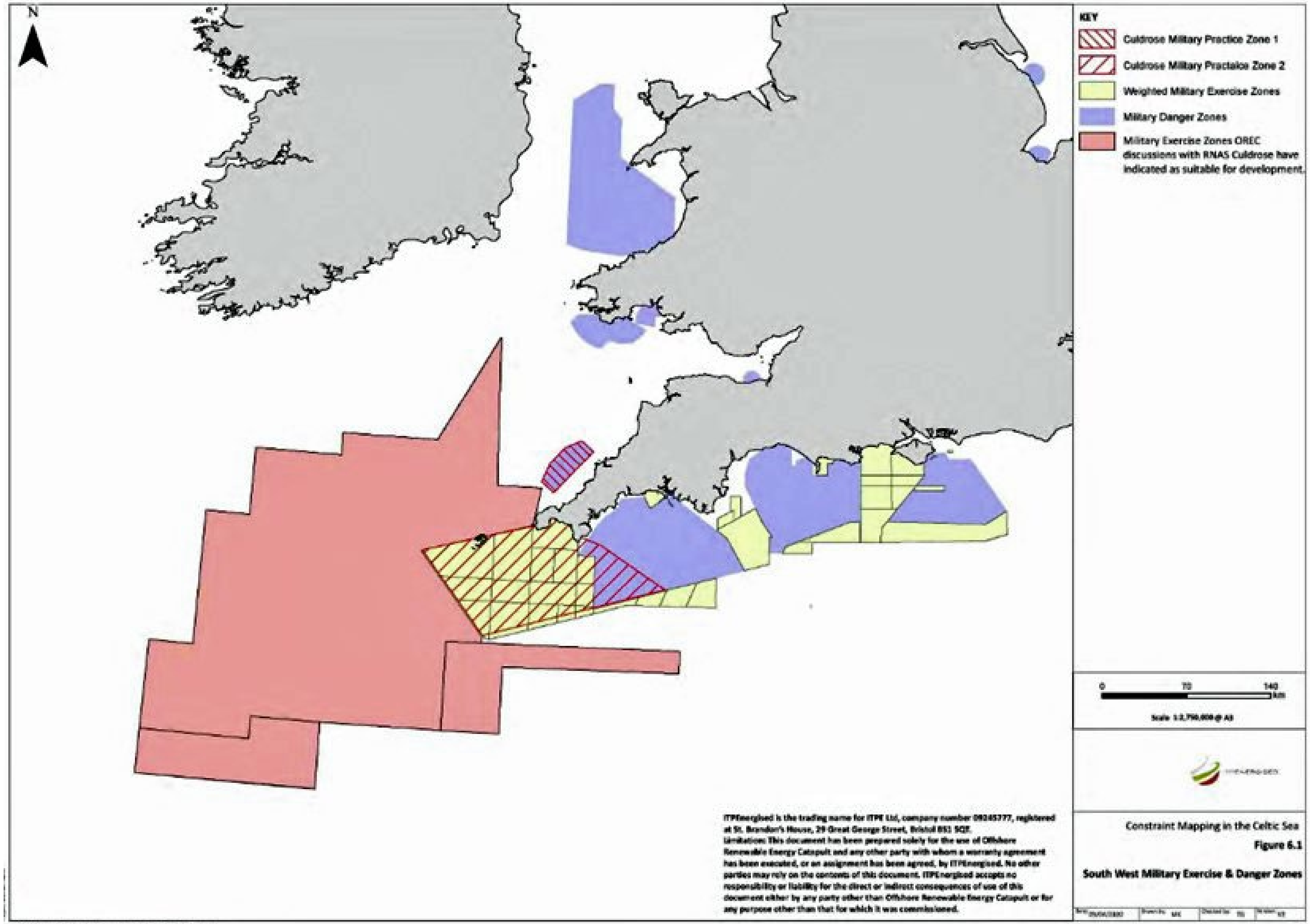


Figure 3-19. Military exercise and danger zones in the Celtic Sea (ORE Catapult, 2020)

Renewable energy

There are a number of FLOW projects already under development in the Celtic Sea, within Planning or in the early concept phase (Table 3-12; Figure 3-20). Blue Gem Wind's Erebus Demonstration secured a marine licence in February 2023 and Valorous Wind Farm has completed scoping (Blue Gem Wind, 2023). The Hexicon TwinHub offshore wind demonstration was consented in 2022 (Global Energy Monitor, 2023; TwinHub, 2023). Further details of FLOW case studies in the Celtic Sea are provided in Appendix 4.

Several other proposed wind farms are located in Irish waters of the Celtic Sea, such as the pre-construction Emerald Wind Farm, Celtic Sea wind farm and North Celtic Sea wind farm (early concept), the Inis Ealga wind farm (early concept), and Blackwater Wind Farm (early concept) developed by Flotation Energy.

Table 3-12. Summary of renewable energy sites in the vicinity of the Refined Areas of Search

Site name	Operator	Country	Type of site	Project status	Capacity
TwinHub	Hexicon	England	FLOW demonstrator	Fully consented	40 MW
Llŷr 1 [a]	Floventis Energy (Cierco Ltd and SBM Offshore)	Wales	FLOW test and demonstration project	Planning – scoping submitted	100 MW
Llŷr 2 [a]	Floventis Energy (Cierco Ltd and SBM Offshore)	Wales	FLOW test and demonstration project	Planning – scoping submitted	100 MW
Emerald	Simply Blue Group	Ireland	FLOW	Planning – scoping stage	1.3 GW
Erebus	Blue Gem Wind (TotalEnergies and Simply Blue Group)	Wales	FLOW test and demonstration project	Planning – marine license consented February 2023, awaiting section 36 decision	96-100 MW
Valorous	Blue Gem Wind (TotalEnergies and Simply Blue Group)	Wales	Early commercial FLOW	Planning – scoping completed	300 MW
White Cross [b]	Offshore Wind Limited (Cobra and Flotation Energy)	England	FLOW	Planning – scoping completed	100 MW
Llywelyn	BlueFloat Energy and Renantis (formerly Falck Renewables)	Wales	Commercial scale FLOW	Concept – scoping stage	300 MW
Petroc	BlueFloat Energy and Renantis (formerly Falck Renewables)	England	Commercial scale FLOW	Concept – scoping stage	300 MW

Site name	Operator	Country	Type of site	Project status	Capacity
Gwynt Glas	DP Energy Ireland Ltd and EDF Renewable Energy	Wales	FLOW	Concept	1 GW
South Pembrokeshire Demonstration Zone	WaveHub Ltd	Wales	Wave energy demonstration Zone	Pre-planning – EIA started	90 MW

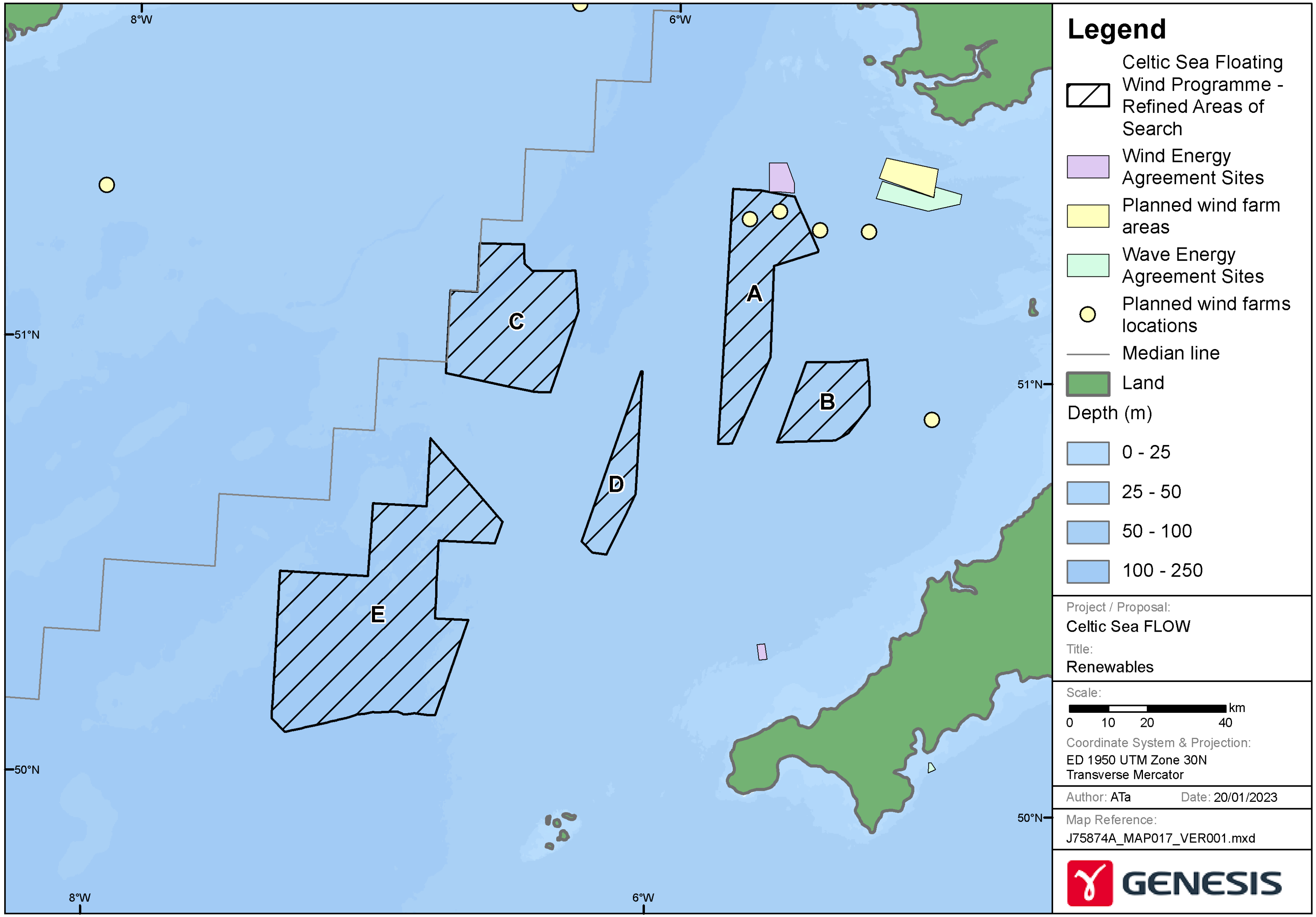


Figure 3-20. Renewable energy sites in the vicinity of the Refined Areas of Search for the Celtic Sea Floating Wind Programme

Oil and gas infrastructure

There are limited oil and gas assets in the Celtic Sea and there are no current oil and gas facilities within any of the Refined Areas of Search (Figure 3-18). Four decommissioned wells are present in Area C and the closest gas installation is *c.* 83 km northwest of Area C.

There is one active Celtic Sea Deep Smart Buoy and one Celtic Sea Deep Guard Buoy within Area C, however these are in place for research purposes.

Recreation

Recreational activities (e.g., windsurfing, snorkelling, use of motorised and non-motorised vessels, personal watercrafts, swimming and SCUBA diving) tend to occur along the coastal areas of the Celtic Sea and are unlikely to occur in the vicinity of the Refined Areas of Search given their offshore locations.

Wrecks

To date, Historic England has archived approximately 40,000 wreck sites in UK seas (Rowberry, *et al*., 2019). Wrecks are protected under the Protection of Wrecks Act 1973, which allow the Secretary of State to designate a restricted area around a wreck to prevent uncontrolled interference. These protected areas are likely to contain the remains of a vessel, or its contents, which are of historical, artistic, or archaeological importance.

Figure 3-21 illustrates the presence of wrecks within the Celtic Sea. A total of 32 wrecks are located within the Refined Areas of Search. The highest number of wrecks are present in Area E (11) followed by Area A (nine), Area B (six) and three in Areas C and D.

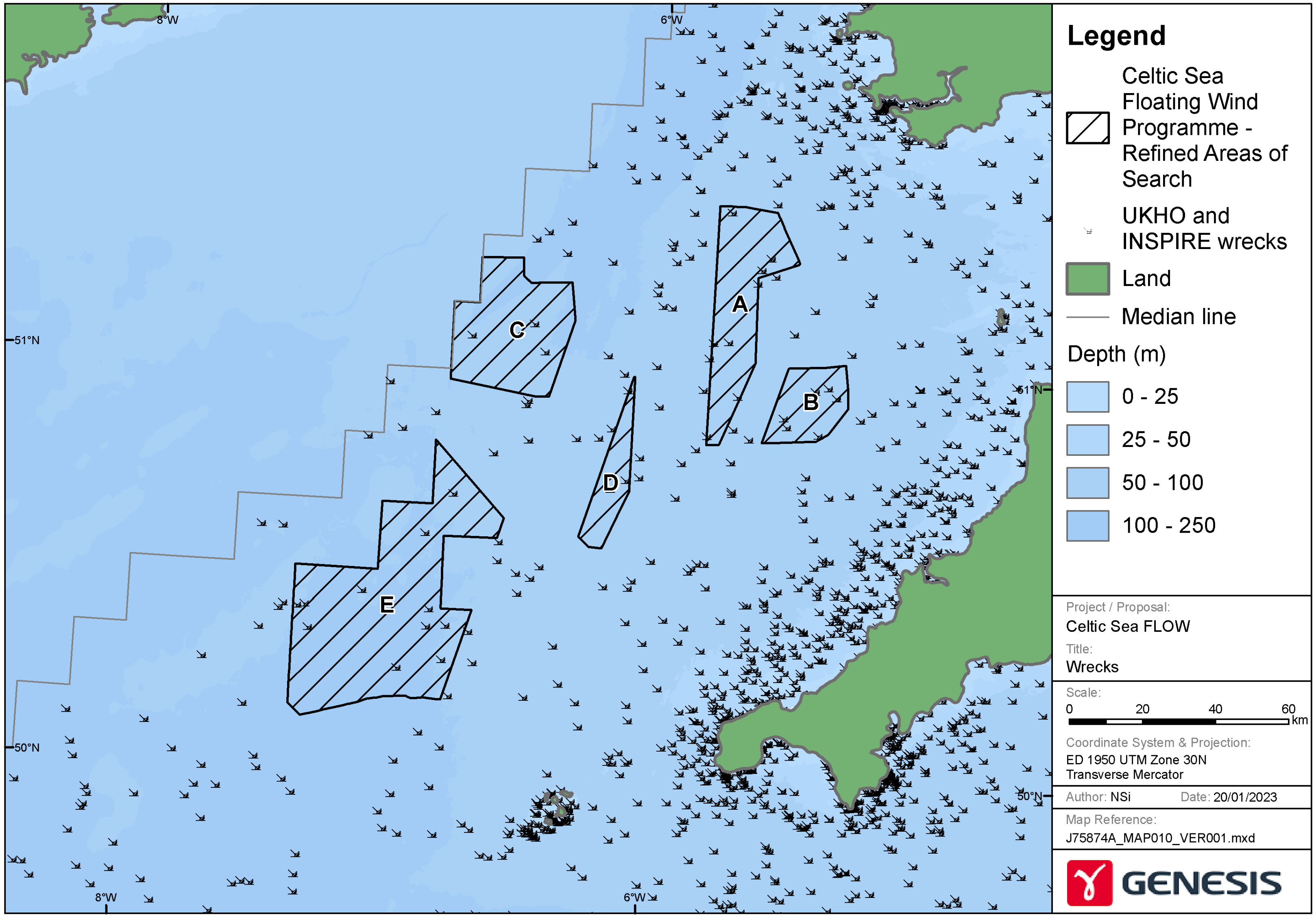


Figure 3-21. UKHO and INSPIRE wrecks in the vicinity of the Refined Areas of Search for the Celtic Sea Floating Wind Programme

4. Assessment of environmental impacts and pressure pathways

When introduced into the marine environment, FLOW can affect the environmental receptors identified in Section 3 in a number of ways. The following sections identify and describe these effects, before discussing how impacts and pressure pathways (interactions with the physical and biological environment) may differ between floating and fixed foundations. In doing so, Objective 2 has been addressed. Note that for each source of environmental impact, there are often multiple pathways and receptors. As described in Section 1 (Method), the identification of pressures is in line with Natural England's Advice on Operations tool.

Objective 3 has also been addressed throughout this section, where the impacts on habitats and species, including features/sub feature or supporting habitat sensitivity to those pressures have been assessed for known and new pressures associated with the development of the FLOW design envelope. Pressures have been identified, described, and assessed against established pressure benchmarks (i.e., those used in the Natural England Designated Sites tool, according to the method described in Section 1).

In addition to the differences between floating and fixed foundations, impacts may also vary within the FLOW design envelope, depending on characteristics such as floating foundation type, mooring line type, anchor type, and inter-array cable layout or burial status. Differences in receptor sensitivity and environmental impact are primarily due to changes in underwater surface areas, volumes occupied in the water column, and footprint on the seabed (Horwath *et al*., 2020). The worst-case scenario design envelope of FLOW has been assessed in relation to each environmental receptor or group of receptors. i.e., benthic, ornithology, marine mammals etc. In doing so, Objective 4 has been addressed.

Appendix 1 provides a comprehensive summary of recommended risk-profiling ranking for each pressure considered to be relevant to FLOW. Justifications have been provided as to why risk profile recommendations are the same as those already provided in the Advice on Operations tool for offshore wind, or different. In addition, the table summarises receptors considered to be most sensitive to each pressure, as well as recommended technology types within the FLOW technical design envelope.

Under each impact heading, mitigation measures have been identified to minimise the potential impacts associated with wind farms in general, FLOW specifically, as well as anchor, mooring line, and floating foundation types where information is available (Objective 5). All mitigation measures discussed throughout this section are summarised in Appendix 2.

Evidence gaps have been identified throughout the development of this report. These are set out clearly at pressure-specific level under each impact heading throughout the following sections. A number of general recommendations are also presented in Section 6. Together, these sections address Objective 6. All evidence gaps discussed throughout this section are summarised in Appendix 3. It should be noted that pressures for which a large volume of literature was available appear to have more evidence gaps in some cases.

However, the opposite is also true, whereby the number of evidence gaps reflects the level of detail available in literature, allowing more specific evidence gaps to be identified for those pressures. For pressures where there is less literature available on the topic (and thus topics where less research has been conducted), evidence gaps are broader and more all-encompassing as current research and evidence is not sufficient to refine them further. For this reason, caution should be taken not to assume that more evidence gaps mean that an impact has been studied less. Table 11-1 indicates those pressures for which a comparatively large volume of literature is available.

Seabed disturbance

Seabed disturbance is described as physical disturbance caused by activities that affect the seabed either directly or indirectly. The anchors, mooring lines, and inter-array cables associated with FLOW developments represent sources that may lead to seabed disturbance during all lifecycle stages i.e., construction, operation and maintenance, and decommissioning. Seabed disturbance can take many forms, and the following sections describe a number of these in turn.

Disturbance to the seabed by any means ultimately leads to disturbance of benthic communities. Natural disturbance occurring on the seabed forms part of an ecosystem's natural processes; allowing for better nutrient accessibility and recycling, and benthic communities are well adapted to natural levels of disturbance (Harris, 2014). The construction and presence of FLOW turbines (i.e., with anchors, mooring lines, and inter-array cables all in contact with the seabed) significantly increases the frequency and duration of disturbance (Maxwell *et al*., 2022).

Receptors that are sensitive to seabed disturbance include those located on, near, or in the seabed, such as sediment types, various benthic habitat types, benthic communities, demersal fish species and potentially some fish spawning/nursery areas. In addition, pelagic species could be impacted by the indirect effects of seabed disturbance, such as increased suspended solids in the water column and water turbidity, or changes in prey populations.

As described in Section 3, there is the potential for a number of coral and sponge species to occur in the Refined Areas of Search. Corals and sponges are long-lived sessile macroinvertebrates that provide habitat complexity and a range of ecosystem services that create aggregations of biodiversity in the deep sea (Hourigan *et al*., 2017). Examples of species present in the Refined Areas of Search include Devonshire Cup Corals and British Stony Coral. FLOW turbine anchors could do considerable damage to these ecosystems, as has been shown from boat anchors in tropical coral and sponge ecosystems (Harriott and Dinsdale, 2004). Further evidence from Davis *et al*. (2016) notes that any biota that comes into contact with a dragging anchor or a sweeping anchor chain will sustain some sort of damage, whether being swept from the sea floor, or being crushed altogether. Additionally, there are numerous studies documenting the negative effects of bottom contact fishing gear on deep-sea corals and sponges (Fuller *et al*., 2008; Lumsden *et al*., 2007; Salgado *et al*., 2018).

Although most impacts associated with seabed disturbance are negative, there are also a few positive outcomes as a result of constructing wind farm developments. Fishing activities are prohibited in most offshore wind farm areas during construction and operation of the installations. This has been shown to have a strong positive impact on abundance and diversity of benthic communities and the demersal fish assemblage (Bergström *et al*. 2013). The main drivers for the positive effects are the increase in habitat heterogeneity, the reef effect and the removal of the bottom trawling from the area (Bergström *et al*., 2014; Stenberg *et al*., 2015; Inger *et al.,* 2009; Ray *et al.,* 2022).

For example, fishing at Hywind Scotland FLOW is allowed but is believed to be limited to use of passive gear since trawls are difficult to operate in between the turbines with their anchors. Active gear has to be moved or activated by the sampler in order to catch fish (e.g., electrofishing, seine netting, and trawling; Portt *et al.,* 2006; Winger *et al.,* 2010). In contrast, passive gear is left out for a period of time before being retrieved, relying solely on the animal's movement and interaction towards it for capture to occur (e.g., minnow traps, Windermere traps, fyke nets, and gill nets; Portt *et al.,* 2006).

Equinor (operator of Hywind Scotland) is collaborating with Marine Scotland to better understand how fishers can safely operate around and within FLOW farms. In 2022, Marine Scotland tested three kinds of fishing gear (creels, fishtraps and jigging lines) at the Hywind Scotland site. Whilst not all of these fishing methods are used commercially around Hywind Scotland itself, the purpose was to demonstrate how methods used globally can interact with floating offshore wind farms. The results of this survey are not yet available (Equinor, 2022).

As a result of attraction effects, FLOW turbines can also act as fish aggregating devices (FADs) that concentrate marine fish and facilitate their capture, resulting in increased catch rates for some species. In future, this could become a development opportunity to create a limited entry recreational fishery (Fayram and de Risi., 2007). The potential for FLOW turbines to act as FADs are discussed later in the physical presence section.

Evidence gaps

In general, seabed disturbance pressures were understood for the majority of marine activities involved with FLOW.

Evidence gaps have been identified regarding the impacts of all seabed disturbance pressures (i.e., abrasion, penetration, introduction of hard substrate, suspended sediment and smothering) on specific sediment and habitat types (e.g., EUNIS habitat types such as offshore circalittoral coarse sediment). In light of this evidence gap, a number of offshore wind developments reporting similar habitat types to the Refined Areas of Search have been noted. Analysis of monitoring surveys conducted at those sites in future would potentially address this evidence gap.

To improve the understanding of seabed disturbance impacts on specific sediment/habitat types, monitoring surveys should be conducted, or numerical modelling carried out to predict potential impacts of various scenarios on these sediment/habitat types. As this is applicable to all pressures within the seabed disturbance section, this evidence gap has not been discussed under each subheading and any evidence gaps discussed within the following subsections are specific to that pressure / type of seabed disturbance.

Abrasion/disturbance of the substrate on the surface of the seabed

Abrasion/disturbance of the substrate on the surface of the seabed is relevant to epiflora and epifauna living on or at the surface of the substratum. Many activities that can cause abrasion are also penetrative (e.g. dredges, anchors, piling) and it is important to distinguish between surface effects and the sub-surface penetrative effects, which are addressed in the next pressure (Tyler-Walters *et al*., 2018).

Abrasion/disturbance of the substrate on the surface of the seabed is caused by all footprints on the seabed from FLOW activities (both permanent and temporary). This includes but is not limited to:

- permanent footprints of all infrastructure installed on the seabed (e.g., placement of anchors, mooring lines, inter-array cables and any associated scour protection)
- temporary footprints on the seabed during installation activities (e.g., installation equipment such as jack-up barges, clump weights, trenching activities for cable installation, dredging activities for seabed preparation)
- Long term (60 years operational life)/ temporary footprints during the operational phase caused by scour (erosion), or the dynamic movement of mooring lines and anchors on the seabed as a result of wave/current action (ABPmer *et al*., 2011)
- temporary footprints caused by the removal of infrastructure during the decommissioning phase

For fixed foundation turbines, installation and/or removal of turbine foundations (including piling) during the construction and/or decommissioning phases represent the greatest source of seabed disturbance. Seabed disturbance during construction and decommissioning may be comparably less for FLOW, as there are less operations at sea (i.e., most components are constructed in a port and towed offshore). Despite this, installation and/or removal of FLOW anchors presents a source of seabed disturbance that must be considered, albeit with a likely smaller overall footprint of impact than piling a fixed foundation.

Inter-array cables are often buried in fixed foundation offshore wind installations. In some cases of FLOW, the inter-array cables may also be buried or weighted where the dynamic cable reaches the seabed, between the floating substructures they connect. If inter-array cables for a FLOW project are to be buried, it is likely that the impacts of inter-array cables during the construction stage will be similar to fixed foundation offshore wind. However, if inter-array cables are surface laid, the extent of abrasion on the seabed will be greater for inter-array cables in a catenary configuration, as more of the cable touches the seabed compared to lazy wave configuration (Rentschler *et al.,* 2020).

Whether buried or surface laid, the inter-array cables between the turbines represent a sizable physical and ecological footprint, particularly for a commercial-scale project (Maxwell *et al*., 2022). The area of seabed disturbance is greater for inter-array cables in a loop-based configuration on the seabed, in comparison to a string-based design. For both fixed and floating foundation designs, inter-array cables can be in either configuration on the seabed. However, as described in Section 2, loop-based configuration is especially advantageous to FLOW due to increased resilience.

Buried cables are less susceptible to damage from external sources, such as vessel anchors or trawling gear. Ecologically, burial reduces the exposure of organisms to the electromagnetic field emitted by the cables and allows the benthic community to recolonise the area above the cable after installation (Fluharty, 2000; Hutchison *et al.,* 2018). However, during cable laying and burial, construction equipment is used to create a trench (via plowing, jetting, horizontal drilling, or other mechanical methods) that directly disturbs the seabed along the cable route. This activity may cause direct mortality of organisms due to abrasion of the surface of the seabed, temporary loss or disruption of habitat, and suspension of sediment into the water column (SEER, 2022a). Loss of habitat and suspension of sediment into the water column are addressed in a later section.

Furthermore, before installation of a pipeline, pre-sweeping of sand waves is sometimes required in order to level the seabed and obtain a suitable burial depth. One or more dredgers may do the pre-sweeping with pipe-laying vessels following behind. The pre-sweeping operation prepares a smooth enough seabed upon which to lay the pipeline. These activities would directly disturb the seabed beneath. Through analysis of available literature, including a number of environmental statements for offshore wind projects, it is likely that sand wave pre-sweeping would only be necessary for the installation of an export cable to shore, as it will be trenched and buried, as opposed to inter-array cables within a single wind farm site, which would most likely be surface laid (Vattenfall., 2019). If inter-array cables were to be buried for a FLOW project, pre-sweeping may be necessary in this case. As export cables are out with the scope of this report, it is unlikely that sand wave pre-sweeping will present a source of abrasion to the surface of the seabed for FLOW developments in this context. Despite this, even if pre-sweeping activities were to occur, this would not present a significant difference from fixed foundation offshore wind, as both fixed and floating developments would require a level seabed for cable installation. Further information is required to determine how common construction site preparation works such as dredging and sand wave levelling is for FLOW.

The effects and recovery from the installation of undersea cables depends on a variety of factors, including the method (trenching or physical protection), sediment type, and other location-specific details like water depth, waves, and currents and the resilience/ recoverability of the habitat type (MarLIN, 2023). The footprint of the physical disturbance also varies depending on method, length, and number of cables required to accommodate the power capacity of the wind farm. For instance, the tracks used to mobilise a plow for cable installation can create a 2- to 8-meter-wide disturbance on both sides of the cable. While mobile organisms can move and avoid the area of disturbance, the impact to sessile organisms may result in mortality (SEER, 2022a).

During the operation and maintenance phase, it is evident that FLOW potentially has a novel source of seabed disturbance that fixed foundation turbines do not have (depending on mooring line type selected). A heavy ground chain (or rode) is attached to the anchor in catenary or semi-taut mooring designs. The rode increases the tension on the mooring line as it is lifted from the seabed, reducing the shock in the line, which may disturb the seabed during operation. A significant proportion of mooring line may also rest on the seabed during operation (particularly for the catenary mooring line design) and be lifted up and down through surface wave action moving the floating foundation and turbine. This can lead to sediment abrasion and trenching, particularly where the chain touches the seabed (Low *et al*., 2018; Thethi and Moros, 2001). In addition to this, the dynamic inter-array cables may cause abrasion to the seabed during operation.

Scour

The main source of abrasion/disturbance of the substrate on the surface of the seabed for fixed foundation turbines during the operation and maintenance phase, is scour.

When a structure of any kind is placed offshore, the action of waves, currents and tides stirs sediment particles around the structure, picks them up and transports them away from the structure, creating a hole around the structure (erosion). This phenomenon is called scour. The presence of the structure itself can also cause a local increase in current and wave motions, intensifying the impacts of scour. When conditions in the wind farm are conducive to erosion, scour protection is installed around the turbine bases or subsea cables to limit the effects. Scour protection includes rock dump, rock bags, grout bags and concrete, fronded, bitumen and poly mat mattresses, or other hard surfaces that improve the stability of the sediment (Natural England, 2022d; SEER, 2022a). Scour and erosion can even occur around scour protection pads (Whitehouse *et al*., 2008, Coates *et al*., 2011; Horwath *et al*., 2020). In addition, removal of scour protection during decommissioning (by methods such as removal by divers, ROV dredgers, rock removal tool, trailing suction hopper dredge, backhoe dredge, crane lift, subsea grapples and lifting baskets, speed loaders, wet store systems, and mass flow excavators) may also form a source of abrasion/disturbance to the surface of the seabed (Natural England, 2022d).

Scour is a significant concern for developers of offshore structures, as erosion of the sediment in the vicinity of a structure can lead to a lowering of the seabed directly surrounding the structure, undercutting foundations (for fixed foundation types) and anchors (for floating foundation types), thus decreasing the stability and lifespan of the structure (Horwath *et al*., 2020).

Scour can be more pronounced where structures are located in an area surrounded by fine to medium-course sediments, as this sediment type is more easily resuspended in the water column (AWATEA 2008; Whitehouse *et al*., 2011). Ecologically, scour can also contribute to soft-bottom habitat loss, suspension and down-current deposition of fine sediments, and ongoing release of sediment contaminants (Horwath *et al*., 2020). Sediment type is an important factor when considering the potential presence of contaminants within sediments. Sediments with a finer particle size, such as clays and muds (<63 μm), can act as adsorption surfaces for contaminants that may be released into the water column if the sediment is disturbed (Cefas, 2001). Sediments with larger particle sizes (e.g., sands and gravel; >63 μm) are not typically associated with anthropogenic contaminants (Outer Dowsing Offshore Wind, 2022). The effect of contaminants is not considered in this pressure.

Soft mud sediment types also present unfavourable conditions for the risk of scour, due to weak holding power of seabed, and increased possible seabed movement. In the offshore waters of the Celtic Sea, the seabed is dominated by sand, or mixtures of sand and gravel sediments (BEIS, 2022). Scour protection for any offshore structures should be reviewed upon site-specific survey data becoming available.

Scour effects vary as a function of the extent of a foundation's obstruction to flow near the sea floor, which would be a combination of the lower foundation diameter and the amount of scour protection used. Fixed foundations of gravity and suction bucket design present the largest obstructions near the sea floor, followed by monopile foundations, and then tri-pile, tripod, and jack-up foundations. Fixed foundations of jacket design have smaller leg diameters, small amounts of scour protection, and open, lattice-type structures that would create smaller scour effects. Floating foundations potentially present the least concern for scour given they are installed in deep water, where currents are typically weak, and some floating foundation types have relatively small anchors on the sea floor, where scour would be minimal (Horwath *et al*., 2020). In comparison to traditional fixed foundation turbines, turbines with floating foundations have significantly reduced interaction with the seabed. For this reason, FLOW poses a much-reduced potential for scour, with little scour anticipated (Horwath *et al*., 2020).

During a survey of artificial substrate colonisation at Hywind Scotland, the results of the survey also noted that "only very limited scouring effect was found from the anchor chain – sediment interaction". The anchor type at Hywind Scotland is suction caisson. As this study was not focussed on the impacts of scour, no further details on scour are provided (Equinor, 2020).

Risk-profiling

For traditional fixed foundation offshore wind, abrasion/disturbance of the substrate on the surface of the seabed has been risk-profiled as being of "**Medium-High**" risk in the Advice on Operations tool during construction and decommissioning stages. Due to the impacts of installing FLOW anchors and inter-array cables, assessment of available information lends the conclusion that the risk-profiling ranking should remain the same for construction and decommissioning, i.e., "**Medium-High**".

During the operation and maintenance phase for fixed foundation offshore wind, abrasion/disturbance of the substrate on the surface of the seabed has been risk-profiled as "**Low**" risk.

Taking account of the impact of anchor/mooring line abrasion on the seabed, which is unique to FLOW, along with the likely reduced impacts of scour, it is recommended that the risk scoring remains the same as fixed foundation i.e., "**Low**".

Mitigation measures

Mitigation measures to reduce the impacts of abrasion/disturbance of the substrate on the surface of the seabed include placing anchors and mooring lines in areas of lower ecological importance, avoiding important benthic habitats (i.e., structure forming organisms such as corals and sponges) or habitats species with low resilience recoverability from abrasion.

Identifying areas of relatively lower ecological importance would require a thorough assessment of the benthic habitats in potential lease areas. New technologies such as

Autonomous Underwater Vehicles (AUVs) and improvements to towed camera sleds could make this highly feasible and affordable. It is critical that comprehensive pre-installation and ongoing monitoring are implemented for a FLOW farm.

Designated or directed anchoring (Davis *et al.,* 2016) can be used to reduce anchor or mooring line scouring and thus further reduce the impact of anchors on benthic communities. This technique involves using a submersible or other device to guide the anchor during anchor fall to direct exactly where the anchor will land on the seabed.

Reducing the length of the mooring chain may also reduce dragging and scouring, ensuring that any excess length of chain that is needed to adjust for drift does not rest on the seabed, though there will need to be some extra length to account for wave or tidal action (James and Costa Ros, 2015). Additionally, it may be possible to use wave dampening technologies to reduce turbine movement and subsequent sea bottom scour (Jang *et al.,* 2019).

'Nature inclusive design' options, such as the use of reef balls, can also be used to create habitat, particularly in areas where habitat has been degraded by infrastructure (Hermans *et al*., 2020).

Evidence gaps

As abrasion to the surface of the seabed encompasses all footprints on the seabed from FLOW activities (both permanent and temporary), quantitative figures estimating the resultant footprints from all of these activities (including different anchor / mooring line / inter-array cable configurations) would be useful in assessment of associated impacts.

The seabed footprint of the various FLOW subsea infrastructure presents an evidence gap currently. In Table 2-5 and Table 2-6, in the absence of quantitative values of seabed footprints, each anchor type has been comparatively ranked (low/medium/high) in terms of estimated seabed footprint from available literature. In addition, information relating to quantities of scour protection required for the various anchor and mooring line designs was also unable to be found.

Further to this, it is not yet known to what extent temporary seabed disturbance during FLOW turbine installation may occur, as well as the likely footprint for dynamic movement of mooring lines/anchors on the seabed during operation. It has been suggested that the erosional impacts of scour during the operational phase are likely to be reduced in FLOW compared to fixed foundation offshore wind. However, there is no evidence from existing FLOW developments to support this conclusion.

In terms of construction site preparation works such as dredging and sand wave levelling, there is currently insufficient information available to demonstrate how common this practice is for FLOW, and therefore this information should be collected from future projects.

Penetration and/or disturbance of the substratum below the surface of the seabed, including abrasion

As well as abrasion to the substrate on the surface of the seabed, seabed disturbance can also occur due to penetration and/or disturbance of the substratum below the surface of the seabed. The depth of penetration determines which species are affected, e.g. some species live in deep rather than shallow burrows. In general, the macrofauna and near-surface infauna of the sediment are susceptible to this form of physical disturbance. Penetration into hard bedrock is deemed unlikely (Tyler-Walters *et al.,* 2018).

A number of components for offshore wind turbines and associated infrastructure will lead to penetration and abrasion of the seabed and the substratum below the surface of the seabed i.e., piled foundations (for fixed foundation) or anchors (for floating foundation) (ABPmer *et al.,* 2011).

Furthermore, the deployment of anchors from vessels used in installation of the wind farm also penetrate the seabed. The anchors of large shipping and cargo vessels have been found to penetrate the seabed at depths up to approximately 1 m in trials. For example, for an 11.5 tonne anchor penetration of up to 0.88 m occurred in soft sediment when the anchor was dropped and dragged 87 m (Luger and Harkes, 2013). There is a tendency for the anchor to penetrate to deep depths in softer sediment as the opening of the anchor flukes prevents deep penetration in harder sediment (Allan, 1998).

Traditional fixed turbine foundations (e.g., monopiles or pin piles for jacket/ tripod foundations) penetrate into the seabed to provide a sound structure base. Both the outer diameter and penetration depth of a monopile driven into the soil of the seabed depend on the power generation capacity of the wind turbine supported by the monopile. Installed monopile foundations commonly have outer diameters of 4 to 12 m, and penetration depths of between 20 and 70 m (Byrne *et al*., 2015; Wu, X. *et al*., 2019; Vattenfall., 2019).

For FLOW, disturbance to the substratum below the surface of the seabed is caused by the installation of anchors used to stabilise floating foundations. As described in Section 2, between 3 to 9 anchors are typically required per floating foundation. All FLOW turbine anchor types penetrate the seabed, whether they are embedded or piled, to different extents. However, the depth of anchor penetration is significantly less than the depth required for installation of a piled foundation. For example, one study aiming to estimate the soil penetration characteristics of driven anchor piles found that the penetration depths of anchor piles were found to be the deepest in the clay soil, showing values of 3.9 to 4.1 m, and those in the sand layer were the shallowest, showing values of 1.9 to 2.1 m (Song, C.-Y., 2022). As described in Section 2; drag anchors are installed by dragging the anchor through the seabed until it reaches the required depth; suction caisson anchors are embedded into the seabed by negative pressure inside the caisson; gravity anchors are buried to a depth depending on their weight, geometry, and soil characteristics; driven piles are driven or drilled vertically into the seabed; and torpedo anchors are installed by allowing the anchor to free fall through the water column and penetrate the seabed to the targeted embedment depth upon impact. Driven piles are the anchor types that penetrate deepest into the seabed and thus have the most significant impact on the substratum below the surface of the seabed.

Risk-profiling

For fixed foundation offshore wind, penetration and/or disturbance of the substratum below the surface of the seabed, including abrasion; has been risk-profiled as being of "**Medium-High**" risk during all lifecycle phases due to the installation of the piled foundation structure. Despite the fact that overall, the impact of seabed penetration is likely to be lower for FLOW than for fixed (due to the smaller seabed penetration depth, as well as seabed footprint for anchors compared to fixed foundation piles), this report concludes that the risk-profiling should remain the same i.e., "**Medium-High**" risk for all lifecycle phases.

Mitigation measures

Mitigation measures to reduce the impacts of seabed penetration include selection of an anchor design with a smaller penetration depth, such as gravity anchors (which have a high seabed footprint due to larger surface area but can be installed on thin substrate layers), or using less anchors per turbine through anchor sharing.

Evidence gaps

In order to fully assess the impact on seabed penetration for FLOW developments, more detailed information is required on the penetration depth and spatial area for the various anchor technology types. Each anchor type penetrates the seabed to differing degrees, however, specific quantitative figures (i.e., depth of penetration in metres) were unable to be found for each anchor type.

Habitat structure changes – removal of substratum (extraction)

Habitat structure changes can occur when substratum (i.e., sediment) is added or removed from the seabed. This section focusses on the removal of substratum from the seabed. The level and area of impact depend on a number of factors including localised hydrodynamics, type of turbine foundation and seabed substrate (Wilhelmsson *et al.,* 2006).

The quantitative benchmark used to classify "removal of substratum" as a relevant pressure in the MarESA methodology is an extraction of sediment to 30 cm (MarLIN, 2023). It is possible for soft rocks (clays, peats, chalks) to be removed by extractive activities. However, it is very unlikely that hard bedrock would be removed or subject to extraction to a depth of 30 cm. Therefore, this pressure is considered 'not relevant' to hard substratum habitats (Tyler-Walters *et al*., 2018).

For fixed foundation turbines, the use of dredging in the preparation of the seabed for gravity base foundations to ensure a smooth, horizontal seabed for foundation installation, as well as subsequent deposition of the cleared material and drill arisings following drilling of the seabed for installation of monopiles and jacket foundations can lead to both the removal and addition of sediment within a localised area (ABPmer *et al*., 2011; Wilhelmsson *et al.,* 2006).

For FLOW, removal of substratum from the seabed would only occur during the use of the driven pile anchor type. Driven piles (as described in Section 2) are large and hollow metal cylinders, which are driven or drilled and grouted vertically into the seabed, utilising the same technology as that used to attach fixed turbine foundations to the seabed.

As described above in the section on abrasion of the seabed surface, pre-sweeping of sand waves is sometimes required in order to level the seabed and obtain a suitable burial depth before installation of a pipeline. However, it is likely that sand wave pre-sweeping would only be necessary for the installation of a trenched export cable to shore, as opposed to surface laid inter-array cables within a single wind farm site (Vattenfall., 2019). If inter-array cables were to be buried for a FLOW project, pre-sweeping may be necessary in this case. As export cables are out with the scope of this report, it is unlikely that sand wave pre-sweeping will present a source of habitat structure change for FLOW developments in this context. Despite this, even if pre-sweeping activities were to occur, this would not present a significant difference from fixed foundation offshore wind, as both fixed and floating developments would require a level seabed for cable installation. Further information is required to determine how common construction site preparation works such as dredging and sand wave levelling is for FLOW.

Risk-profiling

Due to the use of dredging in the preparation of the seabed for gravity base fixed foundations, habitat structure changes have been risk-profiled as "**Medium-High**" risk for all lifecycle stages of fixed foundation offshore wind.

For FLOW, as only the driven pile anchor type (out of many possible anchor designs to choose from) would result in removal of substratum from the seabed, and the footprint on the seabed/ penetration depth are smaller than that of a piled foundation (hence less sediment removed / habitat structure changes); it is recommended that the risk-profiling should be changed to "**Low**" for all lifecycle stages of a FLOW development.

Mitigation measures

Mitigation measures to reduce the impacts of habitat structure changes (removal of substratum) during FLOW activities would be to avoid using the driven pile anchor type. In addition, selection of an anchor design with a smaller footprint on the seabed, as well as a smaller penetration depth. Suction caisson anchors have the smallest seabed footprint of the anchor types considered in this report; however, a trade-off exists between seabed footprint and seabed penetration depth.

Evidence gaps

As use of the driven pile anchor type is likely to be the only source of removal of substratum from the seabed for FLOW activities, specific quantities of sediment likely to be removed during the use of these anchors would have been beneficial to the assessment of this impact. It is known that driven pile anchors are smaller than piled foundations, however, quantitative figures for volume of material removed from the seabed would make this comparison (as well as relative seabed disturbance impacts) clearer.

Additionally, further information is also required to determine how common construction site preparation works such as dredging and sand wave levelling is for FLOW.

Physical change (to another seabed type / to another sediment type)

The assessment is based on the likely effect of the change in seabed / sediment type. For change to seabed type, this pressure examines the effect of a change from sedimentary or soft rock substrata to hard rock or artificial substrata or vice-versa. It is included to cover the introduction of artificial substrata e.g., the overlaying of sedimentary habitats by concrete, gabions, boulders etc. This pressure is considered to affect all types of substrata, and all habitats are assessed as highly sensitive (Tyler-Walters *et al*., 2018).

For change to sediment type, as a specific sediment type defines sedimentary habitats (biotopes), a change in sediment type will result in change in the biotope classification and the loss of the biotope under assessment. This may occur when sediment from beneath the surface of the seabed is brought to the surface during anchor installation, therefore changing the sediment type on the surface of the seabed. This pressure is 'not relevant' in hard substratum habitats (Tyler-Walters *et al*., 2018).

Physical change (to another seabed type / to another sediment type) includes physical changes to sediment structure i.e., soft bottom habitat loss where the subsea components of an offshore wind turbine (be it fixed or floating foundation) provide new hard substrate on the seafloor (NatureScot, 2023).

For fixed foundations, physical changes to habitats result from placement of structures on the seabed including turbine foundations, meteorological masts, substations, external cable protection and scour protection for foundations (Wilhelmsson *et al.,* 2006; ABPmer *et al*., 2011; OPSAR, 2008). Piled foundations are driven into the seabed (buried) and can change the seabed type within the footprint of the piling works from soft sediment to an artificial substratum (ABPmer, 2008).

For FLOW, physical changes to habitats are likely to result from the installation of anchors, mooring lines, inter-array cables, external cable protection, and possible scour protection. The habitat may be changed to steel, concrete, rock or other substances depending on the type of infrastructure installed. This enables the establishment of benthic communities with a taxonomic composition similar to that of naturally occurring rocky habitats and is known as the artificial reef effect (Karlsson *et al.,* 2022).

Artificial reef effect

The installation of FLOW structures provides marine organisms with new hard substrate for colonisation, thus acting as an artificial reef (Langhamer, 2012). This results in the creation of new habitat that may alter benthic species abundance and biodiversity. The addition of hard substrate may favour some species over others, leading to attraction effects and an increase in species abundance / biodiversity, or potential displacement of some benthic species. Either way, this may result in habitat conversion (SEER, 2022a).

The artificial reef effect is important when constructing, for example, external cable protection or scour protections since it can generate an enhanced habitat. Specifically, artificial structures can create increased species biodiversity in the area (Langhamer, 2012).

Foundations with a larger surface area on the seabed and in the water column provide the most habitat for species to colonise and become established. The lattice configuration of fixed jacket foundations is an example of a fixed foundation type with a large surface area. In terms of floating foundations, the submerged spar buoy floating foundation type can extend to approximately 100 m deep, which could provide greater amounts of habitat opportunities than could monopiles, tripod, tri-pile, jack-up, suction bucket, and gravity foundations, as these only span depths up to approximately 50 m deep due to the depth limits of fixed foundation turbine installation (Horwath *et al*., 2020). It is clear that the potential for the artificial reef effect to occur does not differ between fixed or floating foundations, but rather which type of foundation within each category is selected for a site.

The nature of scour protection used for a structure would also contribute to the magnitude of an artificial reef effect. While scour protection is needed to protect the physical structure of the seafloor, it also increases the extent of altered seafloor, which may be considered a loss and/or gain of habitat depending on conditions (SEER, 2022a). The quantity of scour protection would be expected to be greater for fixed foundations (especially gravity, monopile, and suction bucket foundation types), compared to FLOW where scour protection is not typically used as they are anchored in very deep waters with little scour effects anticipated (Horwath *et al*., 2020).

For inter-array cables that are buried between the wind turbine structures they connect, when passing through rocky areas or other locations where burial is challenging, portions of buried inter-array cables may be left partially exposed and may require physical protection instead of burial. Exposed cable can be protected through the strategic deployment of rocks, concrete mattresses, or half-shell pipes. These protection methods avoid the physical disturbance associated with burial but introduce new hard substrate to the seafloor, and further artificial reef effects (SEER, 2022a). This impact is the same for both floating and fixed foundation types.

A visual inspection of marine growth on structures within the Hywind Scotland FLOW farm describes changes within the wind farm area in the epifouling growth between 2018 and 2020, with regards to coverage and thickness. The floating pilot park is situated in water depths of approximately 120 m, with a seabed characterised predominantly by sand and gravel substrates with occasional patches of mixed sediments. A total of 41 structures, as well as their associated sub-components, including turbines substructures, mooring lines, suction anchors and infield cables, were analysed with regards to diversity, abundance, colonisation, coverage and zonation. A total of 11 phyla with 121 different taxa were observed, with macrofauna as well as macroalgae and filamentous algae being identified on the different structures. The submerged turbines measured approximately 80 m in height and exhibited distinct patterns of zonation. Plumose anemones (*Metridium senile*) and tube-building fan worms (*Spirobranchus* sp.) dominated the bottom and mid-sections (20-80 m) of the turbines, while kelp and other Phaeophyceae with blue mussels (*Mytilus* spp.) dominated top sections of the turbines (0-20 m). The fauna dominating the mooring lines, varied with depth and general zonation's could be distinguished. Ross worm, *Sabellaria spinulosa* and cnidarian *Ectopleura larynx* dominated the chains where the chains were close to and in contact with the seabed, *Spirobranchus* dominated the middle part of the chains and the upper parts of the chains were dominated by Balanoidea*, M.*

senile and *E. larynx*. The suction anchors were dominated by hydroids and the tube building worm *Spirobranchus*. The inter-array cables were mainly buried, however, the section of the cables that were exposed before going into burial were dominated by acorn barnacles (Balanoidea). A general increase in the coverage of the epifouling growth between 2018 and 2020 was observed, whereas the change in thickness between years was more variable (Karlsson *et al.,* 2022; Equinor., 2020).

In order to identify whether the infrastructures generate an artificial reef effect on local fish population, information on fish stock was also collected at the Hywind Scotland FLOW farm. The study concluded that the FLOW installations likely have an effect on the low trophic levels (primary and secondary producers) in boosting production and consequently increasing standing stock, which in turn triggers fish aggregations. The results, on the other hand, do not support the theory of consistent increased fish biomasses in the vicinity of the wind farm over time, but rather a stronger response to the natural occurrence of phytoplankton bloom and subsequent trophic cascade (Akvaplan-niva AS., 2021).

Risk-profiling

Although fixed and floating foundations create different physical environments on the seabed; both types of foundation result in physical change (to another seabed type / to another sediment type). Therefore, it is recommended that the risk-profiling should remain the same for fixed and floating i.e., “**Medium-High**” for all development phases.

Mitigation measures

Mitigation measures to reduce the impacts of physical change to seabed / sediment type include burying inter-array cables where possible, so that they do not require the addition of rock dump for protection, or having free spanning cables which do not come into contact with the seabed.

A suitable trenching route for inter-array cables should also be selected (if possible), which does not pass through rocky areas where burial may be challenging. This will minimise sections of particularly exposed cable / spans and reduce the requirement for spot rock dump.

The nature of scour protection used for a structure also contributes to the magnitude of an artificial reef effect. An appropriate mitigation measure would be selection of infrastructure that introduces minimal hard substrate to the seabed e.g., designs which are less susceptible to scour effects and thus require little to no scour protection.

Evidence gaps

Information on the extent of scour protection / rockdump required for different FLOW anchor and mooring line designs was unable to be obtained (Table 2-5 and Table 2-6 in Section 2). This information would be useful in assessing the possible extent of the artificial reef effect at a FLOW farm.

In addition, further quantification of the seabed footprint for different anchor and mooring line designs would be beneficial in assessment of this impact.

Physical loss (to land or freshwater habitat)

It should be noted that the pressure “physical loss (to land or freshwater habitat)” refers to the physical loss of seabed and marine habitat in the context of this report. This pressure is defined as the ‘permanent loss of existing saline habitat within a site’. Therefore, all marine habitats and benthic species are considered to be unable to recover from a permanent loss of habitat. Receptors within the direct spatial footprint of this pressure are considered to be highly sensitive. Most benthic species will be sensitive and their resistance dependent on their ability to recolonise or relocate (e.g., mobility) (Tyler-Walters *et al*., 2018).

Habitat loss occurs wherever the placement of structures have a permanent footprint on the seabed. For fixed foundations, habitat loss results from the placement of structures on the seabed including turbine foundations, meterological masts, substations, cables, external cable protection, and scour protection (Wilhelmsson *et al.,* 2006; ABPmer *et al*., 2011; OSPAR, 2008).

For FLOW, habitat loss is likely to result from the installation of anchors, mooring lines, inter-array cables, and possible scour protection. If inter-array cables are buried between turbines, the construction equipment used to create a trench (via plowing, jetting, horizontal drilling, or other mechanical methods) directly disturbs the seabed along the cable route and may cause temporary loss or disruption of habitat (SEER, 2022a).

The construction and operation phases for both fixed and floating foundations can potentially lead to temporary and permanent habitat loss.

Temporary habitat loss during construction is potentially less for FLOW compared to fixed foundation, as there is less construction at sea required for FLOW (i.e., most components are constructed in a port and towed offshore).

In addition, the estimated permanent footprint on the seabed of a fixed foundation turbine (based on a monopile design) is approximately 1,960 m^2 per fixed foundation. By comparison the estimated footprint of a FLOW turbine is approximately 113 m^2 per foundation (based on four suction caisson anchors of 6 m diameter, protruding 2 m above the seabed – as this was the only information available at the time of writing). This would suggest that fixed foundation turbines lead to a larger area of habitat loss on the seabed. When compared in terms of percentage of the overall wind farm area, the footprints of both fixed and floating foundations (including external cable and scour protection footprints) are less than approximately 1 % of the overall wind farm area (Horwath *et al*., 2020).

As described in Section 2, a taut mooring system coupled with suction caisson anchors would have the smallest footprint on the seabed. However, not all floating foundation / anchor / mooring line types are suitable for all seabed types. Additionally, not all combinations work together or are appropriate for the conditions in the development area (James and Costa Ros, 2015; Maxwell *et al*., 2022).

The impact of habitat loss from a development is directly related to the permanent footprint on the seabed. The permanent footprint on the seabed and thus level of impact will depend upon the type of turbine systems selected (i.e., floating foundation, mooring line and anchor type), the number of turbines, and the location of the turbines (i.e., what type of sediment and benthic habitat they are situated on) (Maxwell *et al*., 2022).

During decommissioning, where infrastructure and external cable/scour protection cannot be fully removed, habitat loss will be permanent.

Risk-profiling

Despite the fact that overall, the total area of habitat loss is likely to be less for FLOW than for fixed foundation offshore wind (due to the smaller permanent footprint on the seabed per turbine), this report recommends that the risk-profiling should remain the same between them i.e., “**Medium-High**” risk for all development lifecycle phases.

Mitigation measures

One of the best ways to reduce the impacts on benthic habitat is to reduce the overall area or footprint of the turbine anchor, mooring line and cable array. Developers could use a low footprint mooring line configuration such as taut or semi-taut moorings, and a less impactful anchor type (e.g., suction or gravity anchors).

In addition, avoid habitats that are sensitive to permanent loss, i.e., rare, and vulnerable to or low resilience recoverability from permanent habitat loss in line with the “avoid, reduce mitigate” hierarchy. Natural England have published a report “Defining Marine Irreplaceable Habitats”, which advises that as these habitats cannot be replaced, and thereby compensated for, then they should be avoided as a mitigation measure (Natural England, 2023b).

Evidence gaps

As habitat loss is directly related to the permanent footprint of structures placed on the seabed, quantitative information regarding the footprint on the seabed of different anchor and mooring line arrangements, as well as inter-array cables and possible scour protection is key to its assessment.

As described above for abrasion to the surface of the seabed, the seabed footprint of the various FLOW subsea infrastructure presents an evidence gap currently.

An example footprint of a FLOW turbine based on four suction caisson anchors of 6 m diameter, protruding 2 m above the seabed has been used as an estimate of seabed footprint in comparison to fixed foundation turbines for this assessment. However, ideally it would be preferable to have a footprint value for all anchor/mooring line combinations within the design envelope, and it is recommended that this information be collected from future projects.

Smothering and siltation rate changes (light / heavy)

Although they have different effects on the environment, this pressure (smothering and siltation rate changes (light / heavy)) is directly related to the pressure “changes in suspended solids (water clarity)”.

The marine environment contains suspended particulate matter which originates from natural and anthropogenic sources. Siltation (or sedimentation) is the settling out or deposit of silt or sediments suspended in the water column to the seabed. Changes relate to those in relation to natural siltation (Marine Scotland, 2023). Seabed disturbance from any cause can lead to localised and temporary increases in siltation rate and consequentially, smothering (ABPmer *et al.,* 2011).

"Light" siltation is defined as deposition of up to 5 cm of fine material added to the seabed in a single event or continuous deposition of fine material. "Heavy" siltation is defined as deposition of more than 5 cm and up to 30 cm of fine material added to the habitat in a single discrete event or continuous deposition of fine material. Light and heavy siltation are covered by different pressures in the Natural England Advice on Operations tool (Natural England, 2023a); however, they have been assessed in the same section in this report to avoid repetition.

Settlement / deposition of this material can leave benthic organisms susceptible to smothering, whereby a species or habitat is buried either suddenly (e.g., due to storms or installation activities such as dredging) or gradually (e.g., due to changes in hydrodynamics resulting in new areas of accretion) (Miller *et al.,* 2002). Sudden burial is likely to be particularly detrimental to benthic species.

Siltation of either "Light" or "Heavy" level may completely smother smaller species and habitats, particularly sessile organisms. Impacts of light siltation can be hypoxia, physical difficulties in feeding, reproduction, reduction in photosynthesis and potentially death for more sensitive species. Impacts of heavy siltation are mainly hypoxia, inability to feed or photosynthesise and potentially death unless species have tolerance or can re-emerge (Marine Scotland, 2023). Deposited sediment can threaten immobile benthic species and demersal spawning fish and invertebrates, if eggs or individuals are smothered (Thrush *et al.* 2004; AWATEA 2008).

Increased sedimentation may also cause changes in organic matter content in sediments associated with particle size, as well as the release of contaminants within seabed sediment, which could impact the benthic spawning habitat quality of some fish species (Wenger *et al.,* 2017; Horwath *et al*., 2020). As described above, sediment type is an important factor when considering the potential presence of contaminants within sediments (OSPAR, 2008). The effect of contaminants is not considered in this pressure.

Survival of benthic species will depend on their tolerance to, and their ability to escape from burial, which can be highly species-specific (Hendrick *et al.,* 2016). The ability to survive smothering is dependent on a species' ability to vertically migrate through the deposited sediment or the sediment being removed by local hydrodynamics. Some species are capable of migrating tens of centimeters, while only a few centimeters of sediment will result in mortality for others (Miller *et al*., 2002; Hendrick *et al*., 2016; Hutchison *et al.,* 2016). If smothering is a risk, the specific susceptibility of the species in the area would need to be assessed on the best available knowledge (Miller *et al.,* 2002).

A study by Hendrick *et al.,* (2016) conducted a multi-factorial experiment measuring burial responses of six macroinvertebrates commonly found in sediment rich environments, selected for their commercial and/or conservation importance. Assessments revealed that the brittle star (*Ophiura ophiura*), the queen scallop (*Aequipecten opercularis*) and the sea squirt (*Ciona intestinalis*) were all highly intolerant to burial, whilst the green urchin (*Psammichinus miliaris*) and the anemone (*Sagartiogeton lacerates*) showed intermediate and low intolerance respectively to burial. The least intolerant, with very high survival was the Ross worm (*Sabellaria spinulosa*). With the exception of *C. intestinalis*, increasing duration and depth of burial with finer sediment fractions resulted in increased mortality for all species assessed. For *C. intestinalis* depth of burial and sediment fraction were found to be inconsequential since there was complete mortality of all specimens buried for more than one day. When burial emergence was assessed *O. ophiura* emerged most frequently, followed by *P. miliaris*. The former emerged most frequently from the medium and fine sediments whereas *P. miliaris* emerged more frequently from coarse sediment (Hendrick *et al.,* 2016).

For fixed foundations, increased siltation rate particularly occurs during dredging in preparation of the seabed, the deposition of drill arisings following drilling of the seabed for installation of monopiles and jacket foundations, and cable installation. For floating foundations, increased siltation rate particularly occurs during installation of the anchors, mooring lines and inter-array cables, as well as movement of the structures during the operational phase with wave, current and tide action (Maxwell *et al.,* 2022).

In comparison with fixed foundations, as floating foundations are used in very deep water, where currents near the seabed are relatively weak; sediment effects from their anchors would be expected to be minimal. Despite this, movement of anchors may cause similar levels of ongoing sediment disturbance effects compared to scour- and wake-associated sediment disturbance effects of monopile foundations (Horwath *et al*., 2020).

The level and area of impact depend on a number of factors including localised hydrodynamics, type of foundation and seabed substrate (Wilhelmsson *et al.,* 2006). It is assumed that smothering is removed rapidly in areas of high energy but is retained for significant periods in areas of low energy. For example, it can be assumed that a 30 cm deposit in a tideswept or wave exposed habitat will not be retained long enough to have a significant effect. In low energy, sedimentary habitats, the deposit will remain for many tidal cycles and sensitivity is dependent on the ability of the infauna to burrow to the surface and/or resist hypoxic conditions (Tyler-Walters *et al*., 2018).

Foundations that require major bottom disturbance, such as by dredging, are expected to have the largest installation-related suspended sediment levels and sedimentation effects on benthic communities. Sediment deposition can also occur during installation if dredged materials from bottom preparation are discharged into the water column or directly onto the seafloor. Such spoil mounds consisting of waste material from installation activities could persist for many years if they are composed of large particles (English *et al.* 2017). However, discharging dredge material is usually prohibited or controlled to minimise negative effects of direct sediment deposition onto the seafloor (Horwath *et al*., 2020). Benthic disturbance from displacement and suspension of seafloor sediment during construction tends to be temporary and recovery of the physical and biological conditions on the seafloor typically occurs within a few years (SEER, 2022a).

For fixed foundation turbines, effects of suspended sediment / deposition of this suspended sediment primarily occur during installation (especially due to piling of monopile designs). Different types of fixed foundation have different installation strategies and thus different occurrence of suspended sediments.

Floating foundations tend to have smaller effects than fixed foundations during installation even if driven pile anchors are the selected technology type (piles are much smaller). Effects will be even less if installed by deadweight anchors, dynamically embedded anchors, or suction caisson anchors. In addition, it is less likely that pre-sweeping activities will be required for FLOW due to smaller area of seabed required for installation and likely surface-laid inter-array cables (Vattenfall., 2019). Further information is required to determine how common construction site preparation works such as dredging and sand wave levelling is for FLOW.

During installation of buried inter-array cables (for both fixed and floating foundation designs), trenching activities (via plowing, jetting, horizontal drilling, or other mechanical methods) directly disturbs the seabed along the cable route and may cause suspension of sediment into the water column, and subsequent deposition of that sediment (SEER, 2022a).

During operations, smothering and siltation effects for fixed foundation turbines are restricted to the vicinity of the foundation as far as wake effects extend. The magnitude of effect during operation depends on the scour potential of the installation and environmental conditions of the site. Those with decreased scour potential will experience fewer effects of suspended sediment / sediment deposition. This means that different types of foundation design have different effects during operation (Horwath *et al*., 2020).

During operations, effects for floating foundations are likely to be similar to fixed foundations, due to ongoing seabed disturbance from anchor rode (Horwath *et al*., 2020).One study has suggested that compared to fixed foundation turbines, FLOW turbines may cause increased sedimentation during operation as a result of scour from anchors and other components as, in contrast to fixed-foundation structures, these components will be continually moving and hitting on and off the seabed due to action by waves and currents, similar to traditional boat anchors (Davis *et al.,* 2016).

Risk-profiling

For traditional fixed foundation offshore wind, smothering and siltation rate changes (light) has been risk-profiled as being of "**Medium-High**" risk for all development phases. Smothering and siltation rate changes (heavy) has been risk-profiled as being of "**Low**" risk for construction, and operation and maintenance. This pressure is considered to be not applicable to decommissioning.

The findings of this report suggest that the impact of smothering and siltation rate changes during operation should be risk-profiled as "**Medium-High**" risk for both light and heavy for FLOW, therefore the ranking for smothering and siltation rate changes (heavy) is different to fixed foundation. The reason for this is to account for the increased smothering and siltation resulting from the continuous movement of mooring chains and anchors on the seabed during operational phases, based on a worst-case design scenario whereby drag anchors and catenary mooring lines are the selected technology type.

Mitigation measures

Potential mitigation for increases in smothering and siltation rates could include restricting or avoiding construction operations during key species spawning seasons (e.g., herring) to limit disturbance to adult fish, eggs and hatching larvae from increased turbidity and sediment deposition (JNCC, 2021).

In addition, taut or semi-taut mooring lines as the selected technology type would reduce the length of mooring line chain on the seafloor and thus reduce the quantity of sediment being stirred by movement of the mooring lines due to wave or tidal action, particularly in habitats characterised by fine sediments which are more susceptible to resuspension.

Evidence gaps

As above for penetration of the seabed and habitat change (removal of substratum), the volume of sediment that may become suspended in the water column during operation (and thus the area that may be impacted by smothering) depends on penetration depth and volume of substratum removed for the various anchor types.

In addition, as with the impacts of abrasion to the seabed, it would depend on the level of movement taking place in mooring lines on the seabed during operation (i.e., how much sediment they are disturbing due to continual action by waves and currents). For this reason, these evidence gaps are also relevant to smothering and siltation rate changes (light/heavy).

Further to the evidence gaps already identified for other pressures, more research into the scour potential of FLOW infrastructure would be useful to inform this section, as structures with decreased scour potential will experience fewer effects of suspended sediment / sediment deposition. Further information is also required to determine how common construction site preparation works such as dredging and sand wave levelling is for FLOW.

Changes in suspended solids (water clarity)

Whilst the pressure “smothering and siltation rate changes (light / heavy)” addresses the impacts associated with sediment resettling on the seabed, “changes in suspended solids (water clarity)” assesses the impacts of the sediment whilst it is suspended in the water column and resultant light attenuation (turbidity). Although these are two separate pressures, they are both ultimately caused by sediment suspension resulting from seabed disturbance.

Seabed disturbance from any cause has the potential to cause sediments to become suspended in the water column, leading to localised and temporary increases in suspended solids within the water column (ABPmer *et al.,* 2011). This could result in direct impacts on water quality associated with decreased light levels and water clarity, and indirect impacts upon biological receptors. It may also cause avoidance of an area by species due to an increase in sediments (Horwath *et al*., 2020).

Receptors considered to be most sensitive to changes in suspended solids are light-dependant algae and other photosynthetic marine organisms, and suspension-feeding organisms (Tyler-Walters *et al.,* 2018).

Seawater clarity is often assessed based on the concentration of suspended particles in the water column, also called turbidity. Increased turbidity of marine waters has the potential to impact the productivity of photosynthetic marine organisms, by reducing the amount of light that passes through the water column. This potentially reduces the already limited capacity of deep-sea organisms to photosynthesize (Davis *et al*., 2016). In contrast, suspended particles may also increase the nutrient concentrations and therefore positively affecting primary producers (Marine Scotland, 2023). Increases in suspended sediment concentrations can also affect water quality and can mobilise contaminants that may be present in the sediments. The effect of contaminants is not considered in this pressure. In addition, suspended sediment has the potential to clog the feeding apparatus of suspension-feeding organisms, clog fish gills and compromise organisms' abilities to search for food if they are visual predators or foragers (English *et al*. 2017).

As with smothering and siltation rate, the level and area of impact depend on a number of factors including localised hydrodynamics, type of foundation and seabed substrate (Wilhelmsson *et al.,* 2006). Suspended sediment transported by currents, tidal flow, and wave energy are moved away from the immediate vicinity of the structure until it falls out of suspension and to the seafloor (English *et al*. 2017). The type of sediment disturbed also influences the degree of increase in sediment loading, its geographical spread and the period of suspension within the water column. Lighter sediment types like silt are more readily remobilised if disturbed and stay suspended over longer periods, allowing greater geographical dispersal. Heavier sediment types like sand require greater kinetic energy to be resuspended and, due to their greater mass, quickly fall back to the seabed, hence, geographic spread is more limited (Jones *et al*., 2016).

During the operational phase of offshore wind-energy installations, the effects of increased suspended sediment concentration and down-current deposition are restricted to the vicinity of the foundation only as far as the wake effects extend, which is up to a few hundred meters. They do not regionally affect suspended sediment concentrations if turbine foundations are adequately spaced to reduce cumulative wake effects (Horwath *et al*., 2020).

For fixed foundations, monopiles, gravity foundations and suction bucket foundations are expected to result in the most suspended sediment. Tripod, tri-pile, and jack-up foundations are expected to have less suspended sediment due to their relatively lower scour potential. Jacket foundations are expected to have even fewer sediment effects due to lower scour potential and smaller wake effects (Horwath *et al*., 2020).

As above for smothering and siltation rate changes, in comparison with fixed foundations, as floating foundations are used in very deep water, where currents near the seabed are relatively weak; sediment effects from their anchors would be expected to be minimal. Despite this, movement of anchors may cause similar levels of ongoing sediment disturbance effects compared to scour- and wake-associated sediment disturbance effects of monopile foundations (Horwath *et al*., 2020).

Floating foundations that use deadweight anchors or suction caissons also have relatively few bottom-disturbing activities and are not expected to increase suspended sediment concentration and down-current deposition. Floating foundations that use embedded anchors may have similar or more bottom-disturbing activities during installation when compared to fixed foundation monopiles, depending on the size of the anchors and method of installation (Horwath *et al*., 2020).

The extent that anchors, specifically deadweight and drag anchor types, drag along the seabed due to the operational forces on floating foundations is unknown but is likely to produce additional suspended sediment (Horwath *et al*., 2020).

The frequency of sediment suspension to be expected from FLOW is unclear, as is whether particles will be resuspended at a rate which, obscures light sources for extended periods of time, but this should be considered as a potential stressor for these soft-bottom communities (Maxwell *et al.,* 2022).

During installation of buried inter-array cables (for both fixed and floating foundation designs), trenching activities (via plowing, jetting, horizontal drilling, or other mechanical methods) directly disturbs the seabed along the cable route and may cause suspension of sediment into the water column (SEER, 2022a).

Risk-profiling

For traditional fixed foundation offshore wind, changes in suspended solids (water clarity) has been risk-profiled as being of “**Low**” risk, meaning unless there are evidence-based case or site-specific factors that increase the risk, or uncertainty on the level of pressure on a receptor, this pressure generally does not occur at a level of concern and should not require consideration as part of an assessment.

The findings of this report suggest that the impact of changes in suspended solids (water clarity) for FLOW should remain the same as fixed foundation i.e., risk-profiled as “**Low**”.

Mitigation measures

As the impacts associated with changes in suspended solids relate closely to smothering and siltation rate changes, no specific mitigation measures have been identified for changes in suspended solids. See smothering and siltation rate changes section for mitigation measures relevant to changes in suspended solids (Atterbury *et al*., 2021).

Evidence gaps

As the impacts associated with changes in suspended solids relate closely to smothering and siltation rate changes, no specific evidence gaps have been identified for changes in suspended solids. See smothering and siltation rate changes section for evidence gaps relevant to changes in suspended solids.

Physical presence

For physical presence, features likely to be sensitive to the pressures within this section are generally those located in the air space surrounding the above-water components of the turbine (i.e., birds), and those at the surface of the sea or in the water column (i.e., diving birds, fish and marine mammals).

Physical presence relates to impacts caused by the presence of turbines and other project infrastructure, which have been added to the environment, and include:

- visual disturbance
- barrier to species movement
- collision ABOVE water
- collision BELOW water

Each of these will be discussed in turn, in the context of the Natural England Advice on Operations tool, throughout the following sections.

Visual disturbance

Visual disturbance from increased vessel activity, installation activities, and ongoing maintenance activities has the potential to cause marine organisms, such as marine mammals and seabirds, to exhibit attraction or avoidance behaviour at wind farm sites and may lead to displacement of species (Vattenfall, 2006; East Anglia ONE North Limited, 2022).

Visual disturbance is only relevant to species that respond to visual cues, for hunting, behavioural responses, or predator avoidance, and that have the visual range to perceive cues at distance. It is particularly relevant to fish, birds, reptiles, and mammals that depend on sight but less relevant to benthic invertebrates. The cephalopods are an exception, but they are only likely to respond to a visual disturbance at close range (from e.g., divers). Not including introduction of light as addressed by separate pressure (NatureScot, 2023).

The above-water structures of offshore wind farms can have a potential visual effect on birds, whereby birds change behaviour by avoiding the vicinity of the turbines as a response to a visual stimulus (Fox *et al.,* 2006). Some seabirds are relatively more disturbed by vessel traffic and artificial lighting, such as northern gannet (*Morus bassanus*) and common guillemot (*Uria aalge*) and will avoid wind farms during periods of heavy human activity like during foundation installation (English *et al*. 2017; Degraer *et al*. 2019). Species such as red-throated diver are also particularly sensitive to disturbance at sea, displacement from windfarms (Garthe and Hüppop, 2004; Furness and Wade, 2012; JNCC, 2022c) and usually avoid vessels (Kaiser *et al*., 2006). Such species-specific avoidance responses, like increased movement along perimeters, have been observed at Danish windfarms (Vattenfall, 2006). The impacts of avoidance due to visual disturbance include displacement from foraging areas within wind farm sites, which can result in increased competition for food resources at adjacent foraging areas (English *et al*. 2017) or long-term reductions in fitness (Robinson Willmot *et al.* 2013).

The below-water structures of wind turbines can also have a potential visual effect on marine mammals and other animals present in the water column, including diving birds. Some species of diving birds and sea ducks at Danish and German wind project sites have been shown to be reduced or eliminated within wind project sites, and this may have occurred because of the loss of open-ocean foraging habitat; such loss may be a minimal proportion of available habitat in the greater surrounding areas, but could have cumulative effects if birds are forced to use larger foraging ranges to meet energetic demands (Vattenfall, 2006; Lüdeke, 2015).

In addition to the turbines themselves, vessels, vehicles, and people movement can also create visual stimuli which can evoke a disturbance response in mobile species such as marine mammals and seabirds (Chatwin *et al.,* 2013; Jansen *et al.,* 2010). The magnitude of the pressure will depend on the nature and scale/intensity of the activity, as well as the sensitivity of the species in the area.

FLOW turbines benefit from being capable of assembly within port, meaning constructed turbines can be towed to the offshore site for installation. Conversely, fixed offshore wind turbines require *in situ* assembly and installation and thus require more vessels at the construction stage (Banister, 2017; Iberdrola, 2023). The same logic also applies to the removal of infrastructure during the decommissioning phase.

During the operation and maintenance phase, many FLOW farm concepts envisage that turbines have the ability to be disconnected and towed back to port for major maintenance activities (PLOCAN, 2021). As a result, there is likely to be less vessel activity at sea for FLOW turbines, compared to fixed foundation turbines, during the operation and maintenance phase. In addition, some FLOW platform configurations also have a large surface area where helicopter landing pads could potentially be installed allowing turbine maintenance to be achieved by helicopter, further reducing the number of vessels at sea (Bannister, 2017). Despite this, the installation of helicopter landing pads on FLOW turbines is a very early concept and there were no examples of developments utilising this technique at the time of writing. Crown Estate are not considering the use of helicopters for wind turbine maintenance in their design envelope for the HRA currently, however, if included in future it would lead to a significantly different impact on various environmental receptors in comparison to fixed foundation offshore wind.

As a result of likely reduced vessel activity through all development lifecycle stages, the potential for visual disturbance caused by vessel movement is reduced.

Risk-profiling

For fixed foundation wind turbines, the risk profile of visual disturbance has been ranked as “**Medium-High**” risk.

Avoidance effects from visual disturbances are not expected to differ across foundation types except that floating foundations have relatively less infrastructure extending throughout the entire water column (Horwath *et al*., 2020).

As the impacts of visual disturbance from FLOW turbines is thought to be much the same as fixed foundation turbines, given the fact that the above water parts (i.e., the turbine itself) remain largely unchanged, this report suggests that the rankings for visual disturbance should remain the same.

As FLOW turbines are able to be constructed in deeper water and are therefore generally located further from the shore than fixed foundation turbines, they are likely to have less of a visual disturbance to birds than fixed foundation turbines which are restricted to shallower water closer to the shore and can therefore more easily be seen by birds from the coastal protected areas. Bird species that rely on shallow, coastal areas are considered most at risk from displacement by visual disturbance of fixed-foundation turbines, as these locations are currently favoured for fixed foundation wind farm siting (English *et al*. 2017).

Mitigation measures

Several characteristics of wind farms may cause differing visual effects, such as the turbines size, height, number, material and colour. These characteristics should be considered during wind farm design.

In addition, different floating foundation types have a different visual impact due to size and presence in the water column. Smaller foundation types may have less of a visual impact. Spar buoys tend to be the largest foundation type in terms of how far they extend into the water column, with a typical draft of up to 100 m. Semi-submersible (typically 15-20 m draft), barge (7-10 m), and TLP (15-25 m) foundation types all have smaller drafts. Despite this, semi-submersible and barge foundation types have a comparably large surface area (40-50 m length/width for barge and 60-80 m length/width for semi-submersible) than both spar buoys (10-20 m length/width) and TLPs (20-35 m length/width).

Evidence gaps

Visual disturbance impacts are linked to various activities, however, quantification of this was found to be extremely difficult, and thus should be identified on a case-by-case basis for FLOW developments (MMO, 2014).

As the use of helicopter landing pads on FLOW turbines is a relatively new development, information on the resulting reduction in vessel activities, and examples of FLOW developments with helicopter landing pads was not available at the time of writing.

Barrier to species movement

This pressure refers to obstructions to species movement caused by physical barrier or prolonged exposure to noise, light, visual disturbance or changes in water quality. As other pressures address noise, light, visual disturbance and changes in water quality separately, this section focusses on the physical barrier presented by the presence of the wind turbine infrastructure itself.

The pressure is clearly relevant to mobile species such as fish, birds, reptiles, and mammals. However, it should also be considered relevant to macrofauna such as crabs, which undertake migrations to over-winter or to breed, and where populations are dependent on larval or other propagule supply from outside the area. Otherwise, the pressure is considered ‘not relevant’ (Tyler-Walters *et al*., 2018).

The presence of offshore wind foundations and structures may cause a barrier to species movement that can be temporary or longer term (OSPAR, 2008). The scale of the impact will depend on scale of activity and the location and will need to be considered on case-by-case basis to determine relevance to given feature/site.

Population consequences of potential displacement and barrier effects are generally considered to be similar between floating and fixed foundation wind farms, however the consequences of a floating moving platform on bird behaviour may vary with different species (ORE Catapult., 2016).

Offshore wind farms may exhibit barrier effects on migrating birds, bats, marine mammals, and fishes. Barrier effects occur when an installation presents an obstacle to the movement patterns of animals, particularly if it is located between feeding grounds and breeding areas, or along migration routes.

This is a concern for some seabird species, such as wide-ranging albatross (*Diomedea* spp.), that forage at night across large distances, or sea ducks, like scaup (*Aythya* spp.), that raft at night and may commute to and from foraging sites across wind farm sites. If avoidance of these barriers changes species' energy requirements or causes disorientation during migration, there could be negative effects on overall fitness of individuals. Additionally, potential increases in time off the nest could result in increased chick predation for birds (English *et al.* 2017).

This section considers two types of effects resulting from the physical presence of the wind turbine infrastructure on birds;

- barrier effects, where feeding, resting or breeding areas may become inaccessible to the birds due to the presence of a large wind farm in their flight path
- displacement effects, where birds are displaced from their feeding, resting or breeding areas through the presence of a wind farm in these areas (Krijgsveld., 2014)

Both barrier effects and displacement effects can result in habitat loss and potentially a lowered carrying capacity for local populations (Krijgsveld., 2014).

Barrier and displacement effects are also related to avoidance behaviour. The stronger the avoidance of a wind farm, the larger the potential barrier and displacement effects of these wind farms. On the other hand (as discussed in the next section), birds that strongly avoid wind farms will have a far lower risk of colliding with the turbines (Krijgsveld., 2014).

Avoidance of offshore wind farms may cause migrating bird species to use more circuitous routes and expend more energy (Fox *et al.,* 2006). Though the consequences of such barrier effects on flight energetics remain largely unknown (Hüppop *et al.,* 2006). A comparison of pre- and post-construction data from Nysted in the North Sea suggests that, while birds exhibit avoidance responses, the energetic cost of the additional distance travelled to circumvent the offshore wind farm is insignificant (Masden *et al.,* 2009). Monitoring of bird behaviour at the Thanet offshore wind farm in Kent, UK found that 96.8 % of recorded seabirds avoided turbines by flying between turbine rows while the remaining 3.2 % adjusted their flight height to fly below the rotor-swept zone (Skov *et al.,* 2018), again suggesting that avoidance responses may not require more circuitous routes and increased energy expenditure. Conversely, the percentage of flocks of ducks and geese entering the Nysted area decreased by a factor of 4.5 between pre-construction and initial operation periods, signifying a substantial, and possibly a species-specific, avoidance response (Desholm and Kahlert 2005).

Displacement of migratory species including sea ducks, loons, and some species of auks from foraging areas within wind farms may have long-term implications on the fitness of these species, which would not be as readily apparent as the impacts of mortality caused by collision with turbines (Robinson Willmot *et al*. 2013; Maxwell *et al.,* 2022) (discussed in the next section).

Other species, like guillemots and razorbills, have been shown to become habituated to wind turbines and their foundations, and return to use habitat within wind farms (English *et al*. 2017; Lüdeke 2015). Site-specific factors, such as food abundance and foundation configuration, may play greater roles in observed avoidance and habituation (Degraer *et al.* 2019; Lüdeke 2015; Maxwell *et al*., 2022).

As discussed in Section 3, birds are a major feature of the coastal habitats of the UK, with resident, migratory and over-wintering populations present (BEIS, 2022). The UK is located on the course of some of the major migratory flyways of the east Atlantic, with many species not only overwintering in the area, but also using the UK as a stopover during spring and autumn migrations. Birds do not use fixed migratory corridors, rather a broad front, which often covers the whole of the UK (BEIS, 2022). For this reason, birds are a sensitive receptor for the impacts of barriers to species movement.

The physical presence of offshore structures, whether fixed foundation or floating, may also result in the displacement of marine mammals from key habitats such as foraging and breeding grounds. Russell *et al*. (2016), however, found no evidence of harbour seal (*Phoca vitulina*) displacement during the operation of several offshore wind farms in the UK. Russel *et al.* (2014) even demonstrated two seal species' (*Phoca vitulina* and *Halichoerus grypus*) ability to manoeuvre between offshore wind farm components unharmed and inferred that these animals were using the structures to forage. Similarly, Scheidat *et al.* (2011) presented evidence of a substantial increase in acoustic activity of harbour porpoises within the Dutch Offshore wind farm “Egmond aan Zee” and posited that an increase in food availability and/or an absence of vessels may explain the apparent preference (Farr *et al.,* 2021).

Sea turtles also migrate long distances across oceans and would therefore present a sensitive receptor for the impacts of barriers to species movement (ORCA Ireland, 2023).

Fish species also have the potential to be sensitive receptors to the barrier effects of offshore wind farms. Pelagic fish species (e.g., herring, mackerel, blue whiting, and sprat) are typically found in the water column, thus the physical presence of floating foundations, mooring lines and dynamic inter-array cables may lead to attraction or avoidance effects (Taormina *et al*., 2018). Attraction or avoidance effects in fish can also have an indirect effect on other marine organisms, such as marine mammals, due to changes in prey populations. Pelagic species are known to make extensive seasonal movements or migrations. For example, Cod are abundant in the Celtic Sea and are believed to migrate inshore over winter, following summer feeding over deeper waters (Pawson, 1995). Therefore, the attraction or avoidance of FLOW structures could disrupt migration behaviour.

A number of demersal fish species are also known to actively migrate (e.g., juveniles and adults) between areas during their lifecycle. For example, Mackerel are abundant at the shelf edge of the Celtic Sea, migrating to feeding grounds in Cornwall in the winter (Ellis & Heessen 2015).

Contrary to avoidance effects, offshore wind farms can also lead to attraction effects, the increased presence of organisms to a device. Attraction can be caused by an increased presence of food, natural curiosity, or the creation of new habitat, all of which can occur with the introduction of a new structure into the environment.

Researchers found evidence that wind turbines not only attracted fish, providing both shelter and food (from the organisms that grew on the turbines), but also served a role in their life cycle, with young fish attracted to the wind farm where they would grow, then leave to spawn, and then other juveniles would come to the wind farm to grow. In a separate study, they also found that the presence of filter feeders on the turbines, such as mussels, increased the nutrients in the seafloor around the turbines (Sea Grant, 2020).

Although it can have a positive impact, the attraction of various animals to wind energy devices may also increase the impact of various stressors. The consequence of this interaction can vary greatly based on the technology type, existing stressors, and the receptor species. For example, attraction to wind energy and tidal energy turbines may increase risk of collision or noise exposure, while the attraction to new reefing habitats may benefit populations and species diversity.

As a result of attraction effects, FLOW turbines can act as FADs that concentrate marine fish and facilitate their capture, resulting in increased catch rates for some species. FADs increase the catch rates and catchabilities of species that aggregate near them. FADs have been used for centuries to concentrate marine fish to facilitate capture. Many different designs are utilised throughout the world including anchored, drifting, surface, and submerged FADs. Designs for FLOW turbines are similar to other structures, such as oil platforms, that act as de facto FADs. Fixed foundation wind turbines have also demonstrated the potential to act as FADs. The fish aggregating potential for FLOW could become a development opportunity to create a limited entry recreational fishery (Fayram and de Risi., 2007).

Risk-profiling

For fixed foundation offshore wind, the risk of barrier to species movement has been ranked as “**Low**” during construction and decommissioning phases, and “**Medium-High**” during operation and maintenance. As no major differences have been identified between fixed offshore wind and FLOW, it is recommended that the rankings remain the same.

Mitigation measures

Placing turbines in low-impact areas, or “smart siting,” is the critical first step to mitigate impacts, particularly avoiding areas high in biodiversity including but not limited to Key Biodiversity Areas (KBAs), Particularly Sensitive Sea Areas (PSSAs), Important Marine Mammal Areas (IMMAs), or other types of designated critical habitats (Bennun *et al.,* 2021). Since the evidence to demonstrate the environmental impacts of FLOW is limited, siting initial projects in less environmentally sensitive areas is a strategic way to minimise local environmental impacts in line with the precautionary principle, and optimising avoidance of impacts in the planning stages is critical.

Potential barrier effects can possibly be reduced by accounting for the local species composition and the main flight paths of these birds in the planning phase, and by adjusting the configuration of the wind farm to this (Krijgsveld., 2014).

Spacing of turbines within a wind farm also likely has a considerable effect on avoidance behaviour of birds. Avoidance seems to be lower in wind farms where turbines are spaced more widely, and birds flying within wind farms seem to prefer flying in areas where spacing between turbines is larger or where rotors are idle. This means that through careful design of wind farms effects on birds can potentially be reduced. For instance, a major flight route of a bird species can potentially be maintained by designing a corridor through a wind farm with the right orientation, and barrier effects can be prevented by allowing sufficient spacing between wind farms (Krijgsveld., 2014).

Evidence gaps

To be able to assess the occurrence of barrier effects of offshore wind farms on birds, and the extent of these barrier effects, more information is required on species-specific avoidance rates (Krijgsveld., 2014). There is the requirement to engage subject matter experts with relevant ornithological expertise on offshore bird distribution to appraise the questions of barrier effects and attraction of birds in further detail (ORE Catapult, 2022c).

The emerging range of ornithological evidence further offshore from survey effort in other industries should be used to inform potential impacts of FLOW (for example, the increasing body of ornithological evidence associated with decommissioning of North Sea oil and gas assets) (ORE Catapult, 2022c).

In addition, it will be necessary to identify and assess any challenges related to the development of FLOW farms at unprecedented distances from shore (as FLOW farms are generally located further offshore than fixed foundation wind farms, where bird species abundance is different) (ORE Catapult, 2022c).

In order to obtain more information on the attraction / avoidance effects of FLOW on marine mammals, installation of monitoring equipment on structures, for example C-POD click-detectors to detect the bio-sonar (echolocation clicks) of odontocetes (toothed whales, dolphins and porpoises), would provide temporal (time) data on animal activity, as an indication of presence or habitat usage. This information could be used to determine the extent of barrier effects caused by the wind farm presence, as well as identify possible mitigation measures (Brocklehurst and Bradshaw., 2022; Ocean Science Consulting (OSC), 2023).

C-POD technology is planned to be installed on the future FLOW test technologies at the Atlantic Marine Energy Test Site (AMETS) located offshore Mayo, Ireland, as part of the Accelerating Market Uptake of Floating Offshore Wind Technology (AFLOWT) project. The Sustainable Energy Authority of Ireland (SEAI) has been developing the AMETS since 2009, initially envisaged as a grid connected test site for pre-commercial wave technologies. However, the permitted use of the demonstration site is currently in the process of being changed to include FLOW technologies (i.e., the initiation of the AFLOWT project), as well as wave energy technologies (Brocklehurst and Bradshaw., 2022).

Collision ABOVE water with static or moving objects not naturally found in the marine environment (e.g., boats, machinery, and structures)

The collision risk of offshore wind farm structures is well-recognised and is now a major consenting consideration for offshore wind farm projects (Natural England, 2022a; Natural England, 2022b). Several reports have concluded that offshore wind farms pose a collision risk, particularly at migratory "bottleneck" locations, to a range of bird species. In addition, as offshore wind turbines provide a structure for birds to perch, turbines may serve as a greater attractant increasing collision potential for some species (Ainley *et al.,* 2015; May *et al.,* 2020; Musial, 2020).

In short, this section on collision ABOVE water focusses on bird collision with wind turbines above water elements i.e., the turbine itself. The pathway for this pressure is the physical presence of the structure in the air space, and rotation of the turbine blades in the air. The main receptor for this pressure is seabirds. The benchmark relates to passage through an artificial structure and is, therefore, only relevant to mobile species. The pressure is considered ‘not relevant’ to seabed habitats and most benthic species (Tyler-Walters *et al.,* 2018).

Throughout their evolution seabirds have not had to contend with obstacles which extend into their flight space above the water surface. However, the recent introduction and expansion of the offshore wind sector has significantly increased the potential for collisions with turbines (Natural England, 2022a; Natural England, 2022b).

The risk of collision ABOVE water is considered to be highest during the operation and maintenance stage of an offshore wind development, due to the physical presence of the structures and rotation of the turbine blades in the air, as well as the potential presence of maintenance vessels. Collision ABOVE water is still possible during construction and decommissioning stages due to the presence of vessels (especially for fixed foundation offshore wind, due to reduced vessel activity for FLOW).

Bird collisions with vessels occurs and it is documented to be higher particularly at night on lighted ships near coastal areas. These are more frequent under poor visibility.

The risk of this pressure will increase depending on the spatial/ temporal scale and intensity of the activity, the proximity of the activity to the feature i.e., seabirds (in space and time) and the sensitivity of the feature (i.e., seabirds) to the pressure. Cumulative and in-combination effects of activities may increase the risk further.

The artificial lighting from offshore wind farms may attract bird and bat species, thus increasing the potential for collision (Farr *et al*., 2021). Introduction of light is further discussed in a later section.

Turbine collisions form one of the most well-known impacts of offshore wind turbine developments (in general) on seabirds. Collision with moving turbines can result in injury or death to seabirds and depending on the number of individual birds killed or injured, could result in population level impacts (Maxwell *et al.,* 2022).

Assessment of the risk of bird collisions at wind farms principally focuses on risks associated with a bird being struck by a rotating blade when passing through the rotor-swept area. The probability of collision, for a bird on a collision course with a turbine, depends on (i) the flight height of the bird, (ii) the likelihood of the bird altering its flight path to avoid the rotor swept area (i.e. avoidance), and (iii) if the bird passes through the rotor-swept area, whether it is struck by a rotating blade. Before considering these components in turn it should be noted that other collision risks may be associated with wind farms and their operations, such as collision with masts and aerials on the support vessels, or with moorings associated with floating wind platform (Scottish Government, 2023).

The number of birds that collide with wind turbines is very much dependent on the avoidance behaviour of birds around the wind farm and around the individual turbines. Birds that strongly avoid wind farms will have a far lower risk of colliding with the turbines than birds that are indifferent to the wind farms or that are even attracted to them. On the other hand, birds that show strong avoidance of wind farms will have a higher risk of suffering barrier effects and displacement effects, as discussed in the previous section (Krijgsveld., 2014).

Whilst there has been considerable research and discussion about collision risks for turbines broadly (e.g., Cook *et al*., 2018), there are significant gaps in the current understanding of seabird collision risk with FLOW turbines specifically.

The early consensus within the industry is that the wind turbines deployed on floating foundations will be technologically similar to those used in fixed foundation offshore wind in terms of dimensions and capacity. This means that parameters relevant to the occurrence of bird collision such as hub height, surface clearance and rotor diameter are likely to be similar between fixed and floating foundation designs (ORE Catapult, 2021a).

As described in Section 3, all of the seabirds known to occur in the Refined Areas of Search within the Celtic Sea have been identified by Martin (2022) to be vulnerable to collision and displacement resulting from FLOW turbines. Species-specific flight heights have been described in Table 3-8 (Section 3) (APEM-Marine Scotland, 2022).

As the preliminary Crown Estate design envelope states that the minimum rotor surface clearance of the Celtic Sea FLOW turbines will be 22 m (Table 2-3) the identified flights heights of the bird species in the area suggest that there will be potential for seabird collisions with the turbines as several species fly around this height. Recent compilations of bird flight height information indicate that, for some species, most birds at risk of collision are flying in the lower part of the rotor swept area (Davies and Band., 2012). For this reason, the minimum rotor surface clearance of 22 m outlined by the Crown Estate design envelope would be considered worst-case scenario in terms of bird collision risk.

Sooty Shearwaters are considered to have low collision risk as they generally fly very close to the sea surface, often below 5 m, and therefore below turbine blade height, however this is based on very small sample sizes (Paton *et al.,* 2010; Cook *et al.,* 2012; Deakin *et al*., 2022). It is also assumed that Sooty and Manx Shearwaters fly at similar heights (Furness and Wade, 2012). Like Manx Shearwaters, Sooty Shearwaters may fly higher in stronger winds (Spear and Ainley, 1997; Ainley *et al.,* 2015).

Flight heights in relation to distance from wind turbines has been assessed and found that gannets appear to fly lower when flying closer to the wind turbines, however it is noted that this may be influenced by one bird detected far from the wind turbines (APEM-Marine Scotland., 2022)

FLOW is designed for deeper waters than fixed foundation wind turbines, and thus will be deployed farther offshore than existing fixed foundation wind farms. The difference in wind farm location may lead to differing impacts of bird collision (Maxwell *et al.,* 2022).

Seabird presence generally decreases offshore; however, seabird behaviours also change offshore. Offshore environments have higher wind speeds and research has shown that seabirds change their behaviours in response to these wind speeds. For example, one study using boat-based survey observations showed that seabirds have a higher probability of flying higher as wind speed increases (Ainley *et al.,* 2015). Of particular concern, seabirds appear to change flight style, relying more on gliding and flap-gliding movements offshore, while using flapping behaviour near shore (Ainley *et al.,* 2015).

In gliding flight, a bird's wings are held out to the side of the body and do not flap. As the wings move through the air they are held at a slight angle, which deflects air downward, causing a lift force that holds the bird up in the air. Seabirds engaged in gliding may have more difficulty avoiding wind turbines (Ainley *et al.,* 2015; Gibb *et al.,* 2017).

Flapping flight is a far more complicated process than gliding. During flapping flight, the bird's wings move up and down, and systematically change shape. Flapping helps a bird to push itself through the air. On the downstroke, the wing forces the air down, pushing the bird up in the process (The Royal Society for the Protection of Birds (RSPB), 2023).

In addition to this, because they are floating, FLOW also have an increased range of both vertical and horizontal motion compared with stationary fixed-foundation wind turbines (Musial, 2020). This motion could potentially increase the risk of seabird turbine collision as it makes collision risk dynamic in space and time near turbines (Maxwell *et al.,* 2022).

For avian collision risk, the worst-case design envelope is considered to be:

- three-bladed wind turbines of 180 m diameter
- rotors of 90 m length, 5.5 m maximum blade width and an average pitch of 15 degrees
- turbines operated with a minimum surface clearance of 22 m (this clearance is the worst case for ornithology, a greater surface clearance would reduce the potential for bird collisions)
- a large number of wind turbines (as opposed to just a few)
- a wind turbine array spread across a large offshore site

A study was commissioned by Vattenfall to investigate bird collision and avoidance at the European Offshore Wind Deployment Centre (EOWDC), an offshore wind test site with 11 fixed-foundation turbines located off the coast of Aberdeen. Seabirds were tracked inside the array and bird meso-avoidance (a significant change in altitude or direction before arrival) and micro-avoidance (a sudden change of flight when passing a turbine at close range) was measured. Seabird species included herring gull (*Larus argentatus*), black-legged kittiwake (*Rissa tridactyla*), Northern gannets (*Morus bassanus*), great black-backed gulls (*Larus marinus*) and many others. The results of the study concluded that seabirds will be exposed to very low risks of collision in offshore wind farms during daylight hours. This was also substantiated by the fact that no collisions or even narrow escapes were recorded in over 10,000 bird videos during the two years of monitoring covering the April 2020 – October 2021 period (Vattenfall, 2023).

Risk-profiling

For fixed-foundation offshore wind, the risk of collision ABOVE water during the operation and maintenance phase has been ranked "**Medium-High**". Risk is ranked "**Low**" during construction and decommissioning.

As with the visual disturbance pressure, the impacts of collision ABOVE water from FLOW turbines is thought to be much the same as fixed foundation turbines, given the fact that the above water parts (i.e., the turbine itself) remain largely unchanged. Although there are some differences i.e., changing bird behaviour and flight style offshore, as well as the fact that FLOW turbine movement is more dynamic, the fact that there is also a decreased abundance of birds further offshore means that the ranking may be balanced out and further research is needed before it can be proved otherwise. Therefore, this report suggests that the rankings for collision ABOVE water should remain the same for FLOW and fixed foundation turbines.

Mitigation measures

As described above, bird collision risk with offshore wind farm turbines is now a major consenting consideration for offshore wind projects. Therefore, the possibility of reducing those risks through a simple vision-based mitigation is highly desirable. It has the potential to help both governments and developers accelerate the growth of offshore wind to achieve renewable energy targets (Natural England, 2022a; Natural England, 2022b).

Mitigation measures to reduce the likelihood of seabird collision with FLOW ABOVE water include using auditory deterrent devices, and restricting turbine operation at certain times, seasons, or during specific weather conditions (Marques *et al.,* 2014; Ainley *et al.,* 2015; May *et al.,* 2020; Musial, 2020; Maxwell *et al*., 2022; Farr *et al*., 2021).

May *et al* (2020) tested a vision-based wind turbine mitigation measure, whereby turbine rotor blades were painted (one of three rotor blades painted black) to reduce motion smear and thus reduce collision risk for a range of seabirds. The report modelled 70% reduction in annual turbine-blade collision mortality rate in a suite of 19 bird species at a terrestrial location. It should be noted that painting of turbine blades should be implemented at the production stage of turbines; as they are difficult to retro fit (May *et al*., 2020).

Prompted by the findings of May *et al* (2020), Natural England commissioned a study to explore key aspects of the vision, behaviour and ecology of marine birds which contribute to their collision risk under a range of natural viewing conditions (Natural England, 2022b). The aim of the report was to extend the mitigation approach studied by May *et al* (2020) and increase its general applicability to a broader suite of bird species at sea, and to a wider range of viewing conditions. The report also presents a review of the vision of birds, which was used to determine key elements for the design of vision-based mitigation measures aimed at reducing the collision of marine birds with offshore wind farms. The design used was that each blade (both surfaces) was divided into thirds with two of the blades showing black tips, a white middle section and a black section close to the nacelle. The other blade was the reverse of this pattern. The study concluded that there is a justifiable ecological basis to believe that the principle of increasing the internal visual contrast of turbines through blade marking should benefit seabirds. The purpose of blade marking is to increase the conspicuousness of wind turbines across a wide range of natural viewing conditions such that a turbine can be detected by an approaching bird sufficiently early to allow change in their flight path and avoid collision (Natural England, 2022b).

As recent compilations of flight height information indicate that, for some species, most birds at risk of collision are flying in the lower part of the swept area, increasing the clearance above the water surface can significantly reduce the number of flights exposed to collision risk (Davies and Band., 2012).

A study by Johnston., *et al*. (2014) concluded that the positively skewed flight height distributions of all species assessed demonstrates that, under the conditions in which data were collected, raising hub height and using fewer and larger turbines are effective collision mitigations (Johnston *et al*., 2014).

Despite this, preventative initiatives, such as careful siting of FLOW farms to ensure minimal overlap with important habitats, protected areas, migration corridors, and large populations of high-risk species, may be the most effective method to minimize risk to marine species (Maxwell *et al*., 2022).

For collision with vessels during construction and decommissioning, mitigation measures include reducing the number of vessels as much as possible, reducing vessel transits, reducing vessel speed to 10 knots or less, ensuring vessels remain within recognised transit routes, training vessel crew as lookouts, and using dynamic management techniques (Banister, 2017; Conn and Silber, 2013; Maxwell *et al.,* 2022).

Evidence gaps

Whilst there has been considerable research and discussion about collision risks for turbines broadly (e.g., Cook *et al.,* 2018), there are significant gaps in the current understanding of seabird and FLOW turbine collision risk (Maxwell *et al.,* 2022).

Whilst some components of the overall assessment of the collision risk posed by wind farms, and their population-level consequences, can be computed with estimable precision and accuracy, other components, such as the avoidance rate, or in the case of nocturnal procellariform seabirds, the attraction rate, are subject to considerably greater uncertainty, which render estimates of collision rate and population consequences highly speculative (Scottish Government, 2023). More qualitative data is required on the number of collision victims among birds, as well as more field data on attraction/avoidance rates (Krijgsveld., 2014).

To do this, monitoring devices could be installed on turbines to track collisions, such as accelerometers or thermal imaging cameras (although such devices are largely still in development. As an example, Kincardine FLOW farm in Scotland have a bird monitoring plan. It is noted that the Kincardine FLOW farm offers a unique platform for seabird monitoring due to the triangular shape of the floating foundation (semi-submersible design) that not only provides a large surface area for monitoring to take place, but it also provides sufficient space to allow a good viewpoint looking back onto the whole turbine. This would allow very accurate monitoring of bird strike occurrences, that is currently not available from traditional fixed foundation platforms. The size of the substructure provides many opportunities for different seabird monitoring techniques to be undertaken, including mounting a bird radar system that can remotely monitor birds passing through the turbine blades, or monitoring in person by ornithologists from the platform itself (Kincardine Offshore Wind Ltd., 2018).

Increased bird injury and mortality due to turbine collisions also requires further study, including consideration of flight height, flight behaviour, and floating turbine motion (Maxwell *et al.,* 2022).

Bats and offshore wind are also identified as a data gap where further research should be prioritised to identify bat distribution, migration routes, and collision risk with offshore wind turbines (Bat Conservation Trust, 2022).

Collision BELOW water with static or moving objects not naturally found in the marine environment (e.g., boats, machinery, and structures)

In short, this section on collision BELOW water focusses on the risk of collision of marine mammals, turtles, and diving birds with vessels involved in FLOW construction, maintenance, or decommissioning activities, as well as the risk of entanglement (primary/secondary/tertiary) of diving seabirds, turtles, marine mammals, or large fish / elasmobranchs with wind turbine mooring lines. The impact pathway for this pressure is the physical presence of the structure in the water column, and the receptors are diving seabirds, turtles, marine mammals, and large fish / elasmobranchs.

As with collision ABOVE water, the risk of collision BELOW water is considered to be highest during the operation and maintenance stage of an offshore wind development, due to the physical presence of the structures in the water column, as well as the potential presence of maintenance vessels. Collision BELOW water is still possible during construction and decommissioning stages due to the presence of vessels (especially for fixed foundation offshore wind).

As with collision ABOVE water, the risk of this pressure will increase depending on the spatial/ temporal scale and intensity of the activity (i.e., number of turbines present), the proximity of the activity to the feature i.e., diving seabirds and marine mammals (in space and time) and the sensitivity of the feature i.e., diving seabirds and marine mammals to the pressure. Cumulative and in-combination effects of activities may increase the risk further.

Vessel collision

In addition to wind turbine structures themselves, species may collide with the propellor or other parts of the hull (i.e., the ship's watertight enclosure) of vessels used in FLOW construction, maintenance, and decommissioning, causing collision injury or death. In general, the most lethal and serious injuries to mobile species such as marine mammals are caused by large ships (e.g., 80 m or longer) and vessels travelling at speeds faster than 14 knots. Most minor injuries, by contrast, involved collisions with vessels less than 45 m long. Collisions are rarely reported for vessels doing less than 10 km/hour.

Collision with vessels can result in serious injury or death to marine mammals, particularly whales, and when combined with impacts from other vessel-based activities in some regions, could contribute to population-level impacts, particularly for whales (Rockwood *et al.,* 2017). Wind farm installations result in increased vessel presence, during construction, operation and maintenance phases. Vessels must also transit through coastal habitats to reach offshore wind installations, thereby increasing collision risks inshore as well. Many seabird species such as gulls, albatrosses and petrels are considered to be vessel-attracted species as they have learned to forage on fishing discards (Furness, 2003). As a result, vessel collision from wind farm vessels with seabirds is possible, though it is not expected to be higher than with other vessel types. Studies that look at collisions specific to offshore wind, however, have not been conducted (Maxwell *et al.,* 2022).

Turtle species are also vulnerable to vessel strike when they surface to breath, bask or forage at/near the surface. Adult turtles appear to be at increased risk during breeding and nesting season (Bennun *et al.,* 2021).

There may be less of a likelihood of collision with vessels used for FLOW farms in comparison to fixed foundation wind farms for several reasons. Firstly, much of the construction can be done on land with pre-constructed components towed to the site and installed in relatively short amounts of time compared to the time, number of vessels, and level of construction necessary for fixed-foundation turbines attached to the seabed (Banister, 2017). Secondly, in some FLOW floating foundation configurations there is a larger surface area where helicopter landing pads can be installed. This means that maintenance can be done by helicopter, reducing transit times to the offshore turbines and also reducing the potential of vessel-cetacean collision, though helicopters would still be a source of disturbance for marine species, including marine mammals, and also pose collision risk for birds (Banister, 2017; Patenaude *et al*., 2002).

Entanglement

Large cetaceans and basking sharks are thought to be most at risk from entanglement because of their behavioural traits and size (Benjamins *et al*. 2014). However, concerns about the possible risk to smaller marine mammals, diving seabirds, large fish and elasmobranchs have also been raised when considering the potential impacts of large arrays with multiple mooring systems and cables. Natural Resources Wales suggest that for seabirds, interactions with cables and mooring lines are of negligible importance. Natural Resources Wales expect that this impact pathway would only need to be considered should there be many mooring lines per device, increasing the potential risk of entanglement (Aquaterra Ltd & MarineSpace Ltd., 2022).

In the UK, those species of concern in relation to entanglement are protected under the Conservation of Habitats and Species Regulations 2017 and the Conservation of Offshore Marine Habitats and Species Regulations 2017. These regulations establish a network of MPAs to protect habitats and species of national and international importance and make it illegal to deliberately disturb, injure or kill marine protected species, including dolphins, porpoises, whales, otters, seals and basking sharks (Aquaterra Ltd & MarineSpace Ltd., 2022; Garavelli, 2020).

Entanglement risk for FLOW is generally influenced by a number of factors, such as (Benjamins *et al.*, 2014):

- the geometry of the mooring lines (i.e., diameter of lines, whether they are taut or catenary)
- the depth of the draping of mooring lines, if they are of catenary design;
- animal behaviour near turbines
- detection of mooring lines by animals, which will be influenced by the configuration and material used for mooring lines, as well as how far mooring lines move in the water column
- the abundance of derelict fishing gear or other materials in the region, as well as;
- proximity to fishing grounds

Benjamins *et al.* (2014) have provided an in-depth qualitative assessment of relative entanglement risk, taking into consideration both biological risk parameters (e.g., body size, flexibility, and ability to detect moorings) and physical risk parameters of mooring elements (e.g., tension characteristics, swept volume, and mooring curvature).

In addition to mooring lines, similar risks may be associated with FLOW inter-array cables. Though cable burial in depths of up to 1,500 m are common (Carter *et al.,* 2009), developers may deem routing the inter-array cables that interconnect facility components to the seafloor impractical and may instead seek to employ subsurface buoys to sub-merge cables to depths within the water column, thus creating additional obstacles for marine mammals and, depending on the characteristics of these cables, providing additional avenues for entanglement (Farr *et al*., 2021). Despite this, power cables are less critical than mooring lines. Unlike mooring lines, some reports suggest that marine megafauna may be able to break a power cable if they became entangled in it, given that inter-array cables have a lower minimum breaking load than mooring lines (since they are not intended to play any role in keeping a device on station) (Harnois *et al*., 2021). Although this idea has been suggested, there is no conclusive research into what force would be required to break a dynamic inter-array cable, and no evidence of marine mammals having broken a cable. This presents an evidence gap at present, which warrants further investigation in future. As inter-array cables present a lower or similar risk to mooring lines, entanglement with inter-array cables has not been assessed further and the following sections focus on entanglement with mooring lines.

There are three types of entanglement risk: primary entanglement, secondary entanglement, and tertiary entanglement. The following sections will consider each in more detail.

Primary entanglement

Primary entanglement is where animals become caught in the cables or mooring lines of a FLOW structure itself. The risk of primary entanglement potential is greatest for marine mammals, although overall the risk is likely low due to size and structure of the cables and lines. Given the size and physical characteristics of the mooring systems required for FLOW, it is unlikely that upon encountering such facilities, a marine mammal of any size would become directly entangled in the moorings themselves. Mooring systems in the offshore renewables industry typically employ high modulus polyethylene ropes and chains averaging between 100 and 240 mm in diameter (Benjamins *et al*., 2014), while fishing gear, which has been identified as a major entanglement risk for whales (NMFS, 2018), is typically ~1–7 mm in diameter (Bailey *et al*., 2014; Benjamins *et al*., 2014; Maxwell *et al*., 2022). Additionally, the mooring lines have less curvature and are made of more rigid material than fishing lines, meaning the risk of loop creation and subsequent entanglement is relatively low in comparison to fishing gear (Benjamins *et al.,* 2014). Furthermore, marine mammal species are likely to be able to detect large-diameter mooring lines, either through echolocation (in the case of odontocetes), vibrations detected through vibrissae (in the case of pinnipeds), or basic acoustic detection (hearing) since ropes produce noise in proportion to current flow (Benjamins *et al.,* 2014). Detection can occur at a distance as close as tens of meters to the structure and has been shown to occur for odontocetes for lines of much smaller diameter than those used for FLOW turbines (Nielsen *et al*., 2012; Maxwell *et al.,* 2022).

Benjamins *et al. (*2014) found that due to their large size and foraging habits (i.e., rapidly engulfing dense prey aggregations), baleen whales incur the greatest risk of entanglement among cetaceans while small, toothed whales incur the least risk (Benjamins *et al.,* 2014).

Harnois *et al*., (2015) compared the risk of entanglement of marine megafauna for six mooring configurations commonly used in FLOW, namely catenary with chains only, catenary with chains and nylon ropes, catenary with chains and polyester ropes, taut, catenary with accessory buoy, taut with accessory buoy. The parameters used to estimate entanglement risk were tension characteristics, swept volume ratio and mooring line curvature. The conclusions were that catenary moorings and moorings using accessory buoys present a higher risk of entanglement and taut mooring systems represent the lowest relative risk of entanglement. Despite this, entanglement has not been reported for oil platforms with similar configurations.

Secondary entanglement

The method developed in the study by Harnois *et al.,* (2015) did not consider secondary or tertiary entanglement, however, it is acknowledged that derelict fishing gears can add a potentially significant risk of entanglement, especially in a dense array configuration. If a lost or discarded net, moving freely in the water column with the ocean currents, were to become entangled in one or more mooring lines, the entanglement risk, not only to marine megafauna but also to smaller species such as fishes and diving birds, would increase significantly with the size and surface area of the net (Harnois *et al.,* 2015).

Secondary entanglement is where fishing gear or other marine debris become entangled in mooring lines or cables, and this material goes on to entangle animals. This type of entanglement may represent the greater risk in comparison to primary entanglement. Secondary entanglement potential is greatest for species with large appendages (such as humpback whales or leatherback sea turtles) or diving species (such as seabirds) (Maxwell *et al*., 2022). Fish and other prey species can also become caught in the abandoned gear, then serve as bait for larger predators bringing them closer to debris and increasing entanglement risk. It is likely that with increased biofouling around turbine foundations and mooring lines, there will be an increased risk of snagging fishing gear as the wind farm structures become increasingly textured. Thus, there is a need for developers to evaluate 'snagging risk' of derelict fishing gear on cables within the mooring system of floating turbines (Benjamins *et al.,* 2014). Secondary entanglement could pose a significant risk and have population-level impacts, particularly if highly endangered species occur in the areas around a FLOW farm. Entanglement, particularly in derelict fishing gear, represents one of the greatest threats to cetaceans worldwide (Baulch and Perry, 2014).

Tertiary entanglement

Tertiary entanglement is where an organism already entangled in gear swims through a FLOW structure and the gear becomes entangled with a facility component (Farr *et al.,* 2021).

Risk-profiling

There are likely to be more differences between FLOW and fixed foundation offshore wind for collision BELOW water than collision ABOVE water, as the below water elements are where the major design differences are (i.e., the foundation type).

Entanglement is one of the key potential risk-profiling differences between fixed foundation and floating turbines. The increased risks involved with FLOW result from the presence of mooring lines and dynamic cables in the water column (Maxwell *et al.,* 2022).

For fixed-foundation offshore wind, the risk of collision BELOW water during all phases (operation and maintenance, construction, and decommissioning) has been ranked "**Low**" by the Natural England Advice on Operations tool.

Due to the higher risk of secondary entanglement with fishing gear, the findings of this report suggests that the risk of collision BELOW water for FLOW should be increased to "**Medium-High**" for all phases.

Mitigation measures

For mitigation against entanglement of species in inter-array cables (primary entanglement), bury cables where possible (Benjamins *et al.,* 2014).

For entanglement of species in other gear caught on mooring line / inter-array cables (secondary entanglement), solutions are to bury inter-array cables (as with primary entanglement), as well as regularly monitoring and cleaning lines and cables. Reducing biofouling may also reduce potential for secondary entanglement as there will be less surfaces for additional materials to adhere to. A plan for the frequency and type of monitoring, and how derelict gear would be removed should be included in all environmental assessments (Maxwell *et al.,* 2022).

Monitoring approaches for FLOW cable systems are similar to those employed for fixed foundation structures. Floating cable systems will require routine inspections during the operation and maintenance phase of their development, which will be typically conducted by Remotely Operated Vehicles (ROVs). However, these inspections are generally used to confirm the structural integrity of the cable systems rather than conduct environmental monitoring for entanglement and marine debris (SEER, 2022b).

Recommended entanglement monitoring and mitigation techniques include the use of underwater cameras, monitoring mooring and line loads or motion, and the use of underwater vehicles to detect and remove marine debris. For example, the Kincardine FLOW farm in Scotland has integrated load cells attached to mooring lines and subsea cables to periodically monitor line performance and potentially detect the entanglement of floating marine debris, including derelict fishing gear. The load cells will alert Kincardine FLOW farm operators if there is unexpected load on the devices which can then be examined. This information will be reported as part of the survey, deploy and monitor regime. The farm will use ROVs and vessel-mounted sensors (such as multibeam sonar) to periodically survey floating cable systems, which could also monitor for the presence of derelict fishing gear (Kincardine Offshore Wind Ltd, 2018; SEER, 2022b). Depending on how quickly caught nets can be identified and removed as a result of these surveying activities, this may reduce the potential impact of secondary entanglement.

Acoustic Deterrent Devices (ADDs) (otherwise known as Pingers) may be a method of reducing entanglement on mooring lines, though this technique needs additional research (Benjamins *et al*., 2014). ADDs have been used to successfully reduce small cetacean bycatch in some fisheries (Carretta *et al*., 2008; Carretta and Barlow, 2011), however, habituation to ADDs may occur (particularly with pinnipeds (Cox *et al.,* 2001)) and attention must be paid to device durability and maintenance over the long term (Dawson *et al*., 2013). In addition to this, ADDs present an additional source of underwater noise disturbance and could potentially cause avoidance effects / displacement of marine mammals, which must be accounted for when considering their use.

Barlow and Cameron (2003) found that the use of ADDs reduced cetacean and pinniped entanglement rates in a gill net fishery by two-thirds. Conversely, Harcourt *et al.* (2014) found no discernible response of migrating humpback whales (*Megaptera novaeangliae*) to acoustic alarms, suggesting that responses may be species-specific.

It is important to consider that the use of ADDs, may result in increased underwater noise and other negative impacts, such as disturbance and displacement, or attracting some species to turbine areas (Carretta and Barlow, 2011; Findlay *et al*., 2018). This may make their use potentially outweigh benefits especially if entanglement risk is low, and they are not likely to work for some priority species such as large whales (Maxwell *et al*., 2022). Additional challenges regarding the use of acoustic alarms as a means to reduce collision and entanglement include habituation risk (Cox *et al.,* 2001), local habitat exclusion (Carlström *et al*., 2009), and device durability and regulatory compliance (Dawson *et al.,* 2013).

Another mitigation measure identified is the selection of a high contrast mooring line colour that may be more easily observed by receptor species.

Studies have shown that different species may respond to different colour ropes, potentially allowing them to avoid lines (Benjamins *et al*., 2014; Kot *et al*., 2012; Kraus *et al*., 2014; Swimmer and Brill, 2006). Kot *et al*. (2012) demonstrated that minke whales are able to detect and avoid some fishing ropes, and that use of high contrast, black and white ropes in particular may reduce entanglement risk. Similarly, Kraus *et al*. (2014) found that North Atlantic right whales (*Eubalaena glacialis*) could detect red and orange coloured rope mimics at significantly greater distances than green ones. There is currently a limited evidence base in relation to the colour of mooring lines as a mitigation measure to avoid collision, however, it is recommended that this is explored and monitored for its potential as a mitigation measure in future FLOW projects.

Despite this, mooring line colour should be included in environmental impact assessments. Additionally, significant changes to moorings or buoys during construction or operation that may influence entanglement risk should be reported so that configurations can be assessed if primary or secondary entanglements should occur (Maxwell *et al.,* 2022).

In terms of the Crown Estate design envelope, to reduce entanglement risk, particular focus should be given to the number and tautness of lines, and the materials used to construct lines, as these factors are likely to influence the potential for entanglement. For example, taut mooring configurations are preferable because less slack in lines is likely to reduce entanglement potential (Benjamins *et al.,* 2014). Highest relative risk may occur with catenary moorings given that the lines are not taut. Chains and nylon ropes are thought to have a higher snagging potential, as do accessory buoys (Harnois *et al.,* 2015).

Another potential mitigation measure is to carry out a robust assessment and quantification of commercial and recreational fishing activity around FLOW farm locations and adjacent areas, to inform estimates of the amount and types of fishing gear that have the potential to become entangled in FLOW cable systems and thus the likelihood of secondary entanglement (SEER, 2022b). As described under socio-economic receptors in Section 3, the commercial fishing footprint is extensive within Western UK Seas.

The most effective way to reduce marine mammal collision and entanglement may be through siting FLOW farms in areas that reduce overlap with biologically important areas, such as feeding grounds and migration corridors (Farr *et al*., 2021).

Evidence gaps

Primary, secondary, or tertiary, entanglement may result in severe injury or mortality via tissue damage, starvation, or drowning (Cassoff *et al.,* 2011); however, the actual risks posed by FLOW are not yet known (Farr *et al*., 2021).

Due to the large degree of uncertainty associated with the limited experience with the operation of FLOW moorings, the rarity of entanglement events and the fact that they are not always detected, a lack of information exists regarding collision risk of animals (e.g., diving birds, fish, marine mammals) with underwater structures, especially for diving birds. The response of diving birds will depend on their detection of a device and any associated structures. The risk of collision may be increased if the devices alter the characteristics of the current, especially if such changes create new foraging opportunities, since this may impact on the manoeuvrability and underwater swimming agility of birds (changes in water flow are discussed in the next section). Collision risks are most likely to pose the greatest risk in areas of strong water movement, such as areas of strong tidal flow or wave motion. Although entanglement risks in FLOW are currently unknown as there have not been enough known incidences, it is critical to monitor for effects, particularly when sensitive species are present in turbine lease areas (Maxwell *et al*., 2022).

As FLOW develops and if entanglement is physically observed and monitored, more information will become available (Harnois *et al.,* 2015).

Established methods for environmental monitoring can be used to gather information about marine animal behaviour, movement, and use of space in the vicinity of floating platforms, which in turn can be used to evaluate entanglement risk and develop mitigation methods. Potential monitoring approaches include using aerial and drone surveys, remote sensing technologies (e.g., infrared sensors and radar), passive acoustics, underwater cameras, and animal tagging (SEER, 2022b).

While risk of primary entanglement is thought to be low, until that is proven, it may be useful to monitor tension of mooring lines and dynamic inter-array cables used in FLOW. This could be used to detect both primary entanglement of large marine species and secondary entanglements if derelict gear or material is entangled. Tension monitors can be connected wirelessly to remotely alert to the presence of a potentially entangled species. Tension monitors are currently being used for a number of FLOW turbines in Scotland (Maxwell *et al.,* 2022). In addition, the likelihood of marine megafauna being able to break a suspended inter-array cable if they became entangled in it should be investigated further i.e., what force would be required to break an inter-array cable and is there any evidence of this happening at any existing FLOW development.

As well as monitoring tension, AUVs, ROVs or wireless video can potentially be used to monitor for primary or secondary entanglement events at key parts of the turbines, such as the cables. These techniques can be used in conjunction with tension monitoring to ground truth potential entanglements remotely (Maxwell *et al.,* 2022).

Entanglement of marine animals with mooring lines and subsea cables from a marine renewable energy development has not been observed to date and there is no evidence that suggests an event has occurred (Aquaterra Ltd & MarineSpace Ltd., 2022).

Research is needed to develop more effective technologies for monitoring, detecting, and removing marine debris snagged on FLOW cable systems (SEER, 2022b).

As described above, there is evidence to show that mooring line colour may be an effective mitigation measure to avoid marine mammal collision with mooring lines and resulting entanglement. However, research should also be carried out in future to investigate whether marine mammal echolocation may be able to detect some mooring line designs (i.e., material and configuration) better than others. If a marine mammal was better able to detect mooring lines using echolocation, perhaps they may be less likely to collide with it. There is currently no evidence of this, and it has been identified as an evidence gap that may be a useful topic to investigate in future.

The National Oceanic and Atmospheric Administration (NOAA), supported by the Bureau of Ocean Energy Management (BOEM) (government agencies within the United States), are currently developing a modelling tool to evaluate the risk of whale species and leatherback sea turtles in deep water becoming entangled in derelict fishing gear snagged on FLOW cable systems (BOEM, 2022). The tool will assess whale and sea turtle entanglement risk and the potential severity of entanglement, which will assist NOAA and BOEM in identifying mitigation measures that can be implemented to reduce the potential risks of such entanglement in future. At the time of writing, this study is ongoing and the results are not yet available (BOEM, 2022; SEER, 2022b).

Changes to the atmosphere and ocean

There are several potential impacts on the abiotic environment, which as a consequence may lead to impacts on marine wildlife. Offshore wind turbines function as an artificial barrier for wind and ocean currents (Defingou *et al*., 2019). The following sections discuss those pressures related to changes to the atmosphere and ocean, including:

- water flow changes
- wave exposure changes

Hydrology is the branch of science concerned with the properties of the earth's water, and especially its movement in relation to land. Hydrological changes are generally considered to be “lightly impacted” by offshore wind (Abramic *et al*., 2022).

Water flow (tidal current) changes, including sediment transport considerations

This section addresses changes in water movement associated with tidal streams (the rise and fall of the tide), prevailing winds and ocean currents. A shift from a high to a low energy environment (or vice versa) can alter the biota, substratum, sediment transport and seabed elevation. Water flow changes can result in multiple and complex impacts (Marine Scotland, 2023).

There are relatively few studies on the water flow tolerances of species. Most evidence on water flow is based on habitat preferences, that is, the tidal stream regime where the habitat (biotope) or species is recorded. In general, where biotopes occur in high water flow rates or areas of natural variability in tidal stream experienced, receptors are generally not sensitive to changes in water flow. Where a biotope only occurs in weak to negligible tidal streams, receptors are considered potentially sensitive (Tyler-Walters *et al*., 2018). As floating foundations are used in very deep waters, where currents are typically weak near the seabed, biotopes would be considered sensitive to water flow changes.

In terms of the effects of change in water flow on the physical habitat (e.g. the erosion / accretion rates associated with sediments), medium sand (0.25 - 0.50 mm) will be suspended by currents about 0.20-0.25 m/s and it will stay in suspension until flow drops below 0.15-0.18 m/s. Therefore, in sedimentary habitats, a change in water flow may result in change in sediment type (Tyler-Walters *et al*., 2018).

Marine activities generally of greatest concern in relation to modifying hydrological energy flows include tidal energy generation devices (which remove energy) or dredging (which may deepen/widen a channel) (Marine Scotland, 2023). However, any structures placed in the marine environment immediately interact with the local current regime. As the presence of wind turbine structures and a wind farm as a whole have the potential to modify water flows around them, this impact has been assessed.

Structure-induced friction and blocking are two locally generated effects of the wind turbines' underwater foundations (Sumer and Fredsøe, 1997). The prototype of such a structure-flow interaction is the homogeneous flow past a cylinder. This would represent the foundation of a fixed-foundation wind turbine. Locally enhanced levels of turbulence in the wake of the cylinder have been observed by Grashorn and Stanev (2016), with resulting increased sediment erosion and turbidity in the water column (van Berkel *et al*., 2020). Increased sediment erosion and turbidity are discussed in the seabed disturbance section.

The alteration of the seawater's vertical density stratification due to stratified flow past fixed structures causes strong vertical mixing and internal wave generation (Rennau *et al*., 2012; Floeter *et al*., 2017).

Existing peer-reviewed studies provide limited coverage of local wind farm-induced (e.g., within the offshore wind farm footprint) turbulence and destratification impacts on fishes, for example, sediment resuspension or sedimentation, temperature, and nutrient transport. These studies largely neglect possible effects further afield (regional impacts) and generally conclude that ecosystem impacts are of comparable scale to natural variability given the currently existing or planned extent of offshore wind farms (van Berkel *et al*., 2020).

The artificial reef effect may worsen impacts on water flow through changes in current velocities and direction caused by the presence of marine biofouling organisms (Broughton, 2012). The artificial reef effect is discussed in the seabed disturbance section.

Atmospheric and oceanographic dynamics

The development of large-scale offshore wind energy projects has the potential to reduce the wind stress, which could have local and/or regional implications on wind-driven upwelling, nutrient delivery, and ecosystem dynamics. With increasing turbine heights, blade sizes, and spatial scales, concerns in the ability of wind farms to alter the downstream wind field are growing (Raghukumar, *et al.,* 2022).

Offshore wind farms may directly impact hydrodynamics, i.e., the motion of fluids and the forces acting on solid bodies immersed in fluids, inside of and near the wind farm site via two routes:

- modification of the wind field within the wind farm and, consequently, the wave and current fields due to the direct effect of power extraction from the wind (atmospheric dynamics)
- wind turbine foundations' effects on ocean currents and consequently on turbulence, mixing, and vertical stratification

These local alterations result in a modified ocean response to surface wind stress and associated ecosystem impacts (van Berkel *et al*., 2020).

Wake effect (wind)

The wake effect is the aggregated influence on the energy production of a wind farm, which results from the changes in wind speed caused by the impact of the turbines on each other. Aerodynamic drag from wind turbine rotors creates wake structures in the atmosphere associated with decreasing wind speed and increasing turbulence downstream of wind turbines (Lissaman, 1979; Wilson, 1980). An illustration of the wake effect at the Horns Rev II wind farm is shown in Figure 4-1 (Hasager *et al*., 2017). This is one of the challenges that wind farms must overcome. Offshore wind farm power extraction results in reduced wind speeds locally inside the wind farm footprint, as well as regionally as a downwind wake (which can extend 5-20 km in the downwind direction (Christiansen and Hasager, 2005). At the extreme, Ludewig (2015) showed that the wind wake effect may result in a reduction in wind speed in a region up to 100 times larger than the offshore wind farm area itself. The atmospheric wakes propagate downstream both laterally and vertically, reaching the surface at a distance of about 10 rotor diameters (Christiansen and Hasager, 2005; Frandsen *et al.,* 2006). In marine environments, the atmospheric wakes imply wind speed deficits near the sea surface boundary (Christiansen and Hasager, 2005; Christiansen and Hasager, 2006; Li and Lehner, 2013; Emeis *et al.,* 2016; Djath *et al.,* 2018; Platis *et al.,* 2018; Siedersleben *et al*., 2018; Djath and Schulz-Stellenfleth, 2019; Cañadillas *et al*., 2020; Platis *et al*., 2021; Christiansen *et al*., 2022).

As a consequence, wind-driven circulation becomes affected by the atmospheric wind farm wakes, changing the regional hydrodynamic conditions (Ludewig, 2015; Christiansen *et al*., 2022). Idealised studies have shown that, on the one hand, less wind stress at the sea surface causes decreasing horizontal surface currents behind offshore wind farms, which are in the order of centimeters per second (Ludewig, 2015). On the other hand, changes in wind-driven Ekman transport lead to convergence and divergence of surface waters and associated up- and downwelling dipoles along the wake axis (adjacent regions of upward and downward vertical velocity in the water) (Broström, 2008; Paskyabi and Fer, 2012; Ludewig, 2015). At this, the resulting vertical transport can influence the temperature and salinity distribution in a stratified water column, with vertical velocities in the order of meters per day (Broström, 2008; Ludewig, 2015; Christiansen *et al.,* 2022). These results have been confirmed by a modelling study conducted by Nerge and Lenhart (2010) that applied reduced wind stresses in the wake area of an offshore wind farm in the North Sea.

Depending on the sizes of the wakes, Floeter *et al*. (2017) suggest there could be a joint blocking effect involving an entire offshore wind farm. Consequently, part of a water mass approaching an offshore wind farm could tend to part and flow around the wind farm and rejoin after passing the area. This blocking could lead to a wake effect comparable to the island mass effect discussed by Simpson *et al.* (1982), with increased mixing downstream of the wind farm leading to destratification and upwelling effects that may impact primary production. The observations by Floeter *et al.* (2017) do not, however, give clear evidence of such large-sale regional effects, which are probably small (due to the relatively low offshore wind farm blocking effect) compared to natural variability and the wind wake effect (van Berkel *et al*., 2020).

Another study aimed to quantify the changes in wind fields at the sea surface as the result of offshore wind turbine deployments. Simulated arrays of offshore wind turbines were placed and it was found that wind speeds at 10 m height are reduced by approximately 5 %, with wakes extending approximately 200 km downwind of the wind farm areas. The length scale of wind speed reductions was found to be several times the internal Rossby radius of deformation, the spatial scale at which rotationally influenced ocean circulation processes such as upwelling occur (Raghukumar, *et al.,* 2022).

Figure 4-1. Photograph of the wind wake effect at Horns Rev II wind farm (Hasager *et al.,* 2017)

Productivity

Fixed foundation wind turbines generate increased water mixing from the tidal currents passing by the vertical submerged part of the structures, causing downstream turbulence, and down- and upwelling (Cazenave *et al* 2016, Floeter *et al* 2017). It can be assumed that this is true also for floating turbines, given that a significant part of their body is submerged, often reaching beyond the pycnocline in stratified waters in summer, adding 'anthropogenic' vertical mixing on top of natural mixing (Dorrell *et al* 2022; Akvaplan-niva AS., 2021). It is well known that modifications in mixing and stratification also impacts nutrient availability in the euphotic zone.

A likely increase in vertical water mixing, would weaken the stratification process, with a later onset and a shorter overall duration (Luneva *et al*., 2019). The increased availability of nutrients to the surface coupled with potential periodic stratification and destratification events during the spring and summer season are likely to significantly increase, rather than limit, primary production, as modelled by Luneva *et al.,* (2019) (Akvaplan-niva AS., 2021).

The wind wake effect of offshore wind farms affects the hydrodynamical conditions in the ocean, which has been hypothesised to impact marine primary production. The changes in nutrient concentration would start a cause-effect chain that translates into changes in primary production and effectively alters the food chain (Daewel., *et al*. 2022).

Studies have demonstrated that associated wind wakes in the North Sea provoke large-scale changes in annual primary production with local changes of up to ±10% not only at the offshore wind farm site, but also distributed over a wider region. An increase in sediment carbon in deeper areas of the southern North Sea have also been predicted, due to reduced current velocities, and decreased dissolved oxygen inside an area with already low oxygen concentration. The results provide evidence that offshore wind farm developments can have a substantial impact on the structuring of coastal marine ecosystems on basin scales. The results of this study also confirmed the direct ocean response identified by earlier studies to the alterations in the wind field, with clearly defined upwelling and downwelling dipoles in the vicinity of the offshore wind farms (Daewel., *et al*. 2022).

Another study in the North Sea used a bottom-up approach to investigate whether upscaling of offshore wind may have significant effects on fundamental ecosystem processes. The study noted that such changes in the physical functioning of the ecosystem may influence the foundation of the food web: primary production, which in turn will have consequences for higher trophic levels (Deltares, 2021).

Although there is multiple evidence to suggest that the presence of offshore wind farms may increase primary production due to impacts on down- and upwelling, at the same time, the large number of filter feeders likely to be growing on offshore installations have been shown to prey on phytoplankton with potentially negative effects on its concentration (Akvaplan-niva AS., 2021).

It has, however, been hypothesised that, after filtration, nutrients bound in phytoplankton would be readily made available by pelagic remineralisation of the detritus. By this mechanism, it is to be expected that filtration would sustain a longer bloom through faster nutrient recycling and support higher productivity in regions that receive nutrient-enriched and phytoplankton reduced water masses from offshore wind farm areas by currents (Slavik *et al* 2019; Akvaplan-niva AS., 2021).

A study at Hywind Scotland FLOW farm (Karlsson *et al* 2022) has demonstrated a high level of growth on the submerged parts of the turbine bodies and anchoring chains, as well as zonation and a succession process, exhibiting strong similarities to fixed turbines. It can therefore be expected that similar conditions with respect to nutrient levels exist for a FLOW farm as in a fixed foundation wind farm (Akvaplan-niva AS., 2021).

Risk-profiling

For fixed foundation turbines, water flow (tidal current) changes, including sediment transport considerations has been risk-profiled as “**Medium-High**” during operation and maintenance, and “**Low**” for construction and decommissioning activities. However, it is possible that impacts could still occur during construction and decommissioning due to placement/removal of structures and scour protection (Natural England, 2023a).

In the absence of evidence to suggest otherwise, the risk ranking for FLOW should remain the same as fixed foundation for all development lifecycle phases.

Mitigation measures

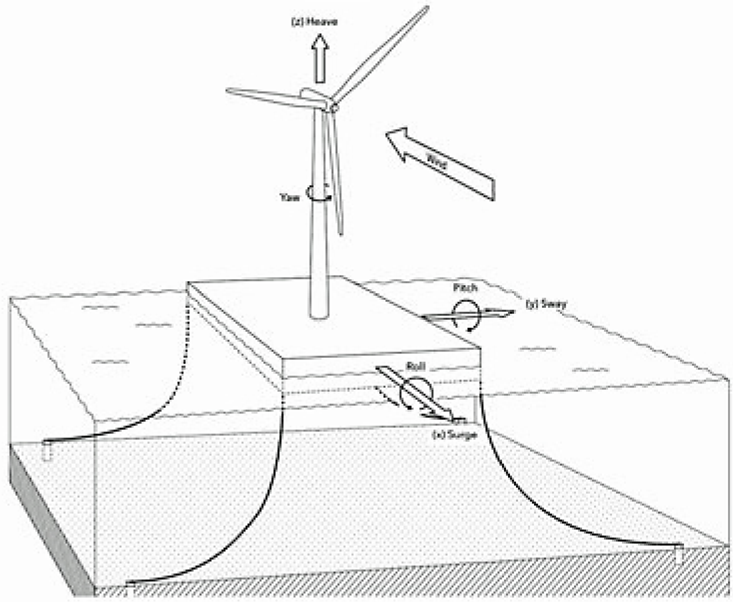
Research on the interaction of wakes from upstream turbines on other turbines in a wind farm received widespread attention for several decades. Typically, the goal is to reduce this interaction for the purpose of maximizing power and/or load minimisation (Berg *et al.,* 2022).

One technique that has gained traction over the years is wake redirection. Here, the rotors are statically yawed to divert the wake away from downstream turbines. While downwind wind turbines may see an increase in their power production, this goes at the cost of the output of the yawed turbine. Although this method has potential, as wind farms grow in size, it becomes increasingly difficult to deflect the wake in such a way that none of the other turbines in the farm are affected. Furthermore, the yawed turbine will experience increased loading, lowering the lifetime of the turbine (Berg *et al.,* 2022).

Wake-to-turbine interaction has also received attention for FLOW farms. As floating turbines are capable of moving over their six degrees of freedom, several different approaches to reduce the impacts of wakes have also been explored in literature. Figure 4-2 shows a floating wind turbine with the six degrees of freedom marked out (DNV, 2021).

- Surge: displacement along the longitudinal axis
- Sway: displacement along the lateral axis
- Heave: displacement along the vertical axis
- Roll: rotation about the longitudinal axis
- Pitch: rotation about the lateral axis
- Yaw: rotation about the vertical axis

For example, pitching the platform using ballast in the buoys. As the platform is pitched, the wake is either deflected upwards or downwards, depending on the pitch angle (Berg *et al.,* 2022).



Surge	Displacement along the longitudinal axis
Sway	Displacement along the lateral axis
Heave	Displacement along the vertical axis
Roll	Rotation about the longitudinal axis
Pitch	Rotation about the lateral axis
Yaw	Rotation about the vertical axis

Figure 4-2. Six degrees of freedom of a floating wind turbine (DNV, 2021)

In recent years, dynamic induction control has shown great potential in reducing wake-to-turbine interaction by increasing the mixing in the wake. With these wake mixing methods the thrust force will vary in time. If applied to a FLOW turbine, it will cause the platform to move. One such approach is the Helix, where each of the blades is individually pitched in a sinusoidal manner. The pitch of each of the blades is out of phase resulting in a non-uniform loading of the turbine. As a result, the Helix applies a varying tilt and yaw moment on the floating turbine. When the floating turbine is subjected to these moments it will start to pitch, roll and yaw. The type of motion is primarily dependent on the type of floating foundation (Berg *et al.,* 2022)

Results of the Helix method have shown that the wind speed at a distance of 5 rotor diameters downstream can be increased by up to 10 % compared to a fixed foundation turbine (Berg *et al.,* 2022)

Evidence gaps

It has been noted that there were very limited studies on the impacts on water flow resulting from offshore wind farms, and in particular there were no studies describing differences between fixed and floating foundations.

Future offshore wind installations are planned to be far more extensive, however, the implications of associated atmospheric changes for the future ocean dynamics are still unclear. The question on how and to what degree the emergent large-scale structural changes in atmosphere and ocean under the premisses of large offshore wind farms, might affect marine ecosystem productivity remains yet unanswered (Daewel., *et al*. 2022).

Wave exposure changes

Anthropogenic sources of wave exposure changes include activities that can directly influence wave action, or that may locally affect the incidence of winds, e.g., a dense network of wind turbines may have the potential to influence wave exposure, depending upon their location relative to the coastline (NatureScot, 2023).

The physical presence of a wind turbine could lead to diffraction or funnelling of waves and currents between the turbines, reductions in the wave energy reaching the coast and changes in local wave patterns.

The quantitative benchmark used to classify “wave exposure changes” as a relevant pressure in the MarESA methodology is a change in nearshore significant wave height >3% for one year (MarLIN, 2023).

In terms of sensitive receptors, little evidence relates changes in significant wave height to changes in communities, especially on hard substrata. However, habitats that only occur in wave exposed habitats are considered ‘Not sensitive at the benchmark level’. Similarly, species that prefer wave exposed habitats are likely to be ‘Not sensitive at the benchmark level’. However, habitats (biotopes) or species that require sheltered conditions or substrata that depend on sheltered conditions may be sensitive (Tyler-Walters *et al*., 2018).

Wake effect (water)

Offshore wind foundations cause obstruction of water flow from prevailing currents, tides, and wave action. Accelerated water movement around a structure creates turbulence and diffraction or funnelling of waves and currents between the turbines as water passes the structure. This is known as the wake effect. Some species may seek refuge from currents in wake areas or benefit from decreased visibility due to increased suspended sediment within wakes, whereas others take advantage of the concentration of prey at turbulent areas (Lieber *et al.* 2019; English *et al.* 2017). Due to changes in water movement patterns, wake effects may affect demersal (i.e., bottom-dwelling) fishes and invertebrates by altering recruitment of larval life stages that settle out of the water column to benthic substrates. Alteration of water movement patterns may also change the availability of food sources for demersal fishes and invertebrates. Suspended sediment concentration and sedimentation can affect not only the availability of planktonic food sources, but also the availability of oxygen and waste removal (Zettler *et al.* 2006, Schröder *et al.* 2006, Wilding 2006, and Maar *et al.* 2009). In areas with tidal currents, turbulence from wake effects has been observed to taper off within a few hundred meters downstream from wind turbine foundations (English *et al*. 2017). At this scale, turbine foundations can be strategically spaced to minimize cumulative effects beyond the site.

The magnitude of wake effects is proportional to the size of the offshore wind turbine foundation. Therefore, wake effects vary across the different foundation types due to differences in diameter of foundation structures and the volume of impervious structure in the water column and at the seafloor (Horwath *et al*., 2020).

Monopile fixed foundations (typically 10 m diameter) have been observed to cause wake effects as far as approximately 200 m down-current (English *et al*. 2017). Suction bucket and gravity fixed foundations have a wider diameter at the sea floor (25 to 30 m); and would likely result in a larger wake effect at depth, but they typically taper toward the surface, where currents are often stronger, so the cumulative wake effect may be similar to monopiles. Wake effects of tripod, tripile, and jack-up fixed foundations are estimated to be smaller because each individual leg that has a smaller diameter compared to some monopile diameters. However, the structures have multiple legs. Because jacket foundations have a more open structure and may displace a smaller volume of the water column compared to monopiles, overall wake effects of jacket foundation types are expected to be weaker than monopile foundations. They may have more, smaller-scale turbulent wakes that attenuate more quickly due to the lattice structure design (Horwath *et al*., 2020).

Floating foundations may have similar wake effects to monopile foundations in surface water layers. Of the floating foundation types, spar buoys have the largest floating structures and would be expected to cause relatively larger wake effects in surface water layers than would semi-submersibles or TLPs with smaller floating structures, but multiple hulls; thus, overall, the wake effect in surface water layers may be similar for the various floating foundation types. In the water column between the platform of a floating foundation and the seabed, the mooring lines only present a small impediment to flow and would only create minuscule wake effects. At the seabed, large deadweight anchors may have horizontal dimensions approaching those of a large monopile (10 m) but have limited height above the seabed and smaller wake effects than monopiles. Embedded anchors for floating foundations (e.g., driven piles, drag embedment anchors, suction-embedded anchors) have smaller profiles above the seabed, compared to deadweight anchors, and would have even smaller wake effects. Furthermore, floating foundations are used in very deep waters, where currents are typically weak near the seabed; thus, wake effects near the bottom would be expected to be minimal for a FLOW turbine (Horwath *et al*., 2020).

Risk-profiling

For fixed foundation offshore wind turbines, wave exposure changes are risk-profiled as "**Low**" during operation and maintenance, as wave exposure changes are possible as a result of physical presence of structures. Wave exposure changes are considered to be not relevant to construction and decommissioning activities for fixed foundation wind turbines.

Wave exposure changes are likely to be less relevant for FLOW, as they are generally located in deeper water further away from the coast, meaning that nearshore significant wave height is less likely to be impacted by the presence of the turbine structures. In the absence of evidence to suggest otherwise, the risk ranking for FLOW should remain the same as fixed foundation i.e., ranked "**Low**" during operation and maintenance and not applicable to construction and decommissioning activities.

Mitigation measures

As the impacts associated with wave exposure changes relate closely to water flow (tidal current) changes, no specific mitigation measures have been identified for wave exposure changes. See water flow (tidal current) changes for mitigation measures relevant to wave exposure changes.

Evidence gaps

Available literature on the topic of wave exposure tends to be grouped with water flow (tidal current) changes to describe changes in hydrogeology/ ocean dynamics in a more general sense, as opposed to specifically describing impacts on wave exposure or nearshore significant wave height. For this reason, this section has focussed on wake effects in water i.e., funnelling of waves and currents around turbine structures. The impacts of FLOW on nearshore significant wave height is an evidence gap.

Noise and vibration

It has become increasingly evident that noise from human activities can potentially impact marine species (e.g., OSPAR, 2009; Richardson, *et al*., 1995; Tougaard, 2016; Southall *et al.,* 2007, 2019, 2021; National Marine Fisheries Service (NMFS), 2018). Sound is important for marine mammals for navigation, communication, and prey detection. Therefore, the introduction of anthropogenic sound could impact/disturb marine mammals.

The following sections discuss those pressures related to noise and vibration, including:

- underwater noise changes
- above water noise
- vibration

Underwater noise changes

This section addresses the impacts of underwater noise associated with wind farms. Offshore wind farms can create noise that has a potential impact on sensitive receptors. This pressure is relevant to mobile species, in particular, fish, marine reptiles, and mammals that respond to sound and/or use sound for echolocation, communication or hunting. MarESA determined that underwater noise changes are only relevant to mobile species and thus this pressure is considered to be 'not relevant' to benthic species and habitats (Tyler-Walters *et al.,* 2018). The evidence on the effects of underwater noise on marine benthic species is limited, however, it is of note that research has demonstrated that anthropogenic sources of sound in coastal and marginal shelf seas may alter infaunal invertebrate activity. This may, in turn, affect geochemical cycling of nutrients (Solan *et al*., 2016), and recent studies have shown negative behavioural responses by the commercially important European lobster *Homarus gammarus* (Leiva *et al*., 2021; Natural England, 2022c).

Both physical and behavioural effects of underwater noise on marine wildlife have been noted (Nedwell and Howell, 2004). The following sections assess the potential impacts of underwater noise changes on those receptors identified to be most sensitive.

Marine mammals

Possible effects on marine mammals can be divided into noise-induced hearing impairment, behavioural disturbance (including fleeing, startling, or hiding), masking, or other injuries such as tissue damage and, in extreme cases, death if the animal is very close to pile-driving activities (OSPAR, 2008).

PTS and TTS thresholds

The perception of underwater sound depends on the hearing sensitivity of the receiving animal in the frequency bands of the sound. For marine mammals it is generally accepted that the auditory system is the most sensitive organ to acoustic injury, meaning that injury to the auditory system can occur at lower sound levels than injuries to other tissues (Tougaard, 2016; Southall *et al*., 2007, 2019; NMFS, 2018). Noise-induced hearing impairment includes permanent threshold shift (PTS) and temporary threshold shift (TTS). PTS is a permanent change in hearing threshold from which marine mammals do not recover, whilst TTS is a temporary change in hearing threshold that mammals recover from over time depending on the severity (the larger the initial TTS the longer the recovery period). Marine mammals will recover from small amounts of TTS within minutes, whereas it could take hours to days to recover from severe TTS (Tougaard, 2016).

Numerous studies have been conducted to estimate the sound levels required to cause auditory injury to marine mammals (e.g., Tougaard, 2016; Finneran, 2013, 2015; Kastelein *et al*., 2013; Lucke *et al.,* 2009; Southall *et al*., 2007, 2019; NMFS, 2018). Various thresholds for PTS and TTS have been proposed using different sound metrics (e.g., zero-to-peak Sound Pressure Level (SPL), peak-to-peak SPL, unweighted and weighted single-pulse Sound Exposure Level (SEL) and cumulative SEL).

Southall *et al*. (2019) established thresholds for different marine mammal hearing groups. The hearing groups are low frequency (LF) cetaceans, high frequency (HF) cetaceans, very high frequency (VHF) cetaceans, and phocid pinnipeds. Animals that have air-filled organs are particularly sensitive to loud noises and large pressure waves due to the amplification of sounds by these organs. For example, pinnipeds have middle ears, like humans, that are filled with air between tympanic membranes and contain middle ear ossicles. Table 4-1 shows marine mammal species categorised according to hearing groups using the cumulative SEL thresholds proposed by Southall *et al*. (2019).

Table 4-1. Marine mammal PTS and TTS thresholds (Southall *et al*., 2019)

Hearing group	Relevant species	Cumulative SEL Thresholds (dB re 1 µPa2s)	
		PTS	TTS
LF cetaceans	Minke whale	183	168
HF cetaceans	White-beaked dolphin, White-sided dolphin, Common dolphin, Killer whale, Pilot whale	185	170
VHF cetaceans	Harbour porpoise	155	140
Phocid pinnipeds	Harbour seals, Grey seals	185	170

Hearing sensitivity in animals varies with frequency. The thresholds shown in Table 4-1 are frequency-weighted according to the generalised auditory weighting functions shown in Figure 4-3 (Southall *et al.,* 2019). The hearing sensitivity curve (audiogram) usually follows a U-shaped curve (where there is a central frequency band of optimal hearing sensitivity and reduced hearing sensitivity at higher and lower frequencies). The hearing sensitivity frequency range differs between species, meaning that different species will perceive underwater sound differently, depending on the frequency content of the sound. Auditory frequency weighting functions for different functional hearing groups can be applied to reflect an animal's ability to hear a sound and to de-emphasize frequencies animals do not hear well relative to the frequency band of best sensitivity (Burns *et al.,* 2022).

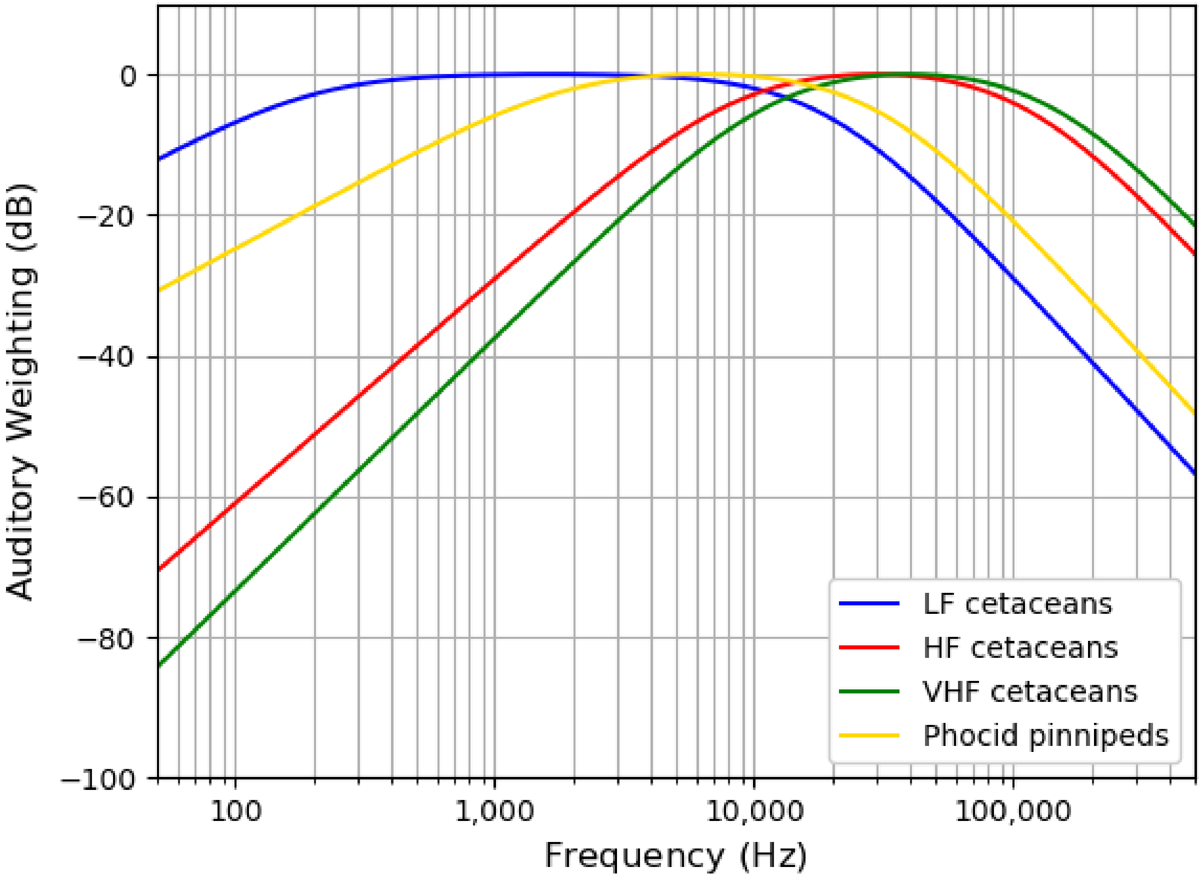


Figure 4-3. Auditory weighting functions for different marine mammal hearing groups (LF/HF/VHF ceteceans, Phocid pinnipeds)

Behavioural disturbance thresholds

Sound at lower levels than those required to induce PTS or TTS to marine mammals can still have an adverse impact since it may alter their normal behaviour i.e., cause behavioural disturbance. Marine mammals can exhibit varying behavioural responses to underwater sound depending on the level and duration of the sound. The most immediate effects are flight reactions which can potentially lead to mortality e.g., due to mammals beaching in coastal waters (D'Amico *et al*., 2009; Balcomb and Claridge, 2001) or calves becoming separated from their mothers.

At lower sound levels, less severe behavioural effects may include changes in swimming behaviour and vocalisation (van Beest *et al*., 2018; Robertson *et al.,* 2013). Any long-term changes in normal behaviour can have implications for the long-term survival and reproductive success of individuals and in extreme cases may have consequences at a population level.

Southall *et al*. (2007) concluded that thresholds for behavioural disturbance were difficult to conclusively define since behavioural responses to sound are highly variable and context specific. Southall *et al*. (2007) therefore recommended assessing whether sound from a specific activity could cause disturbance by comparing the circumstances of the situation with empirical studies reporting similar circumstances.

Fish

Injury thresholds

Popper *et al.* (2014) have defined criteria for injury to fish based on a review of publications related to impacts on fish, fish eggs, and larvae from various high-energy sources. Popper *et al.* (2014) is the most comprehensive review available for potential impacts on fish species. The hearing capability of fish largely depends on the presence or absence of a swim bladder. Fishes that have swim bladders are more sensitive to the impacts of underwater noise as they use these air-filled organs for buoyancy control and some species' swim bladders are connected to their auditory system. Popper *et al*. (2014) derived different injury thresholds for:

- fishes with no swim bladder or other gas chamber
- fishes with swim bladders in which hearing involves a swim bladder or other gas volume
- fishes with swim bladders in which hearing does not involve the swim bladder or other gas volume
- fish eggs and larvae

The thresholds proposed by Popper *et al.* (2014) for mortality and potential mortal injury to fish species from seismic surveys are shown in Table 4-2.

Table 4-2. Thresholds for potential injury to fish

Fish group	Injury thresholds	
	Zero-to-peak SPL (dBre1µPa)	Cumulative SEL (dBre 1µPa2s)
Fishes with no swim bladder	213	219
Fishes with swim bladder involved in hearing	207	207
Fishes with swim bladder not involved in hearing	207	210
Fish eggs and larvae	207	210

Behavioural disturbance thresholds

Documented behavioural effects of sound on fish behaviour are variable, ranging from no discernible effect (Wardle *et al.,* 2001) to startle reactions followed by immediate resumption of normal behaviour (Wardle *et al.,* 2001; Hassel *et al.,* 2004). However, there are no well-established thresholds for assessing behavioural disturbance to fish. Popper *et al*. (2014) concluded that there lacked sufficient evidence to recommend specific thresholds that correspond to behavioural disturbance for fish.

Marine invertebrates

Marine invertebrates have been considered less susceptible than mammals and fish to loud noise and vibration because they generally do not possess air-filled spaces like swim bladders or middle ears. Nevertheless, noise at the levels associated with pile-driving has been reported to cause short-term behavioural responses in marine invertebrates within a distance of approximately 10 m of the disturbance (McCauley 1994); bivalves, a type of mollusc, withdraw their air flow tubes or siphons, polychaetes, a type of worm, retract their appendages and also withdraw rapidly to the bottom of their burrows. Additionally, physiological damage has also been observed to be indirectly caused by underwater noise, such as DNA damage in blue mussels (*Mytilus edulis*) (Wale *et al*. 2016) and protein damage in Mediterranean common cuttlefish (*Sepia officinalis*) (Solé *et al.* 2016; Horwath *et al*., 2020).

Impacts during construction

Increasing development in the marine environment is leading to the discovery of a greater number of undetonated remnants of war, known as unexploded ordnance (UXO). In preparation for offshore construction activities, any UXO in the area are required to be cleared. Clearance of UXO is commonly undertaken by high order detonation, which leads to loud blasts and disturbs marine mammals. The impacts of UXO clearance on marine mammals is universal and has already been highly researched. There is the potential that the scale of UXO clearance required for a development may present a difference between fixed foundation and FLOW. However, it is currently not clear from FLOW developments what area is required to be cleared of UXO and therefore the impacts of UXO clearance are not discussed further in this report.

Most avoidance-causing effects to fishes, marine mammals, and potentially sea turtles occur during foundation installation at the construction stage, due to increased noise and vibration from installation activities, such as pile driving (Anderson 2011; Dähne *et al*. 2013). Pile driving creates underwater noise and pressure waves at levels observed to cause avoidance behaviour in marine mammals (Nedwell *et al*. 2003; Richardson *et al*.1995), and that also may potentially cause mortality and tissue damage in fish (Popper and Hastings 2009).

Pile driving noise (for 4 to 5 m diameter piles) can be as high as of 260 to 270 dB re1µPa at source (Nedwell *et al*., 2003) at a range of 20 Hz to > 20 kHz, with most energy around 100 to 200 Hz (Nedwell and Howell, 2004; Madsen *et al.,* 2006). However, factors such as pile diameter, water depth, geology and seabed topography can all influence noise generation and propagation, so values are likely to vary from site to site (OSPAR, 2008).

Noise levels produced by hammers used for installation of fixed foundations are sufficient to cause mortality of marine life, such as marine mammals and fish with swim bladders and their larva (Bailey *et al.* 2010; Richardson *et al.* 1995; Popper *et al.* 2014). Such effects typically occur at close range (i.e., 3 m) from the pile or less. Further away from pile driving, internal injuries can occur to marine life that vary depending on the sensitivity of species (Finneran and Jenkins 2012). At greater distances, pressure waves produced by pile driving are reduced to lower levels, with less potential to damage the hearing. The extent that pressure waves impact a given species depends on noise levels, duration, and the hearing sensitivity of that species (Popper *et al.* 2014; Horwath *et al*., 2020).

Non-lethal and non-injury causing noise levels and pressure waves can elicit avoidance reactions from marine animals, such as startling, hiding, or fleeing. There is evidence for behavioural avoidance in harbour porpoises during pile driving (Carstensen *et al*., 2006). These effects do not appear to be permanent because porpoises have also been observed returning to an area after pile driving ceased (Dähne *et al.,* 2013; English *et al.* 2017; Horwath *et al*., 2020).

Pile driving occurs during installation of some monopile, jacket, tri-pile, tripod, and floating foundations. Therefore, acoustic effects are anticipated to be relatively similar across these foundation types, though the size of piles used for floating foundations is often much smaller than monopile and effects would be also less. Other installation methods or activities, like vibratory pile driving, reverse circulation drilling for some monopiles, or dredging for site preparation of gravity foundations, also emit noise that could cause avoidance, although those activities would likely cause lower noise levels than pile driving. Fewer noise-emitting activities occur during installation of suction bucket foundations (for fixed foundation designs) and floating foundations that use suction caissons, drag, dead-weight, or embedded anchors (Horwath *et al*., 2020).

Due to a high level of pre-fabrication, the underwater noise during FLOW installation is limited to towing and anchoring activities. From the noise perspective the anchorage is of special importance. Noise emissions of the anchoring process depend on the type of mooring such as drag or suction anchors, ballasted weights or small drilled or impact driven piles. Drilled or driven piles are comparable to those of solid foundations in terms of noise emission (Walia, 2018).

Floating foundation anchors can also be installed by impact pile driving, with a smaller anticipated impact associated with smaller piles (compared to fixed foundation wind turbines). Although piling is still required for the helical pile anchor type, installation is considered to be quieter than that for driven piles (Harris, 2019). Other installation methods or activities, such as dredging for site preparation of gravity foundations, vibratory pile driving, and reverse-circulation drilling, also produce noise. However, those activities would create lower noise levels that are not as impactful to organisms because of the nature of the sound wave, which is steady and continuous rather than impulsive like impact pile driving. Overall, the least noise-emitting activities occur during installation of suction bucket fixed foundations and floating foundations that use suction caissons, drag, dead-weight, or embedded anchors (Horwath *et al*., 2020).

Environmental assessments generally conclude that mortality of benthic invertebrates caused by noise or vibration during construction occurs in areas that will otherwise be impacted with temporary disturbance to the seabed. For instance, in areas where benthic organisms are vulnerable to noise from foundation installation, they are also likely to be impacted by the physical installation (SEER, 2022).

Impacts during operation and maintenance

The majority of noise in the marine environment due to the operational stage of an offshore wind farm is related to mechanical vibration in the wind turbine drive train, i.e., the gearbox and the generator. Operational noise produced by wind turbine generators sitting atop the foundations may radiate through the foundation and into the water column and, in the case of fixed-foundation turbines, into the seafloor. Effects on marine organisms as a result of this (e.g., behavioural changes) would be similar across fixed foundation types (Horwath *et al*., 2020). Unlike fixed foundations, operational noise associated with floating foundations would not be likely to affect benthic species as the noise would not radiate into the seafloor and would result in a smaller spatial scale of effects for non-benthic species (Horwath *et al*., 2020).

Turbines with monopile fixed foundation designs produce the highest sound pressure level of the foundation types at lower frequencies (<200 Hz), with levels of 149 dB re1µPa within 5 m of the foundation at 560 Hz. The jacket fixed-foundation type produced the highest sound pressure level at high frequencies (>500 Hz) with 177 dB re1µPa at 700 Hz and 191 dB re1µPa at 925 Hz within 5 m of the jacket. These high sound pressure levels at high frequency produced by the jacket are associated with structural resonances for which the high sound pressure level is strongly localised to volumes very close to the jacket and dissipate rapidly moving away from the foundation.

During operational phases, behavioural responses by marine species to operational wind turbine noise appears to be minimal; modelled scenarios presented in Marmo *et al.* (2013) predicted that only a small proportion (<10%) of minke whales (*Balaenoptera acutorostrata*) and harbour porpoises (*Phocoena phocoena*) would exhibit behavioural responses up to around 18 km away from an offshore wind farm, while the majority of animals studied would not show a behavioural response, indicating low potential for displacement.

Monitoring at Horns Rev offshore wind farm in the North Sea has revealed that the operational noise had no detectable effect on harbour porpoise abundance (Tougaard *et al.,* 2006). Furthermore, analysis of noise measurements from two Danish (Middelgrunden and Vindeby) and one Swedish (Bockstigen-Valar) fixed foundation offshore wind farm concluded that operational noise levels are unlikely to harm or mask acoustic communication in harbour seals (*Phoca vitulina*) and harbour porpoises (Tougaard *et al.,* 2009; Farr *et al*., 2021).

A sound source characterisation study has been conducted of the Hywind Scotland FLOW, involving *in situ* acoustic recording over three months (October 2020 to January 2021). Continuous tonal noise, associated with rotating rotor and generator components below 500 Hz, was clearly evident and showed corelation with wind speed (Burns *et al*., 2022). The other key feature of the overall Hywind noise was the presence of frequent broadband transient sounds with a median duration of 1.5 s. These transients were audibly associated with strain and friction in the mooring system and showed a strong positive corelation in occurrence with wave height. Directional analysis of transient noise from three of the Hywind turbines indicated that the mooring noise is predominantly generated in mooring components close to the floating spar-buoy foundation and not from components further down each mooring cable. The total noise level produced by one turbine was found to range from 162.5 to 167.2 dB re1μPa²m². In terms of noise footprint from the entire five-turbine wind farm, modelling has shown that the distance to the averaged background sound pressure level (SPL) (110 dB re1μPa) from the centre of the offshore wind farm (i.e., where the radiating noise decays to approximately the broadband ambient level) at the quietest state (10 knots of wind) was approximately 4 km, and in 25 knots of wind it was 13 km. All daily sound exposure levels recorded during the study were found to lie below the thresholds for temporary or permanent hearing threshold shifts (i.e., hearing loss) from exposure to non-impulsive sounds for each marine mammal functional hearing group (NMFS 2018). This suggests that there is no risk of auditory injury from the operational of the Hywind Scotland FLOW farm. A high-frequency cetacean (porpoise) would need to remain within 50 m of a turbine for 24 hours before there would be a risk of temporary hearing threshold shift (15 knots of wind) (Burns *et al*., 2022).

Another potential source of underwater noise for FLOW farms is twisting/snapping noises produced by the sudden re-tension in a mooring line following a period of slackness, resulting in a ‘pinging’ or ‘snapping’ noise. This may be an issue at some sites depending on the technology type and receptor sensitivity.

A study conducted for Equinor in 2011 on the Hywind DEMO system off the coast of Stavanger, Norway, identified several tonal elements to the sound signature and an additional transient ‘snapping/clicking’ noise, potentially associated with the mooring system (Martin *et al*. 2011). This is the only FLOW farm to date where this phenomenon has been reported. The more recent source characterisation study of the Hywind Scotland FLOW farm revealed a significant amount of mooring noise, however, there was very little evidence of the intense, very sharp, impulsive ‘snap’ sound that had previously been detected at the Hywind Norway site. One of the aims of the project was to understand whether the ‘snapping’ transients, believed to be caused by the prototype mooring system, were still present (Burns *et al*., 2022). As the Hywind Norway site is the only FLOW farm to date where snapping noise has been reported, it is unlikely to present a significant source of underwater noise for FLOW developments. This was the conclusion reached in the environmental impact assessment report for the Pentland FLOW farm in Caithness, Scotland (Xodus Group Ltd / SMRU Consulting., 2022; Highland Wind Limited, 2022; Statoil, 2015).

Vessel use

In addition to the wind turbine structures, vessel activity involved in construction, maintenance, and decommissioning activities is also a major source of underwater noise. Although the majority of this will come from the propeller cavitation, onboard machinery and turbulence around the hull can also result in underwater noise being transmitted. Different parts of the vessel and different vessels emit underwater noise at different frequencies. Generally, lower frequency with increasing vessel size. Low frequency sounds tend to travel farther and have the potential of impacting larger areas than higher frequency sounds (OSPAR, 2009; Gill and Bartlett, 2010; McKenna *et al.,* 2012; McKenna *et al*., 2013). Small sea going vessels typically produce broadband noise at source levels of 160-180 dB re 1μPa-m (average). During the construction phase, there will be increased vessel activity, and less-so during the operation and maintenance phase. During the decommissioning stage of an offshore wind farm, vessel noise is thought to be the main source of persistent noise, although underwater noise may also come from any cutting and lifting operations.

Risk-profiling

For fixed foundation turbines, underwater noise has been risk profiled as "**Medium-High**" for construction and decommissioning stages, but "**Low**" for operation and maintenance, as underwater noise from turbines and maintenance vessels is considered unlikely to be significant.

The research collated in this report suggests that for floating foundations, underwater noise is thought to be less of a risk and less impactful. Particularly as there is not always pile-driving involved in installation of the anchors, and when there is, the piles are likely to be much smaller than those used for a fixed foundation monopile. There is also less vessel activity involved in FLOW. Despite this, it is not yet known how frequently piling activities will take place as part of FLOW farm construction. Therefore, in line with precautionary principle, underwater noise should remain unchanged at "**Medium-High**" risk for all development lifecycle stages (construction, operation, and maintenance) at this stage, with the caveat that FLOW projects without piling activities could potentially be lowered.

Mitigation measures

Underwater noise impacts can be mitigated by employing standard noise mitigation measures implemented in the UK (which are generally focused on marine mammals) (i.e., soft start piling (for both fixed foundations and FLOW driven anchor piles), ADDs, and Marine Mammal Observers (MMOs)) (Xoubanova and Lawrence., 2022). MMOs can call for cessation of activities if a marine mammal is spotted during installation when pile driving (for both fixed foundations and FLOW driven anchor piles).

In addition, modified construction methods can be used and schedule restrictions to time-sensitive windows if the area is within a breeding range, avoiding siting within migration corridors and coastal pinniped resting areas, and using vessel speed restrictions (English *et al.* 2017; Horwath *et al*., 2020). In relation to fish, The Development Consent Order for Rampion includes seasonal restrictions on piling in order to avoid sensitive periods for Black Sea bream and herring (The Rampion Offshore Wind Farm Order, 2014).

Furthermore, technology types which are quieter to install could be selected. Fewer noise-emitting activities occur during installation of floating foundations that use suction caissons, drag, dead-weight, or embedded anchors (Horwath *et al*., 2020).

There are several potential mitigation measures in respect to the reduction of sound sources to minimise noise levels. These have been proven to mitigate the noise produced during pile installation of fixed foundation turbines, however, there is no evidence of their use in FLOW to date. As the installation process for driven pile anchors used in FLOW follows a similar procedure to installing monopiles (although on a smaller scale), it is likely that some of these technologies could be applicable to FLOW in future, with varying degrees of suitability (Federal Agency for Nature Conservation., 2013; Dähne *et al*., 2017). Merchant and Robinson (2020) and Verfuss *et al* (2019) provide comprehensive reviews of the current state of knowledge on the feasibility of different noise abatement options. Examples include:

- **bubble curtains** – A bubble curtain is formed around a pile by freely rising bubbles created by compressed air injected into the water through a ring of perforated pipes encircling the pile (Federal Agency for Nature Conservation, 2013; Dähne *et al*., 2017). Bubble curtains are demonstrated to be effective in waters up to 45 m, however, they are less effective as water depth increased due to dispersion of bubbles. This makes bubble curtains less feasible for FLOW applications (Xoubanova and Lawrence., 2022).
- **casing-based systems (e.g., isolation casing and cofferdams)** – A simple isolation casing consists of a steel pipe around the pile reflecting a part of the noise back inside. More complex systems have additional layers containing air (foam, composites, or bubbles). Similar to isolation casings, cofferdams are rigid steel tubes surrounding the pile from seabed to surface. In contrast to isolation casings, the interspace between pile and cofferdam is completely dewatered. Hence pile driving takes place in air and not in water thus decoupling the propagation of sound from the body of water (Federal Agency for Nature Conservation, 2013; D¨ahne *et al*., 2017). Casing-based systems are also demonstrated up to 45 m and are constrained by the availability of large enough systems for the water depth. As with bubble curtains, this also means they may not be suitable for application to FLOW (Xoubanova and Lawrence., 2022).
- **encapsulated resonator systems (e.g., hydro sound dampers)** – Hydro sound dampers are elastic balloons and robust Polyethylene foam elements fixed to nets or frames placed around the pile. The underlying principle is identical to that of a bubble curtain with the exception that the frequencies at which the maximum noise reduction is provided are adjustable by variations in the balloon size (Federal Agency for Nature Conservation, 2013). Hydro sound dampers are in principle unlimited by water depth and thus may be the most suitable mitigation measure in respect the reduction of underwater noise sources from FLOW. Adverse weather conditions (high current speeds and wave heights) may present challenges at certain times and locations (Merchant and Robinson., 2020).

Based on a review of available evidence for the use of mitigation measures in respect to the reduction of sound sources to minimise noise levels for offshore wind applications, it is clear that encapsulated resonator systems (e.g., Hydro sound dampers) may be the most suitable technology to reduce underwater noise from FLOW, due to unlimited water depth for application.

Evidence gaps

Whilst there is significant data on hearing in pinnipeds and cetaceans, there are significant data gaps in our understanding of how underwater noise affects fish and invertebrates. Existing tools to help assessments need improving, as there are no well-established thresholds for assessing behavioural disturbance to fish. Popper *et al.* (2014) concluded that there lacked sufficient evidence to recommend specific thresholds that correspond to behavioural disturbance for fish.

For this reason, the following next steps in research are recommended to address this evidence gap (Xoubanova and Lawrence., 2022):

- development of updated noise exposure criteria for fish to take account of the particle motion component of noise
- development of audiograms for key species using behavioural analysis
- strategic research to investigate the scale of the effect of noise exposure on fish and invertebrates that may result in population level impact on economic impact to fisheries
- development of detailed guidance to help the assessment of behavioural effects on fish
- provision of guidance on the approach to be taken for assessment of impacts on invertebrates in the absence of standard noise exposure criteria for this group;
- collection of improved data and information on the behavioural effect of noise on fish and invertebrates
- testing of noise abatement methods at wind farms during construction and their effectiveness in mitigating impacts on fish (standard noise mitigation measures implemented in the UK (as described above) are generally focused on marine mammals, rather than specifically designed to minimise impacts on fish)

In addition, in comparison to pinnipeds and cetaceans, far less is known about possible impacts on hearing in turtles and therefore similar next steps in research are required on this species group also (Bennun *et al.,* 2021).

As well as evidence gaps about the impacts of underwater noise on specific sensitive receptors, there is also a substantial evidence gap on the use and success of underwater noise mitigation measures for FLOW, as opposed to fixed foundation offshore wind. Most technologies have been tried and tested for fixed foundation offshore wind farms, but not for FLOW, and thus more research is required to determine if similar mitigation measures are applicable to the different offshore wind farm designs.

Above water noise

Although underwater noise tends to be the main focus in terms of acoustic impacts of offshore wind, above water noise also warrants consideration. This section addresses the impacts of above water noise associated with wind farms. Birds are the most sensitive receptor to above water noise.

Operational offshore wind turbines have relatively high noise emissions (over 110 decibels). This could be a consideration if sensitive bird species actively avoid noise sources. There is some evidence that Manx Shearwaters are attracted to generators on St Kilda by sound. It has also been noted that the potential attraction of shearwaters to low-frequency noise, and implications for attraction to wind turbines and associated structures and vessels, requires further consideration (Deakin *et al.,* 2022).

Birds are well-known for their acoustic communication and their hearing abilities have been intensively investigated for decades. Examining bird hearing is important given the growing realisation that anthropogenic noise is encroaching on bird habitats and impacting species in myriad of ways (Mooney *et al.,* 2019).

Above water noise can arise from many activities in the marine environment. The use of machinery, vessels, explosives, and people will result in an increase in above water noise. Some examples of sources of airborne noise are drilling rigs and support vessels used to service aquaculture facilities, vessels used in coastal developments and flood defences, military activities, aggregate extraction, cabling operations, pilling etc. However, the magnitude of pressure would depend on the scale, intensity, and duration of the activity.

During the operational phase of a wind farm, above water noise from wind turbines comes in two forms. The first is aerodynamic noise from the blades slicing through the air leading to the characteristic “swish-swish” noise and the second is mechanical noise associated with machinery housed in the nacelle of the turbine. As described in the underwater noise section, most noise from the operational phase of wind turbines is related to mechanical vibration in the drive train. This contributes to underwater noise when it travels through the turbine foundation and potentially into the seabed (in the case of fixed foundation turbines), however, it also propagates through the air and creates above water noise.

For example, the dominant operational noise from the Hywind turbine system has been found to be distinct tonal sounds (i.e., relatively narrowband, continuous sounds typically associated with running machinery). Two dominant tones were evident below 100 Hz, and a further set of tones was evident between approximately 350 and 460 Hz. These tones were moderately stable in frequency, but, at times, displayed significant instability that is likely to reflect the variability in the revolutions per minute of the rotating turbine as the wind speed fluctuates (Burns *et al*., 2022).

Noise made by turbines may also be an important stressor during all phases of wind energy generation (surveying, construction, operation and maintenance and decommissioning) (Mooney *et al.,* 2020). Studies concluded that noise produced by floating structures will mainly be lower-frequency sounds with dominant frequencies of ~1 kHz or less (Madsen *et al.,* 2006; Tougaard *et al.,* 2020). Noise from fixed foundation turbines, however, is highly variable depending on wind speed, the size of the turbine, the type of platform used and other variables related to the ambient environment (Marmo *et al*., 2013; Mooney *et al.,*2020; Tougaard *et al.,* 2020). The distance over which noise from fixed foundation wind farms extends is only a few kilometers in low ambient noise conditions (Tougaard *et al.,* 2020), however, it is largely unknown how noise levels differ for floating versus fixed foundation turbines, though it is likely to be highly dependent on the type of mooring used, and the size and number of turbines, and local weather and oceanographic conditions among other factors (Maxwell *et al*., 2022).

Above water noise produced during decommissioning of offshore wind farms is considered to be similar to that of construction, although levels will be lower overall as it is assumed that piling (as used during installation of fixed foundations or piled anchors for FLOW) will not be used. Above water noise may also result from cutting and lifting operations (although this would mostly lead to underwater noise).

Risk-profiling

For fixed foundation turbines, above water noise has been risk profiled as “**Medium-High**” for construction and decommissioning stages, but “**Low**” for operation and maintenance as above water noise from turbines and maintenance vessels is unlikely to be significant.

Above water noise levels associated with the construction of FLOW are likely to be markedly less than with construction of pile-driven fixed foundation turbines, as there are not always piling activities involved (and even if there are, driven anchor piles are smaller than fixed foundation piles), as well as the fact that there is less offshore activity and vessel movement involved in construction and decommissioning. Therefore, above water noise during construction and decommissioning should be risk-profiled as “**Low**” for FLOW.

However, above water noise levels are expected to be similar during operation and maintenance phases, although little information is available on this (Maxwell *et al*., 2022). During operation and maintenance, above water noise results from turbines and maintenance vessels and therefore will likely be similar between fixed foundation and FLOW, thus should remain ranked “**Low**”.

Mitigation measures

There are two primary approaches to reducing potential noise impacts: reducing the noise levels at the source (e.g., operating equipment at the lowest practicable noise level) and spatially and/or temporally separating the noise-producing activity from the sensitive species. For example, for migratory species, impacts can be reduced by limiting construction activities to seasons when fewer animals are present or when animals are not engaging in biologically important activities (e.g., foraging, breeding) (Maxwell *et al*., 2022).

Evidence gaps

A data gap has been identified in that baseline data on above water noise levels in offshore wind farm areas is needed, particularly studies that estimate noise at various distances from turbines to determine baseline levels prior to construction, installation, and operation of FLOW turbines, with control sites for future monitoring. These data can be used in conjunction with animal distribution to identify priority areas for monitoring and mitigation during construction and operation, particularly to determine when construction and maintenance can best occur. It is critical to understand sound propagation at varying distances from lease sites to understand how sound moves in certain areas, and across different frequencies, and this will be different for floating than for static, fixed foundation turbines, and will vary by location and even across seasons due to environmental conditions (Bailey *et al.,* 2014).

In addition, further research quantifying seabird hearing abilities and sensitivity to noise would be beneficial in assessing the impacts of above water noise produced by wind turbines (Mooney *et al.,* 2019).

Vibration

This section relates to the vibrations produced by certain activities, such as dredging (which may be used in seabed preparation during construction of fixed foundation turbines) as the draghead is carried over the seabed or grab is operated, trenching for cable laying, and construction activities involving piling (especially if vibropiling is used; whereby a vibratory hammer is positioned on top of the surface and produces vibration, combined with vertical pressure, to drive the pile into the substrate). As the impacts associated with vibration relate closely to underwater and above water noise, impacts have only been summarised briefly in this section.

The majority of benthic invertebrates (and, hence their communities) have limited or no known response to noise, although vibrations in the water column, at close proximity, may result in an avoidance response (Tyler-Walters *et al.,* 2018). Therefore, receptors considered to be sensitive to vibration are benthic communities.

During operation and maintenance, the majority of vibration in the marine environment due to wind turbines is related to mechanical vibration in the drive train (similar to the main source of above/underwater noise). It should be noted that most vibration transmitted into the water column will radiate as underwater noise, most vibration is transmitted through the ground/seabed. As described above, operational noise produced by wind turbine generators sitting atop the foundations may radiate through the foundation and into the water column and, in the case of fixed foundation turbines, into the seafloor. Effects on marine organisms as a result of this (e.g., behavioural changes) would be similar across fixed foundation types (Horwath *et al*., 2020). Unlike fixed foundations, operational noise associated with floating foundations would not be likely to affect benthic species as the noise would not radiate into the seafloor and would result in a smaller spatial scale of effects for non-benthic species (Horwath *et al*., 2020).

Vibration may occur due to decommissioning of offshore wind farms depending on the methods used to remove turbines and foundations. The impact of vibration does not include vessels for any stage (construction, operation and maintenance, or decommissioning) as it is assumed not to be significant.

Risk-profiling

For fixed foundation turbines, vibration has been risk profiled as “**Low**” for all lifecycle stages. During construction, vibration is possible due to methods of construction e.g., dredging, piling, cable installation. During operation and maintenance, vibration is unlikely to be significant. During decommissioning, vibration is possible depending on decommissioning methods used.

Impacts from vibration are likely to be of less concern for FLOW in comparison to fixed foundation turbines due to smaller scale piling activities (if driven anchor piles are the selected technology type) and less contact with the seabed meaning transmission of vibrations into the seafloor is much less likely. However, the risk rankings should remain the same as for fixed foundation offshore wind i.e., “**Low**” risk across all lifecycle stages to reflect that piling activities are still possible.

Mitigation measures

As the impacts associated with vibration relate closely to underwater and above water noise, no specific mitigation measures have been identified for vibration. See underwater/ above water noise sections for mitigation measures relevant to vibration.

Evidence gaps

As the impacts associated with vibration relate closely to underwater and above water noise, no specific evidence gaps have been identified for vibration. See underwater/ above water noise sections for evidence gaps relevant to vibration.

Electromagnetic changes

Electromagnetic fields (EMF) are generated by devices and cables that carry an electrical current (Haberlin *et al.,* 2022). Sources of offshore wind related EMFs include inter-array cables between turbines and substations, and export cables. Note that cable connections to substations and power grids (export cables) are outwith the scope of this report and will not be assessed further. This section addresses electromagnetic changes caused by the EMFs produced by inter-array cables. Both dynamic cables suspended in the water column and cables surface laid or buried on the seafloor are considered.

Receptors include benthic communities, as well as demersal and pelagic organisms. Species sensitivity depends on the ability of the species to sense the EMF and the degree to which this affects the species (Tyler-Walters *et al.,* 2018).

EMFs from inter-array cables associated with turbines can cause behavioural modification in benthic, demersal, and pelagic species, particularly the ability to detect or respond to natural magnetic signatures, potentially altering fish survival, reproductive success, or migratory patterns. EMFs from natural sources also exist in the marine environment. Some marine animals, such as sharks, salmon, and sea turtles, can detect naturally occurring electric and/or magnetic fields and use those signals to support essential life functions, such as navigating and searching for prey (SEER, 2022c).

Vertical movements occur frequently in both demersal and pelagic species; demersal species (those on or near the seabed) can regularly move in the water column (Nichol and Somerton, 2002; Hobson *et al*., 2007), and pelagic species (those in the water column) often depend on benthic habitats for foraging and reproduction (Overholtz and Friedland, 2002). Therefore, a pelagic species may still encounter the EMF of a buried or surface laid cable if it is placed within an important benthic habitat. Likewise, a demersal species may encounter EMF from a dynamic cable suspended in the water column. For this reason, it is important that EMF studies consider species movement ecology (Fluharty, 2000; Hutchinson *et al.,* 2020b).

While field studies have been conducted on the effects of EMF from cables buried in the seabed (e.g., Hutchison *et al.,* 2018), there is a limited understanding of the EMF impacts of cables suspended in the water column (as would be the configuration for FLOW inter-array cables) (Gill and Desender, 2020; Hutchison *et al*., 2020b). Suspended cables are more vulnerable to wear through hydrodynamic stress (fatiguing pressure and twist) and biofouling, and increased wear can cause technical problems, as well as increase EMF impacts. More work needs to be done to understand attraction or aversion effects of suspended cables, particularly on pelagic species (but also demersal as explained above) (Taormina *et al.,* 2018; Maxwell *et al.,* 2022).

Power cables have been shown to have the potential to emit EMFs in the range of detection of sensitive species. AC power transmission cables are more commonly used for offshore renewable projects; however, DC cables are also currently used and are expected to become more widely used as the siting of projects moves further offshore (Hutchinson *et al*., 2020b; Xoubanova and Lawrence., 2022). It is common practice to block the direct electric field from the external environment by using conductive sheathing. Thus, the EMFs from both AC and DC power cables emitted into the marine environment are the magnetic field and the resultant induced electric field (Normandeau and Gill., 2011).

Normandeau and Gill (2011) used design characteristics of 24 undersea cable projects (assuming 1 m burial depth) to model expected magnetic fields. For eight of the ten AC cables modelled, the intensity of the field was roughly a direct function of the voltage (ranging from 33 to 345 kV) on the cables, although separation between the cables and burial depth also influenced field strength. The predicted magnetic field for these cables was strongest directly over the cables, with an average maximum magnetic field value of 7.85 telsa (μT) and decreased rapidly with vertical and horizontal distance from the cables, as shown in Figure 4-4 (Normandeau and Gill., 2011).

The quantitative benchmark used to classify “electromagnetic changes” as a relevant pressure in the MarESA methodology is a local electric field of 1 volt per meter, or local magnetic field of 10 μT due to anthropogenic means (MarLIN, 2023). As the average maximum magnetic field value was 7.85 μT for AC cables in the above study, it would not be considered a significant pressure in this case.

A study by Love *et al.,* (2016) also found that the strength of EMF from AC subsea cables dissipated quickly with distance from the cables (i.e., approached background levels at about one metre) (Love *et al.,* 2016).

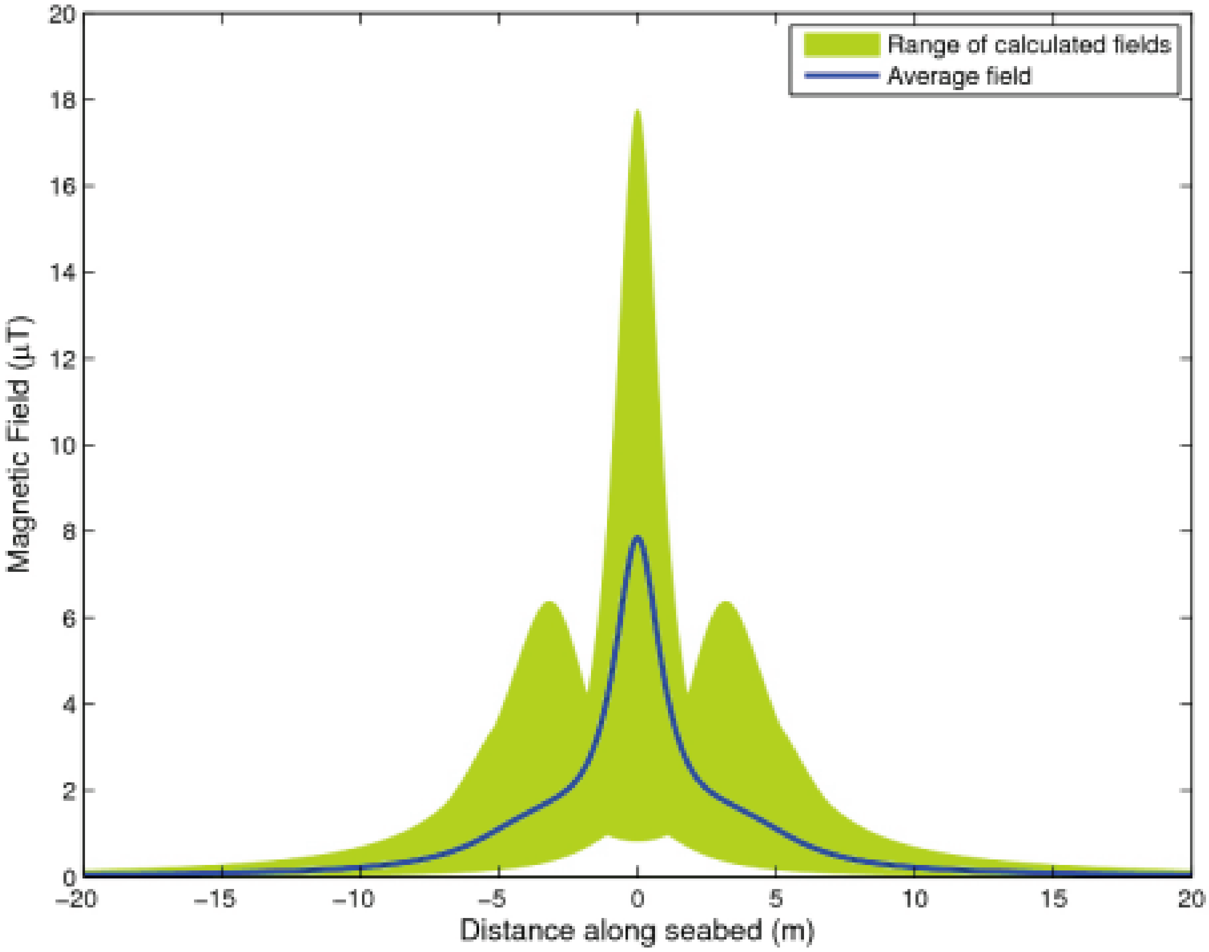


Figure 4-4. Modelled average and range of magnetic field strength at the seabed surface for ten buried AC cables (Normandeau and Gill., 2011)

Magnetic fields resulting from nine DC cable systems were also modelled. Similar to AC cables, the strength of the magnetic field around DC cables was a function of voltage (ranging from 75 to 500 kV) and cable configuration. The average field generated by these cables, without accounting for the influence of the Earth's magnetic field (geomagnetic field), is shown in Figure 4-5. As with AC cables, the field strength is at its maximum directly above the cable, with a maximum average value of 78.27 μT, and declines with both vertical and horizontal distance from the source. Unlike the magnetic field from AC cables, however, the magnetic field from DC cables can influence the intensity of the local geomagnetic field, as well as its inclination and declination, thus the orientation of the cable relative to the geomagnetic field should be accounted for when considering the effects of DC cables (Normandeau and Gill., 2011).

As the average maximum magnetic field value was 78.27 μT for DC cables in the above study, this would be considered a significant pressure according to the MarESA methodology (MarLIN, 2023).

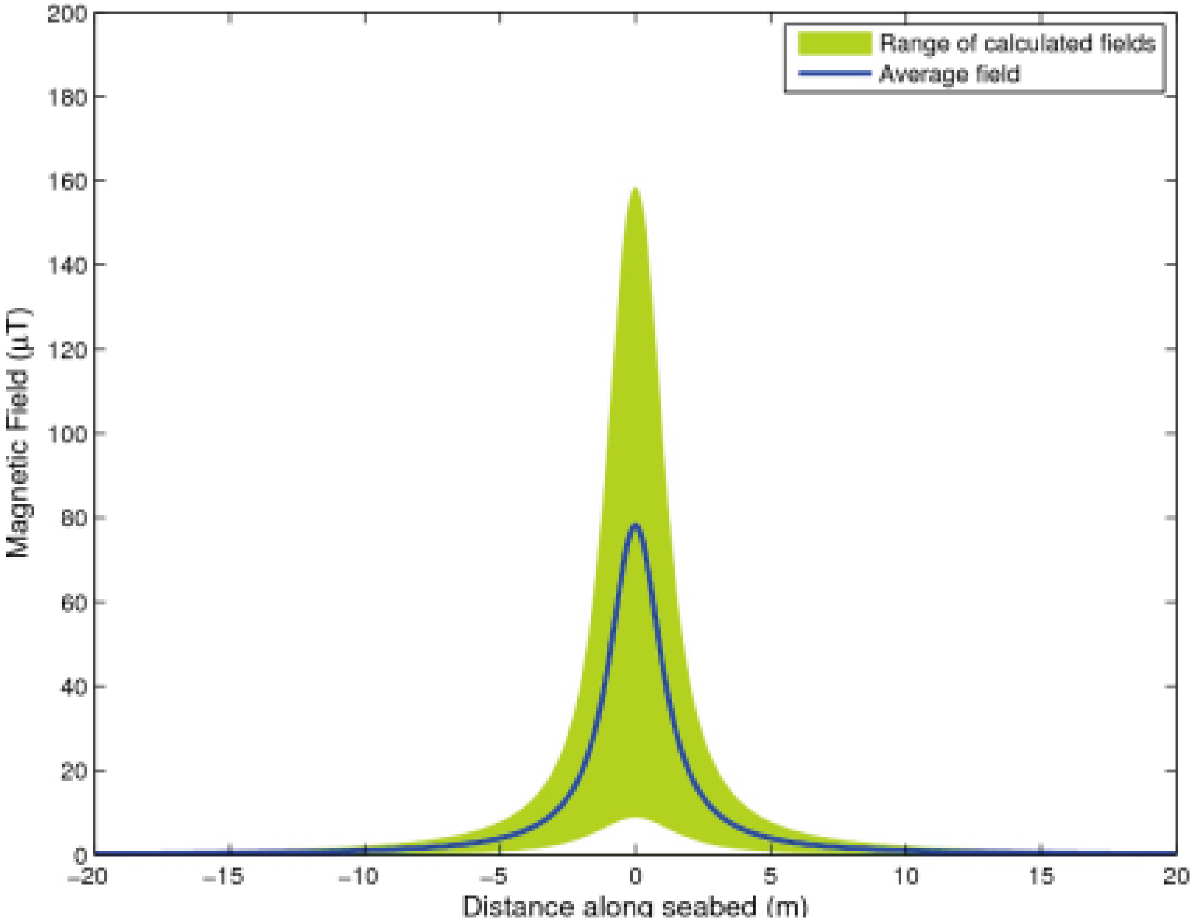


Figure 4-5. Modelled average and range of magnetic field strength at the seabed surface for nine buried DC cables (Normandeau and Gill., 2011)

Magnetic or electric senses have been reported for a wide range of marine animals. The ability to sense either electric or magnetic fields has been identified or theorised for a range of marine wildlife including some fish species, elasmobranchs (i.e., sharks, skates, and rays), cetaceans (i.e., whales and dolphins), some sea turtles, and invertebrates (i.e., some snails, lobsters, and crabs) (SEER, 2022c). The ability to detect electric fields is well documented for elasmobranch fish species. These are generally considered to be the most electro sensitive species group as they possess a highly sensitive electro-sensory system (ampullae of Lorenzini). In addition, species such as lampreys, sturgeons and a few teleost fish also have advanced electro-sensory systems, although most teleosts (the largest group of bony fishes) do not. Few invertebrates have been tested for an electric sense, however, there is evidence of a response to EMFs from various species, including crustaceans such as crabs, shrimp and lobsters (Normandeau and Gill., 2011). The following subsections address the impacts of EMF on different groups of receptors.

Fish and invertebrates

The generation of EMFs is of concern for fish species in close proximity to wind farms (Gill *et al*., 2014). Studies have shown that some fish species are magneto-sensitive and use geomagnetic field information for orientation purposes (Normandeau *et al*., 2011; Peters *et al.,* 2007). EMF effects can alter the ability to detect or respond to natural magnetic signatures, potentially altering fish survival, reproductive success, or migratory patterns (Normandeau *et al*., 2011).

Studies on fish and invertebrate species have demonstrated that EMFs produced by cables and other structures do not present a barrier, although behaviour can be affected. Exposure to the EMF from a buried high voltage direct current (HVDC) cable instigated increased foraging behaviour in a demersal skate species (Hutchison *et al.,* 2020) and magnetic fields in lab experiments were found to affect the behaviour of brown crab and induce stress at levels likely to be emitted from buried cables (Scott *et al*., 2021, 2018). Many of these studies used small numbers of animals with a single cable or structure and uncertainty remains over the effect of a scaled-up development with extensive interconnecting cables, which may be buried, unburied and dynamic (Haberlin *et al.,* 2022). A number of other relevant studies are summarised here.

Formicki *et al.* (2019) have documented early-stage effects of magnetic fields in some fish (gametes, sperm mobility, fertilization rate, embryonic development). Furthermore, Putman *et al.* (2014) show that the EMF environment of early life stages may influence EMF perception in later life stages (Hutchinson *et al*., 2020).

Love *et al* (2016) found no evidence that there were significant differences in fish communities or in invertebrate assemblages between energised and unenergised subsea cables in the Pacific Region.

Cresci *et al* (2019) studied the orientation mechanisms in haddock larvae through observations of haddock larvae swimming in the Norwegian Sea and in a magnetic laboratory. The findings of the research in both settings identified that haddock larvae orientation at sea is guided by a magnetic compass mechanism. A similar study by Cresci *et al* (2020) focused on herring larvae and found no evidence of magnetic compass orientation for this species, indicating that the orientation direction of herring larvae is not magnetic during this early life stage.

Taormina *et al* (2020) studied the potential impact of EMF on the behaviour of recently settled juvenile European lobster and found that juvenile lobsters did not exhibit any change of behaviour when submitted to an artificial magnetic field gradient (maximum intensity of 200 μT) compared to non-exposed lobsters in the ambient magnetic field. In addition, no influence was noted on either the lobsters' ability to find shelter or modified their exploratory behaviour after one week of exposure to anthropogenic magnetic fields (225 ± 5 μT) which remained similar to those observed in control individuals (Taormina *et al*., 2020)

Scott *et al* (2021) investigated the effects of different strength EMF exposure (250 μT, 500 μT, 1000 μT) on the commercially important decapod, edible crab (*Cancer pagurus*). Stress related parameters were measured (L-Lactate, D-Glucose, Total Haemocyte Count) in addition to behavioural and response parameters (shelter preference and time spent resting/roaming) over 24 h periods. Exposure to 250 μT was found to have limited impacts, however exposure to 500 and 1000 μT was found to disrupt the L-Lactate and DGlucose circadian rhythm and alter Total Haemocyte Count. The findings were that crabs showed clear attraction to EMF exposed shelters with significant reduction in time spent roaming. The study recommended the need for *in situ* measurements of EMF from existing cables and suggested that a working limit of a maximum of 250 μT could result in minimal physiological and behavioural changes within this species and should be considered during marine renewable energy devices design and implementation (Scott *et al*., 2021).

In general, sessile species or those with low mobility may not have evolved sensitive electro or magneto receptors and may be unaffected by changes in these fields in terms of navigation and prey location. However, these fields may have some physiological effects and some life stages, e.g. larvae, may be more sensitive than adults. Deleterious effects of super-high and low frequency electromagnetic radiation have been recorded for sea urchins (Shkuratov *et al.,* 1998, Ravera *et al.,* 2006). Ravera *et al*., (2006) found that the threshold for formation of anomalous embryos was about 0.75 ± 0.01mT, which is lower than the pressure benchmark. Other physiological effects in animals exposed to magnetic fields include the induction of heat shock proteins in mussels (Malagoli *et al*., 2004), and altered limb regeneration rates in fiddler crabs (Lee and Weis, 1980; Tyler-Walters *et al.,* 2018).

Nevertheless, the evidence to assess these effects against the MarESA pressure benchmark for electromagnetic changes is very limited and the impact of this pressure cannot be assessed for most benthic species or habitats (Tyler-Walters *et al.,* 2018).

Elasmobranchs

Long-lived, slow reproducing elasmobranch species (sharks, rays, skates etc.) are of particular concern and are generally considered to be the most electro-sensitive species group due to their highly sensitive electro-sensory system (ampullae of Lorenzini) (Normandeau *et al.,* 2011; Hutchison *et al*., 2018; Maxwell *et al*., 2022).

Elasmobranchs naturally detect bioelectric emissions from prey, conspecifics and potential predators and competitors (Gill *et al*., 2005). In addition, it is well-documented that they are known to detect magnetic fields (Normandeau *et al.,* 2011).

As reported by Normandeau *et al*., (2011), the perception of an EMF by an electro- and/or magnetosensitive species is complex and dependent upon several factors such as cable characteristics, electric current, cable configuration, cable orientation relative to geomagnetic field, the swimming direction of the animal, local tidal movements and characteristics of the species life history and developmental stage (Normandeau *et al.,* 2011).

Gill e*t al* (2009) studied whether elasmobranchs responded to controlled EMF with the characteristics and magnitude of EMF associated with offshore wind farm power cables. The study took an experimental research approach where sections of subsea cables were enclosed (mesocosm study) to allow assessment of the responses of elasmobranchs in a semi-natural setting. The research found that the benthic elasmobranchs studied (thornback ray (*Raja clavata)* and small-spotted catshark (*Scyliorhinus canicular)*) can respond to the presence of EMF of the type and intensity associated with subsea cables (a powered AC cable (100A, 7 volts), which emitted a magnetic field of 8 µT and an induced electric field of 2.2 µV/m). However, their response was found not to be predictable and appeared to be species and individual specific. Thornback rays were found to be more likely to move around within the EMF zone, whilst a significantly higher number of catsharks were found in the EMF area of the powered cable, and they were found to move significantly less, which is consistent with feeding behaviour. From this study, however, there was no evidence to suggest any positive or negative effect on elasmobranchs as a result of encountering the EMF (Gill *et al.,* 2009; Xoubanova and Lawrence., 2022).

Further research on lesser spotted catsharks *S. canicula* (i.e., Kimber *et al*., 2011) found that when presented with two artificial EMF, there was a preference for stronger DC fields over weaker ones and a preference for AC rather than DC fields. No preference was demonstrated between an artificial and natural DC electric field, which means these findings suggest that these predators could potentially confuse prey bioelectric fields with artificial electric fields during foraging (Kimber *et al*., 2011). Later studies showed that catsharks were however able to learn that artificial electrical fields were not associated with food, which was memorised for up to three weeks (Kimber *et al.,* 2014).

The biological importance of the behavioural effects recorded in the above studies (Gill *et al*., 2009 and Kimber *et al.,* 2011) is that free-ranging elasmobranchs encountering a single cable will likely respond as if the EMF represents potential food. However, if they do not obtain any prey, then they would be expected to move on and search elsewhere, since they are able to learn if an EMF represents food, but only if the EMF is consistent and predictable (Kimber *et al.,* 2014). The implication in this case, is that there is a low likelihood of significant biological impact associated with a single cable with a constant EMF. However, this interpretation will only hold if the EMF from the single cable is predictable otherwise learning becomes difficult (Kimber *et al.,* 2014; Hutchison *et al.,* 2018).

In the case of an offshore wind farm development, cables may vary spatially along their length (as a consequence of cable properties and burial depth), and at different times due to variations in power generation. In this scenario where the EMF is inconsistent, the elasmobranchs will not be able to learn that there is no prey associated with the cable EMF, resulting in them spending time foraging around cables, but obtaining no food. These outcomes would constitute energetic costs as the animals will expend energy searching with no return of energy intake through consuming prey. There is also the lost opportunity cost of spending time searching and responding to the area where cables are located rather than other more rewarding areas of the seabed (Hutchison *et al.,* 2018).

EMF deterrents have been successfully tested as depredation mitigation devices in fisheries to reduce shark bycatch. Magnetic shark repellents utilise permanent magnets, which exploit the sensitivity of the Ampullae of Lorenzini in sharks and rays. As this organ is not found on bony fish (teleosts), it is selective to sharks and rays. This highlights the potential EMF has to alter shark behaviour in the vicinity of offshore wind developments, however, in some studies results have been mixed or not significant (Mitchell *et al.,*2018; O'Connell *et al.,* 2014).

Risk-profiling

Electromagnetic changes are considered to be "**Not Applicable**" to fixed foundation offshore wind in the Natural England Advice on Operations tool. In the tool, electromagnetic changes are considered to be relevant to activity "power cable: operation and maintenance" and are risk profiled as "**Low**".

This is an impact pressure pathway that is of relevance to FLOW and therefore needs to be assessed here. It is anticipated that the use of suspended, dynamic inter-array cables for FLOW (rather than static cables that run solely along the seafloor for fixed foundation turbines) may increase the scope of anthropogenic EMFs in the water column and potentially interact with a greater diversity and abundance of marine organisms (Bennun *et al*., 2021; Gill and Desender, 2020; Hutchinson *et al*., 2020b; Normandeau *et al.,* 2011; Taormina *et al.,* 2018; Maxwell *et al.,* 2022; ORE Catapult, 2022b). Note that any effects of EMFs resulting from inter-array cables may be less than those from export cables due to the lower capacities involved (although export cables are outwith the scope of this report) (ORE Catapult, 2022b).

At present, EMF is considered unlikely to significantly alter survival and fitness of sensitive species (Farr *et al.,* 2021; Gill and Desender, 2020; Taormina *et al.,* 2020), however, studies outside the laboratory are few and a limited number of species have been investigated. Overall, when in close proximity to subsea cables, some animals have demonstrated behavioural responses in a few studies, such as increased foraging and exploratory movements. However, so far, behavioural responses of individuals have not been determined to negatively affect a species population, but further research is needed to refine our understanding of the effects of EMFs on wildlife (SEER, 2022c).

As the specific impacts of EMF from FLOW inter-array cables represents a knowledge gap at present, it is recommended that this pressure should be risk-profiled similarly to the activity “power cable: operation and maintenance”, i.e., risk-profiled “**Low**” in the absence of significant evidence to suggest otherwise.

EMF changes are only considered to be relevant during the operation and maintenance phase of FLOW and are not applicable during construction or decommissioning (SEER, 2022c).

Mitigation measures

Suspended cables are more vulnerable to wear through hydrodynamic stress (fatiguing pressure and twist) and biofouling, and increased wear can cause technical problems, as well as increase EMF impacts. Thus, dynamic cables should be monitored regularly for wear and tear (Taormina *et al*., 2018).

Burying cables may reduce impacts of EMF on fish and other species. Field strength dissipates quickly, and burial of cables increases distance between source and species receptors, so may be an effective mitigation. However, some cables will need to be suspended in the water column in order to connect floating turbine cables to the seafloor, and the effectiveness of cable burying is unclear in reducing EMF impacts (Bennun *et al*., 2021). Although burying cables could potentially reduce the impacts of EMF, the trenching activities involved forms a trade-off with increased seabed disturbance impacts to benthic ecosystems (Maxwell *et al.,* 2022).

Evidence gaps

EMF is recognised as a key area of interest, and a potential evidence gap, across the offshore wind and wider power transmission industry. There are however potential evidence gaps concerning how FLOW-specific features (such as dynamic cables in the water column, or free and partially buried cables) interact with the marine environment (ORE Catapult, 2022c).

Currently, conclusive evidence is insufficient and additional knowledge about receptor species' (both benthic and pelagic, and at different life stages) exposure to different EMFs (i.e., sources, intensities), and the determination of the EMF environment, is needed (ORE Catapult, 2022c). Some studies could be completed before FLOW developments are built by running laboratory-based experiments. If time and or budgets are limited, an effective approach to understand these impacts would be to group functionally or biologically similar species and test individuals from each group (Maxwell *et al.,* 2022). There is an emerging body of new research within a laboratory setting and, albeit to a lesser extent, the field environment associated with EMF effects arising from electricity transmission. Some of this research indicates measurable effects and responses to EMF on a small number of individual species, however it is not considered appropriate to apply these findings wholesale to advance the wider understanding of potential EMF effects from FLOW (ORE Catapult, 2022c).

Further targeted physiological and behavioural free-ranging studies are also required to determine the energy and time costs associated with the impacts on species from EMFs (Hutchison *et al.,* 2018), including field studies using tagging and tracking systems to gather evidence, and long term *in situ* studies to assess the effects of chronic EMF exposures on egg development, hatching success and larval fitness (Gill and Desender, 2020).

In addition, the limited studies that have taken place tend to focus on one single cable, however, consideration should be given to studies which allow the collection of evidence on repeated exposure due to the encounter of multiple cables (as would be the configuration of wind farm inter-array cables). This would facilitate the development of evidence in respect of cumulative impacts which is currently lacking (Xoubanova and Lawrence., 2022).

While field studies have been conducted on the effects of EMF from cables buried in the seabed (e.g., Hutchison *et al.,* 2018), there is a limited understanding of the EMF impacts of dynamic cables suspended in the water column (Gill and Desender, 2020; Hutchison *et al*., 2020b). More work needs to be done to understand attraction or aversion effects of suspended cables, particularly on pelagic species, e.g., the potential for EMF to impact on marine mammals due to the possible presence of floating cables in the water (but also demersal due to species movement as explained above) (Taormina *et al.,* 2018; Maxwell *et al*., 2022). *In situ* monitoring of dynamic FLOW inter-array cables and their impacts on pelagic species would be valuable to addressing this knowledge gap and substantiating any current predictions (ORE Catapult, 2022c).

Temperature increase

Temperature increase relates to events or activities resulting in an increase to the local water temperature. This section addresses temperature increase caused by heat emissions from the operation of inter-array cables, both dynamic cables suspended in the water column and cables surface laid or buried on the seafloor. Note that cable connections to substations and power grids (export cables) are outwith the scope of this report and will not be assessed further. Receptors include benthic communities, as well as demersal and pelagic organisms.

Operation of cables in general will result in some heat being emitted from the cable and subsequent warming of the surrounding environment. As well as potentially impacting the environment, this loss of heat reduces the efficiency of the cable. Thermal emission and its impacts will depend on the type of cable, transmission rate and the receiving environment. An illustration of an example temperature distribution in a cable is shown in Figure 4-6 (Høyer-Hansen *et al.,* 2022).

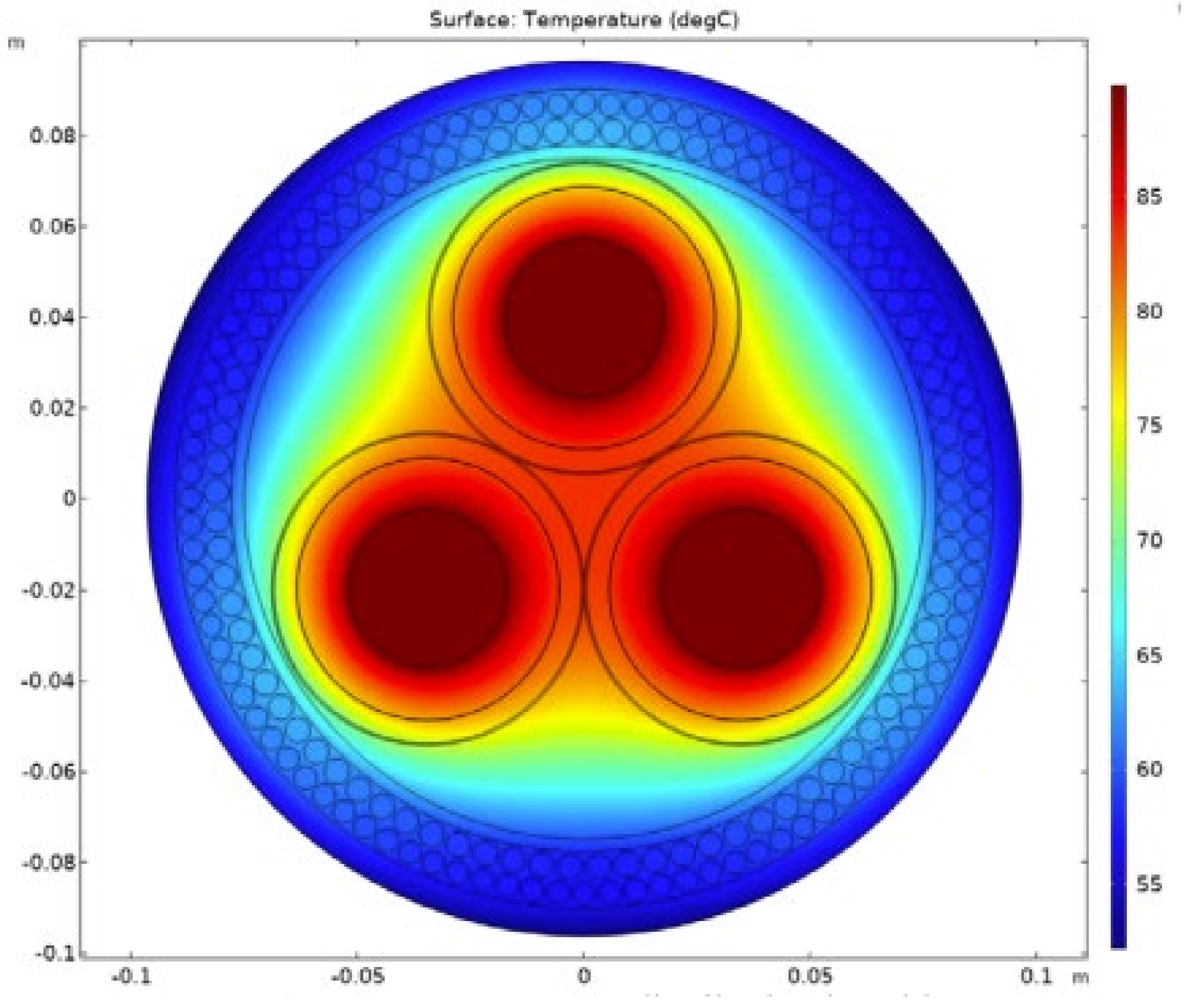


Figure 4-6. Example temperature distribution in a cable (Høyer-Hansen *et al.*, 2022)

When cables are surface laid (i.e., not buried), heat dissipates into the water column surrounding a cable. Heating effects will be localised to the proximity of the cable and quickly dissipate though the water column. By contrast, when cables are buried, heat emitted from a buried cable can increase the temperature of the surrounding seabed (by 0.15–2.5°C) and seawater (by a negligible amount) (SEER, 2022c). The quantitative benchmark used to classify “temperature increase” as a relevant pressure in the MarESA methodology is a 5°C increase in temperature for one month, or a 2°C increase for one year (MarLIN, 2023).

Cable thermal emissions have been empirically measured for the export cable at the Nysted wind farm in the Beltic Sea, Denmark. The maximum temperature increase measured in the sediment was 2.5°C at 25 cm directly above the cable (cable of voltage 132 kV with a burial depth of 1 m). According to the MarESA methodology, the temperature increase observed for the Nysted wind farm cable would be considered relevant. In comparison to export cables, inter-array cables have a much lower voltage/capacity and therefore the temperature increase associated with the inter-array cables of a FLOW farm is likely to be much smaller than for an export cable. For example, the inter-array cables at the Kincardine FLOW farm are of 33 kV capacity (Kincardine Offshore Wind Ltd., 2018). Despite this, it should be noted that higher voltage inter-array cables reduce transmission losses and thus may become more frequently used for inter-array cables in future. The Aberdeen Offshore Wind Farm (fixed foundation) has higher voltage inter-array cables of 66 kV (Vattenfall and RSK., 2021). No information could be found documenting any temperature increase associated with the inter-array cables of offshore wind farms.

An increase in temperature can have an impact on spawning, reproduction, larval development, larval settlement, and recruitment. If changes in temperature prevent reproduction or larval development, then a population may be lost through recruitment failure. Local populations may acclimatise to the prevailing temperature regime and may exhibit different tolerances to other populations subject to different temperature conditions. Therefore, caution should be used when inferring tolerances from populations in different regions (MarLIN, 2023).

Benthic infauna, which typically inhabit the top 10 centimetres of the seabed, are outside the volume of sediment affected by significant temperature changes from cables that are generally buried below 1–3 meters of sediment. In addition, although temperature variations are most pronounced in surface waters of the sea due to factors such as global warming, any marine organism living in seabed sediments will experience similar annual temperature fluctuations due to seasonal effects. Temperature changes resulting from power cable heat emissions are within the range of natural temperature variations and, although there are limited studies of local effects of small temperature changes on benthic infauna, heat emissions are expected to have an insignificant effect on benthic organisms because of the low temperature change and limited spatial extent affected (SEER, 2022a).

Modelling of cable heating for the Viking Link interconnector (a HVDC electricity interconnector proposed to link the electricity transmission systems of the UK and Denmark) suggested that even for the worst-case scenario of bundled cables, any increases in temperature will be limited to a very narrow band above the cables with negligible lateral heat transfer. The footprint of any effect will therefore be extremely narrow, less than a 1 metre strip above the cable although it was not possible to define the area precisely and it would also vary in response to current load. It was concluded that it is very unlikely that temperature changes would be ecologically significant at a local scale, i.e., the footprint of the heating effect. Since this footprint is so small the potential for population level effects is considered to be negligible. The study concluded that only deep burrowing invertebrates (those which burrow beyond the upper few centimetres of sediment) are considered likely to be potentially exposed to anything more than trivial heating effects from cable operation (National Grid Viking Link Ltd. and Energinet.dk., 2017). Burrowing fauna are somewhat buffered from natural temperature variations in seabed sediments and thus more sensitive to potential temperature increases associated with submarine power cable operation. In addition, they are closer to the source of temperature increase (the buried cable) and therefore more likely to be impacted given that the heating effects will be localised to the proximity of the cable. This is in alignment with the MarESA methodology whereby species with a restricted distribution, those that only occur in isolated areas or thermally stable environments (e.g., deep water), or those that are at their southern or northern limits in UK waters, are not likely to resist changes in temperature at the benchmark level (MarLIN, 2023).

Habitat for pelagic fish species and highly migratory species is largely defined by water temperature and can be highly variable between seasons and years (Morita *et al.,* 2010; Webb *et al*., 2020). The thermal habitat preferences of pelagic fish species and highly migratory species are therefore not likely to be impacted by FLOW as the presence of the floating turbines and moorings will unlikely change local water temperatures significantly, barring some shading effects, though hydrodynamics may be altered in the vicinity of turbines (discussed in water flow changes) (Schläppy *et al.,* 2014; van Berkel *et al.,* 2020; Maxwell *et al* 2022).

Risk-profiling

As with EMF changes, temperature increase is considered to be “**Not Applicable**” to fixed foundation offshore wind in the Natural England Advice on Operations tool. In the tool, temperature increase is considered to be relevant to activity “power cable: operation and maintenance”, and is risk profiled as “**Low**”.

This is a pressure that is of relevance to FLOW and therefore needs to be assessed here due to potential heat emitted from the inter-array cables. FLOW farms require cables being run across the seafloor, as well as dynamic cables suspended in the water column, increasing the potential of impacts over fixed foundation turbines (Bennun *et al*., 2021; Gill and Desender, 2020; Hutchinson *et al*., 2020b; Normandeau *et al.,* 2011; Taormina *et al.,* 2018; Maxwell *et al.,* 2022).

As the temperature increase resulting from FLOW inter-array cables is unlikely to change the local water temperatures significantly, it should be ranked similarly to the activity “power cable: operation and maintenance”, i.e., risk-profiled “**Low**.”

Temperature increase is only considered to be relevant during the operation and maintenance phase of FLOW and is not applicable during construction or decommissioning (SEER, 2022c).

Mitigation measures

Inter-array cables are required to be designed to minimise thermal loss, with the primary objective of maximising efficiency, thus the heat released from cables will be minimal (Maxwell *et al.,* 2022).

Evidence gaps

During conduction of this literature review, it has become clear that there are a number of evidence gaps associated with the impact of temperature increase.

Firstly, whilst there was some information on temperature increase associated with wind farm export cables, an evidence gap exists whereby there is a lack of research into the temperature increase caused by inter-array cables specifically. No evidence could be found documenting known temperature increases to have been caused by any wind farm inter-array cables. This is an important differentiation as export cables are larger and of higher voltage than inter-array cables, thus the impacts of temperature increase will be different.

In addition, there is a lack of research investigating the environmental impact of temperature increase resulting from subsea cables generally i.e., potential impacts of this temperature increase on benthic communities or other marine life. A number of predictions and assumptions are made, however, there is limited evidence of local effects of small temperature changes on benthic infauna.

Furthermore, there is also a lack of information available to suggest potential mitigation measures that could be employed to reduce any temperature increase associated with subsea cables.

Introduction of light

Introduction of light refers to a change in incident light via anthropogenic means. This section addresses the impacts of the introduction of artificial light in the marine environment as a result of construction, maintenance, operational lighting on wind turbine structures, plus navigation and operational lighting on vessels and structures. Birds and sea turtles are the receptors most sensitive to introduction of light, but also other marine species (Defingou *et al*., 2019). Introduction of light is unlikely to be relevant for most benthic invertebrates, except where it is possible to interfere with spawning cues. However, there is no evidence to that effect. The introduction of light could potentially be beneficial for immersed plants, and it is also possible that continuous lighting may lead to increased algal growth, but again, there is no firm evidence to support this (MarLIN, 2023).

Vessels, lighthouses, light-induced fisheries (e.g., harvesting squid), oil and gas platforms, and renewable energy developments are all examples of sources of artificial light in marine environments that may have significant influences on the reproductive physiology, migration, and foraging habits of many marine species, as well as avian collision risk (Montevecchi, 2006).

During offshore wind farm construction, temporary work lighting would illuminate work areas on vessel decks or service platforms of wind turbines or associated infrastructure on platforms. In addition, cable laying may occur 24 hours a day during certain periods, and these vessels would be illuminated at night for safe operation. In addition, all vessels operating between dusk and dawn are required to have navigation lights turned on. Similar artificial light sources are expected during decommissioning. During operation, shipping safety lights and safety aviation lights are placed at the base and top of the wind turbines respectively. International and national regulations regarding ship and air safety require that wind turbines, either individually or collectively as a wind farm have to be marked with obstruction lights during hours of darkness. In addition to this, there would be lighting from maintenance vessels during the operation and maintenance phase (Defingou *et al*., 2019).

A number of factors can affect light transmission, both in air and water. In air, the transmission of light can be affected by atmospheric moisture levels, cloud cover, and type and orientation of lights. In water, turbidity levels and waves, as well as type of light, can affect transmission distance and intensity (Defingou *et al*., 2019).

Ecological effects of direct inputs of light from anthropogenic activities may be the diversion of bird species from migration routes if they are disorientated by or attracted to the lights (MarLIN, 2023). High numbers of migrating birds are known to cross the UK as a migration route (as described in Section 3). Orientation of these migrating birds relies on a number of mechanisms from magnetic compass over polarised light to night cues such as sunset and stars. The disturbances of night-migrating birds by artificial lights range from disorientation to exhaustion and/or collisions. More precisely, birds migrating during nights with bad weather conditions may be attracted by light in offshore structures and become disoriented, leading to collision with the structures, which can cause injury or direct mortality (as discussed in the section relating to collision ABOVE water) (Defingou *et al*., 2019).

Light from vessels may also be of concern where significant levels of activity occur in close proximity to sensitive bird habitats including coastal inshore waters (OPSAR, 2008; Dwyer *et al.,* 2013; Pearce-Higgins *et al.,* 2012).

Regarding lighting, sea turtle hatchlings have shown attraction to artificial light in the sea risking indirect mortality from disorientation, energy loss and increased predation in the vicinity of the light source (Defingou *et al*., 2019).

Risk-profiling

For fixed foundation offshore wind, the risk of introduction of light during all development lifecycle phases has been risk-profiled “**Low**” by the Natural England Advice on Operations tool.

During construction and decommissioning, there will be less offshore activities and vessel movement involved with FLOW and thus the impacts of artificial light during these stages is likely to be less than that of fixed foundation wind farms. As the above water elements of the turbine structures themselves will remain largely unchanged between fixed foundation and floating foundation designs, the impact of light introduction during the operation and maintenance phase is considered the remain the same between the two designs.

In the absence of significant evidence to suggest otherwise, the risk profile for introduction of light should remain unchanged between fixed and floating foundation i.e., FLOW should be risk-profiled “**Low**” for all development lifecycle phases.

Mitigation measures

Although offshore wind farms in general will undoubtedly contribute to the presence of artificial light in the marine environment, the use of blue and green lighting may reduce disorientation in nocturnally migrating birds more than red and white lighting (an industry standard), thus reducing avian collision risk at offshore facilities (Poot *et al.,* 2008; Farr *et al*., 2021).

Furthermore, BOEM has published Guidelines for Lighting and Marking of Structures Supporting Renewable Energy Development. The guidance recommends a number of mitigation measures based upon review of existing studies and literature related to impacts to birds, bats, marine mammals, turtles, and fish from offshore lighting, and the experience gained from reviewing operational offshore wind facilities' lighting (BOEM, 2021). Suggested mitigation measures include:

- lighting should be minimised whenever and wherever possible, including number, intensity, and duration
- flashing lights should be used instead of steady burning lights whenever practicable, and the lowest flash rate practicable should be used for the application to maximise the duration between flashes. BOEM recommends 30 flashes per minute to be a reasonable rate in most instances
- direct lighting should be avoided, and indirect lighting of the water surface should be minimised to the extent practicable once the wind facility is in operation
- lighting should be directed to where it is needed, and general area "floodlighting" should be avoided
- area and work lighting should be limited to the amount and intensity necessary to maintain worker safety
- using automatic timers or motion-activated shutoffs for all lights not related to aviation obstruction lighting or marine navigation lighting should be considered
- aviation obstruction lighting that is most conspicuous to aviators, with minimal lighting spread below the horizontal plane of the light (BOEM, 2021)

Evidence gaps

The impacts of introducing artificial light to the marine environment is generally well-studied as it is an impact which is common to most offshore marine activities i.e., oil and gas. However, evidence specific to offshore wind farms and FLOW in particular, is lacking.

There is also a lack of available evidence on whether it is possible introduction of light could interfere with benthic invertebrates and/or spawning cues, as well as to prove claims that the introduction of light could potentially be beneficial for immersed plants or lead to increased algal growth.

As introduction of light can be a cause of the barrier effect, further research is also needed to quantify attraction/avoidance effects of FLOW on birds (as described for barrier effects).

Introduction or spread of invasive non-indigenous species (INIS)

Introduction or spread of invasive non-indigenous species (INIS) refers to the direct or indirect introduction of species that are not native to a specific area and that tend to spread, resulting in damage to the environment, economy, or human health. Receptors that are sensitive to this pressure include native species with which INIS may compete or alter local biodiversity.

Managing INIS is one of the greatest challenges for the conservation of terrestrial, freshwater, and marine native biodiversity (Pyšek and Richardson, 2010). Invasive species have been reported as the second most common cause of species extinctions (Bellard *et al.,* 2016) while their ecological impacts can propagate along the food web and affect ecosystem functioning (Gallardo *et al.,* 2016). Invasive species also often have important socio-economic and health impacts (Vilà and Hulme, 2018) and can cause important loss of ecosystem services (Walsh *et al.,* 2016). Consequently, their management is crucial for biodiversity conservation and human wellbeing. International institutions have explicitly recognised the need to control and eradicate biological invasions and have set relevant targets (e.g., the Aichi Target 9 set by the Convention on Biological Diversity) (Giakoumi., *et al*. 2019).

Government guidance applicable to England and Wales provides a list of 30 species of INIS animal that are listed as of concern because of their (1) invasiveness, and (2) ability to establish in several nations across Europe. An example species, which is considered to be widely spread, is the Chinese mitten crab (*Eriocheir sinensis*) (Defra and APHA, 2020).

Vessel ballast water, biofouling, and “stepping-stone” effects caused by the presence of offshore wind structures may facilitate the spread of such species (MarLIN, 2023).

Vessel ballast water and biofouling

Vessels used for installation, maintenance, and decommissioning of offshore wind farms may facilitate INIS introduction because organisms could be transported in ballast water (the water used to maintain the ship’s weight) or be transported to new locations via biofouling i.e., the accumulation of microorganisms, plants, algae, or small animals where it is not wanted on surfaces such as ship hulls or other structures that cause degradation to the primary purpose of that item. Thousands of marine species can be carried in ships’ ballast water and all vessels have biofouling to some extent, even if recently cleaned or anti-fouled (International Maritime Organisation (IMO), 2012; Davidson *et al.,* 2010).

The risk of introduction from vessels would vary between wind turbine foundation types, depending on where specialised vessels required for construction, operations, and maintenance originate from. There would be a higher potential for invasive species to be transported on or in a vessel originating from a foreign port, or from an area already experiencing an invasion, than compared to a vessel originating from a nearby port or local area without known INIS occurrences (Horwath *et al*., 2020).

Wind turbine stepping-stone effects

Wind turbine foundations not only serve as hard structure for local communities but can also be rapidly colonised by invasive species (Mineur *et al*. 2012). Often regarded as a valuable conservation tool, the artificial reef effect of anthropogenic structures is well-documented at offshore wind farms, oil and gas platforms, and subsea pipelines (as described under physical change to seabed type) (e.g., Love and York 2005; Krone *et al*., 2013; Claisse *et al*., 2014; Reubens *et al*., 2014).

However, the introduction of artificial hard substrates may also invite colonisation by INIS species, whose threat to marine biodiversity can have far-reaching ecological and economic consequences (Molnar *et al.,* 2008). For example, Bulleri and Airoldi (2005) found that the proliferation of artificial marine structures in nearshore areas facilitated the spread of a non-indigenous green algae (*Codium fragile* ssp. tomentosoides) along the coasts of the north Adriatic Sea. However, no offshore wind farm studies to date have demonstrated significant deleterious effects on reef fish or benthic communities (Copping *et al*., 2016). Cumulative, regional-scale beneficial artificial reef effects may occur when offshore wind projects are sited in proximity to each other, although such siting would also increase the cumulative risk of invasive species range expansion due to the “stepping-stone” effect that could facilitate their spread across a region (Horwath *et al*., 2020).

From a regional perspective, offshore wind foundations in a large expanse of soft-bottom substrate can provide stepping-stones for invasive species to expand further. Invasive species can spread between foundations and nearby hard-bottom areas that might otherwise be too far to reach, like groups of islands or previously uncolonised sections of coastline (Degraer *et al*. 2019; English *et al.* 2017; Kerckhof *et al*. 2011; Vattenfall, 2006).

Many intertidal and sub-tidal species have larvae (i.e., a distinct juvenile form that many animals undergo before maturation or metamorphosis into adults) that spend a period of time drifting as plankton at sea, which allows them to disperse across long distances before they settle to the bottom and adhere to hard substrate, where they grow and mature. Spread of invasive species like barnacles, mussels, and limpets is of particular concern because they have mobile, planktonic larvae and require hard substrate to recruit. Wind farm foundations can introduce new hard substrate into offshore waters that otherwise would have limited or no existing hard substrates, thereby providing new hard-bottom habitat that the mobile larvae of invasive species can populate, to the detriment of native species (Kerckhof *et al*. 2011; Glarou *et al.* 2020).

Adams *et al*. (2014) modelled how offshore wind projects off Scotland and Northern Ireland could act as stepping-stones. Based on the modelling, the foundations could create new dispersal pathways for invasive species and facilitate their progression to northern areas, from the Northern Irish coast to the Scottish coastline, that were otherwise impossible or difficult for invasive species to access (English *et al.* 2017).

Risk of the spread of INIS primarily varies with geographic location. For example, the offshore locations of deep-water FLOW farms may make stepping-stone colonisation pathways less likely than fixed foundation turbines located closer to shore (Farr *et al*., 2021). Furthermore, ocean current dynamics can influence transportation of INIS to wind farm sites and presence of INIS in the vicinity may increase the likelihood of spread to new structures (Horwath *et al*., 2020).

In addition, the risk of INIS introduction may differ between wind turbine foundation types, based on whether the foundation type is built in a port versus on land and whether it is carried on top of a ship or towed through the water to the installation site.

Most floating foundations, as well as gravity (fixed) foundations, and suction bucket (fixed) foundations can be built in the water within ports, and then towed to a wind farm site. While being built in water within a port, the structures can be colonised by marine organisms, which then can be transported on the structures to the offshore wind farm site. During the operational phase, floating foundations may also be towed back to port for major maintenance, which could transport organisms that colonised the structures on-site to a port, or transfer organisms from the port back out to the wind farm site. For this reason, FLOW farms may be at greater risk of impacts from INIS than fixed foundation turbines.

Moreover, gravity fixed foundations or dead-weight (gravity) anchors for floating foundations that are made of concrete may be more porous and susceptible to being colonised than foundation or anchor types made of steel (Horwath *et al*., 2020).

Risk-profiling

The risk of introduction of INIS through vessel ballast water or biofouling is likely to be similar for fixed foundation and FLOW, other than the fact that vessel activities are reduced for FLOW.

The development of both fixed foundation and FLOW wind farms creates new hard structures for colonisation (all be it different types of structure) and can lead to introduction of INIS through the artificial reef effect, which leads to the stepping-stone effect. The offshore locations of deepwater, FLOW farms may make these pathways less likely than fixed foundation turbines in located in shallower water nearshore (Farr *et al*., 2021).

Overall, the risk of introduction or spread of INIS is generally greater for floating foundations in comparison to fixed foundations, as they tend to be towed to site following construction in a port, as well as towed to and from port for maintenance activities during the operational phase. This increases the potential for the introduction of invasive species at the wind farm site (Horwath *et al*., 2020).

For fixed foundation offshore wind, the risk of introduction or spread of INIS during all development lifecycle phases has been ranked “**Low**” by the Natural England Advice on Operations tool. Considering the available evidence, is recommended that the risk ranking should remain the same i.e., “**Low**” during all development lifecycle phases for FLOW. The reason for this is that there is information both for and against FLOW leading to increased risk of INIS introduction and thus this impact is not considered to present a significant difference between the foundation designs.

Mitigation measures

Managing INIS is particularly challenging in the ocean mainly because marine ecosystems are highly connected across broad spatial scales (Giakoumi., *et al*. 2019)

Mitigation measures for introduction or spread of INIS include regularly cleaning structures so they are free of biofouling, and to construct floating foundations *in situ* at the offshore site instead of in port (however, this is likely not the most practical option and would form a trade-off with a number of other pressures).

Ongoing monitoring to assess the state of INIS at a site during operation may include (APEM, 2021):

- **rapid assessment surveys** – focussing on all epibiota growing on submerged features (such as floating foundations, pilings, mooring lines, anchors for a wind farm). Samples are photographed *in situ* and preserved for laboratory identification if required.
- **settlement panels** – normally conducted in association with the rapid assessment, settlement panels are deployed to measure the recruitment of fouling species on the site. They can be made of plastic squares suspended below the water and left for around six months, at which point they are then removed, and the biota analysed in the laboratory.
- **vessel inspections** – vessel inspection should be a routine part of biosecurity mitigation measures and should take place at all stages of the project lifecycle. To assess the extent of biofouling a rapid vessel inspection can be conducted from the surface if the water is clear enough. Alternatively, a pole camera, ROV, or experienced marine ecologist diving or snorkelling can be used to examine the amount of growth. Guidance is available to score different levels of biofouling (APEM, 2021).

All sites should have a robust Biosecurity Plan to be implemented if INIS are detected during monitoring activities. Control methods to reduce or limit the risk of any activities that could spread INIS can then be considered. Methods would mainly consist of activities associated with movement of INIS, such as reducing vessel movements. Additionally, the plan should include provisions for contingency planning if a new species is detected. The main objective is to limit as far as possible the risk of introduction or spread of INIS to the site and reduce the likelihood of INIS being translocated off-site (APEM, 2021).

The final option in most cases is the application of population level control or eradication of INIS. This could be as simple as removing the affected item from the water, or it can be as complex as a site-wide eradication attempt. Most sites would require a range of eradication methods used in-combination to be effective; however, selection will largely be driven by cost and logistical feasibility. No eradication method to date has been 100% effective and consequently, eradication is often deemed ineffective or not cost-efficient. Eradication of marine invasive species has only been achieved when species were detected early, and management responded rapidly (APEM, 2021; Giakoumi., *et al.* 2019). Control/eradication methods fall into four main categories (APEM, 2021):

- **removal/air drying** – the cheapest and easiest way to treat small to medium-sized objects is to simply remove the item from the sea and air dry for between 48-72 hours, as this will typical desiccate any attached aquatic organisms. This works well on anything from a rope up to small/ medium-sized boats but is not practical for larger objects or structures.
- **chemical treatment –** chemical treatment can be used in a number of ways to accelerate smothering or air drying and has been successfully applied in a range of scenarios. Bleach can be used in high concentration to speed air drying and is frequently used in aquaculture sites to treat mussels, where the accelerants kill epiphytes but not the mussels. Bleach has also been used to speed up smothering, where high doses were added to bags to increase effectiveness. Bleach rapidly

dissociates in the marine environment into its constituent ions, making it a fairly “environmentally safe” option.

- **smothering –** smothering is used when the object requiring treatment is immovable (e.g., on the seabed) or it is not practical to move. Various methods of smothering have been implemented to remove INIS, including covering the seabed with non-breathable material (plastic or soil), wrapping objects with polyurethane to make them watertight and making custom made bags to fit around structures. The aim is to stop the water flow and create anoxic conditions, thus containing and removing the INIS.
- **mechanical scouring –** often used in conjunction with Removal/Air Drying, mechanical scouring can be conducted using jet washers or scrapers to remove material from the desired object. Every care should be taken to contain the material removed using screens or booms and capture for sending to landfill or composted where appropriate. Although not typically conducted underwater, mechanical removal can be undertaken in the same way as on land, but extra care must be taken not to fragment and disperse INIS whilst doing this. As such mechanical removal in the water column has limited practical applications (APEM, 2021).

In marine environments, freshwater pulses can be another effective way of treating large areas or structures, where the salinity of the environment is reduced to a level below the natural tolerance levels of the INIS being eradicated (APEM, 2021).

As an example of possible mitigation measures specifically for a FLOW development, the following control measures have been introduced at the Kincardine FLOW farm in Scotland to mitigate against INIS (Kincardine Offshore Wind Ltd., 2018):

- the Principal Contractor and all subcontractors (operating in the marine environment) will adhere to the relevant legislation and adopt best practice with regards to the control of INIS.
- the Environmental Management Plan details the procedures adopted by the Principal Contractor and all subcontractors to prevent the introduction of INIS.
- vessels of 400 gross tonnage (gt) and above to be in possession of a current International Anti-Fouling System (AFS) certificate.
- vessels of 24 m or more in length (but less than 400 gt) to carry a declaration on AFS signed by the owner or authorised agent accompanied by appropriate documentation such as a paint receipt or contractor’s invoice.
- ship hull inspections and biofouling management measures will be documented, as appropriate, by the appropriate sub-contractor and, if applicable, this will be recorded in the contractor’s Planned Maintenance System (PMS) or Common Marine Inspection Document (CMID).
- submersible and immersible equipment such as ROVs will be subject to pre and post-use checks that will include checks for any of marine growth which must be removed prior to the deployment of equipment’s.
- where applicable, all vessels will comply with the International Convention for the Control and Management of Ships' Ballast Water and Sediments 2004

(BWM/CONF/36) convention, developed and adopted by the International Maritime Organisation (IMO)).
- where applicable, the management of ballast water will be undertaken in accordance with an approved Ballast Water and Sediments Management Plan and records of such management in a Ballast Water Record Book in accordance with the provisions of the Convention (Regulation B4) (Kincardine Offshore Wind Ltd., 2018).

Evidence gaps

There is a wealth of literature and guidance available on the topic of mitigation measures for managing introduction or spread of INIS in the marine environment for offshore sites generally, however, an evidence gap has been identified in that there are no studies focussing on practical application of these mitigation measures to FLOW farms, or evidence of their use and success in practise.

In addition, no case studies, or examples of FLOW developments where INIS have been identified were available at the time of writing.

It was noted that in 2017, a number of articles were published stating that research had begun by the Scottish Association for Marine Science (SAMS) to examine how FLOW farms could provide a new route for invasive species to spread across the oceans (The Maritime Executive, 2017). Hywind Scotland FLOW was to be used as an example to study the impact of taking the floating turbines from their port of assembly on the Norwegian west coast to their release in Buchan Deep. Despite this, no published research papers on the topic could be located during the present literature review.

Contamination

This section addresses the potential impacts of contamination to the sea associated with FLOW developments and the resultant pressures imposed upon the marine environment. Pressures have been identified to include:

- litter
- hydrocarbon & PAH contamination
- transition elements & organo-metal (e.g., TBT) contamination
- introduction of other substances (solid, liquid or gas)
- synthetic compound contamination

Each of these will be discussed in turn, in the context of the Natural England Advice on Operations tool, throughout the following sections.

Evidence gaps

In general, pollution/contamination pressures were identified for a number of activities, especially in the case of marine litter, synthetic compounds, transition elements and organo-metal contamination. However, quantification was often not available, and literature raised some concerns on the lack of information on interaction of pollutants arising from different activities (MMO, 2014).

As this is applicable to all pressures within the contamination section, this evidence gap has not been discussed under each subheading and any evidence gaps discussed within the following subsections are specific to that pressure / type of contamination.

Litter

Marine litter is a global concern affecting all oceans of the world. Marine litter is defined as any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment. Marine litter consists of items that have been made or used by people and deliberately discarded into the sea or rivers or on beaches; brought indirectly to the sea with rivers, sewage, storm water or winds; or accidentally lost, including material lost at sea in bad weather. Marine litter originates from many sources and causes a wide spectrum of environmental, economic, safety, health, aesthetic and cultural impacts. The very slow rate of degradation of most marine litter items, mainly plastics, together with the continuously growing quantity of the litter and debris disposed, is leading to a gradual increase in marine litter found at sea and on the shores (United Nations Environment Programme (UNEP), 2023).

Litter is clearly relevant for large macrofauna receptors such as fish, birds, and mammals. There is no available evidence on the effects of ‘litter’ on benthic marine species. While there is documented evidence on the accumulation of microplastics in some species and habitats, no ecological effects have been shown to date. The only exception is the effect of ghost fishing on large crustaceans (crabs etc.) (Bullimore *et al*., 2001; Tyler-Walters *et al.,* 2018).

Ecological effects of marine litter can be physical (smothering), biological (ingestion, including uptake of microplastics; entangling; physical damage; accumulation of chemicals) and/or chemical (leaching, contamination from litter) (NatureScot, 2023).

Marine litter can be released into the marine environment by shipping vessels including cargo, bulk carrier, military, surveillance, research, passenger ships and non-commercial vessels, either accidentally (inappropriate storage) or deliberately (Potts and Hasting, 2011; Lozano and Mouat, 2009). Shipping litter includes pallets, strapping bans and drums, as well as litter derived from containers lost at sea. Cargo may also be washed overboard during stormy weather and contribute to coastal litter levels. Shipping related litter contributes approximately 2 % of the litter found on UK beaches. Shipping related litter contributed approximately 45 litter items per kilometre around the UK on average between 2003 and 2007 (UKMMAS, 2010; Lozano and Mouat, 2009).

Marine litter is generally considered to be “lightly impacted” by offshore wind (Abramic *et al.,* 2022). Regarding the life cycle of an offshore wind farm, decommissioning processes have been identified as the most likely direct sources of marine litter (excluding microplastics), though it will depend on the type of foundation and whether appropriate preventive measures are taken (Topham and McMillan, 2017; Abramic *et al.,* 2022).

During the operational phase, it is possible that natural weathering of wind turbine blades may have the potential to release microplastics into the marine environment. A turbine blade is simply explained as fiberglass mats, epoxy resin and hardener. Epoxy, in contrast to polyester, contains 33 % Bisphenol A which is considered very harmful to health.

Solberg *et al.,* (2021) estimated an annual emission of microplastics of approximately 62 kg per year per turbine (based on a 4.2 MW onshore turbine in Norway) as a result of erosion. Loss of Bisphenol A will apply to those areas of the blade that are not covered by surface treatment, i.e., damaged areas, and whether epoxy is used in the surface treatment. Where polyurethane cover layers are used, Bisphenol A will likely not be released until the cover layer has worn away. In this case, the mass losses are microplastic that will enter the food chain (Solberg *et al*., 2021).

Offshore turbines are likely to result in a larger quantity of microplastic pollution from weathering processes than onshore turbines due to salt water and more challenging weather conditions. Given the high density of turbines in many offshore wind developments, there is therefore the potential for considerable microplastic pollution from both FLOW and fixed offshore wind developments.

Conversely, in shallow waters (maximum 8 m), Wang *et al.,* (2018) showed that the hydrodynamic changes caused by offshore wind farm structures reduced microplastic abundance in the water and sediment in the area surrounding the wind farm. However, as FLOW is generally constructed in deeper water, it remains unknown as to whether this theory would hold true.

Risk-profiling

For fixed foundation offshore wind, the risk of marine litter during all project lifecycle phases has been ranked “**Low**” by the Natural England Advice on Operations tool, as normal shipping rules are considered to apply. The risk of this pressure will increase as a result of non-compliance to legislation, codes of conduct or best practice (Natural England, 2023a).

There is no evidence to suggest that FLOW should result in the production of more marine litter or have an increased likelihood of the occurrence of marine litter in comparison to fixed foundation offshore wind and therefore this report suggests that the risk ranking should remain unchanged i.e., “**Low**” risk for all project lifecycle phases. Normal shipping rules are also considered to apply to FLOW.

Mitigation measures

Potential mitigation measures for the impact of marine litter include complying with normal shipping rules, legislation, codes of conduct and best practice (Natural England, 2023a). In addition, marine litter survey and assessment prior to decommissioning could be carried out (Abramic *et al.,* 2022).

Evidence gaps

Marine litter was reported to be produced by a number of marine activities in literature. However, it was often difficult to identify the source of litter, and evidence was usually not accompanied by quantification (MMO, 2014).

There was no evidence available for documented marine litter from FLOW developments specifically. Early research has suggested that erosion from offshore wind turbines have potential to contribute significant quantities of microplastics to the marine environment annually (Solberg *et al.,* 2021). Further research is required to assess the potential for microplastic pollution from turbines utilising various materials and under different environmental conditions.

Hydrocarbon & PAH contamination

During construction of a FLOW development, accidental spillage may occur directly into the water column. The spill may then disperse as a plume on the water surface, within the water column or fall directly to the seabed. Construction vessel diesel spills are the most likely source of hydrocarbon contamination during a FLOW development. Given the nature of diesel in water the impacts of such a spill are likely to be most impactful at the surface.

One of the primary chemicals of environmental concern from FLOW developments are those associated with increased vessel traffic and subsequent increased potential for accidental spills (Kirchgeorg *et al.,* 2018). Deliberate discharges of oil or oil/water mixtures from ships are prohibited within the North West European Waters Special Area, established by the International Maritime Organization under MARPOL Annex I in 1999. This includes all waters around the UK and its approaches. Regardless of this, accidental discharges still occur. Information on accidental discharges of oil from ships and offshore platforms is compiled by the Advisory Committee on Protection of the Sea (ACOPS) on behalf of the Maritime and Coastguard Agency (MCA) each year. Although the majority of incidents are minor, several incidents occur annually that have led to the actual or potential release of significant amounts of oil (typically from large shipping vessels and tankers).

In the event of an accidental hydrocarbon spill several marine species and habitats could be adversely affected:

- seabirds are particularly sensitive to the effects of surface oil pollution, and some oil pollution incidents have resulted in mass mortality of seabirds (e.g. Munilla *et al*., 2011; Votier *et al*., 2005). If such an event were to occur in Refined Areas of Search then this would be of particular concern given the presence of 5 species on the 'Red' list of the IUCN List of Threatened Species.
- several marine mammal species are observed throughout the year in the vicinity of the Refined Areas of Search, with short-beaked common dolphin the most prevalent (Table 3-4). However, as for birds it is recognised that an accidental spill would result in hydrocarbons occurring across a very extensive area. There is little documented evidence of cetacean behaviour being affected by hydrocarbon spills, whilst the likelihood that a feeding cetacean would ingest a sufficient quantity of hydrocarbons to cause sublethal damage to its digestive system, or to present a toxic body burden, is low (IPIECA-IOGP, 2015).
- the area affected by a spill may overlap with spawning and nursery grounds of a number of fish species which are of conservation concern either at OSPAR or European or International Red list level. However, once the oil disappears from the water column, fish generally lose their oil content very quickly. This rapid loss of oil from fish tissue is linked to the fact that fish will metabolise accumulated hydrocarbons very rapidly (Krahn *et al*., 1993).

Risk-profiling

FLOW turbines benefit from being capable of assembly within port, meaning constructed turbines can be towed to the offshore site for installation. Conversely, fixed offshore wind turbines require in situ assembly and installation and thus require more vessels at the construction stage (Banister, 2017; Iberdrola, 2023). The same logic also applies to the removal of infrastructure during the decommissioning phase. During the operation and maintenance phase, many FLOW development concepts envisage that turbines have the ability to be disconnected and towed back to port for major maintenance activities (PLOCAN, 2021). As a result, there is likely to be less vessel activity at sea for FLOW turbines, compared to fixed foundation turbines, during the operation and maintenance phase. In addition, some FLOW platform configurations also have a large surface area where helicopter landing pads could potentially be installed allowing turbine maintenance to be achieved by helicopter, further reducing the number of vessels at sea (Bannister, 2017). As described previously, the installation of helicopter landing pads on FLOW turbines is a very early concept and there were no examples of developments utilising this technique at the time of writing. As a result of likely reduced vessel use, the potential for vessel collision and subsequent hydrocarbon spills during construction of a FLOW development may less than that of fixed offshore wind developments. Consequently, this report suggests that the risk ranking should remain unchanged i.e., “**Low**” risk for all project lifecycle phases.

Mitigation measures

In order to mitigate the potential for accidental hydrocarbon spills from collision of FLOW construction vessels appropriate notifications to mariners and Kingfisher Bulletin prior to operations. This allows other vessels in the area to be aware of the vessel activity in the vicinity of the FLOW development. Vessel safety can further be increased by compliance with MGN 654 (MCA, 2021) and providing appropriate markings on United Kingdom Hydrographic Office (UKHO) Admiralty charts. The establishment of a buoyed construction area and application of exclusion zones up to 500 m during construction can also reduce collision risk. Further to this, reducing vessel numbers where possible, applying limits to vessel speeds and establishing effective coordination and communication to manage vessel movements can also minimise risks.

Evidence gaps

Although there is an abundance of information into the impacts of hydrocarbon spills to the marine environment there is little attention paid to this in the environmental and technical reports of FLOW developments. In order to capture all aspects of environmental concerns FLOW developments should incorporate worst-case spill modelling, arising from vessel collisions and/or equipment malfunctions, into their environmental assessments.

Transition elements & organo-metal (e.g., TBT) contamination

Cathodic protection systems are the most used methods of corrosion protection for steel-constructions in marine environments. The systems work by reducing the electrical potential of the metal structures in order to slow down oxidation processes during offshore wind farm operations. This is achieved either by galvanic anodes or inert anodes. The anodes provide the protection current to polarise the metal surface by either the galvanic reaction of another material rather than the steel structure (galvanic anodes) or the active current (inert anodes) (Kirchgeorg *et al.,* 2018).

Aluminium (Al) based galvanic anodes are mainly used for offshore structures as they have a much higher electrochemical capacity in seawater than zinc or magnesium anodes (HTG, 2009). The annual required material and subsequent water-bound emissions from galvanic anodes are range from several kilos (for e.g. monopile foundations) to tons per year (for huge jacket structures of platforms). By assuming a minimum platform lifetime of 25 years Kirchgeorg *et al* (2018) calculated the potential corrosion emissions to sea by galvanic anodes. In the case of fixed turbines the Al anode mass required was found to be between 13,000 kg (monopiles) and 32,000 kg (tripod). Organic coatings can be applied to turbine structures which reduces the Al anode mass required to between 6000 kg (monopiles) and 10,700 kg (tripod). Kirchgeorg *et al* (2018) therefore found that for an offshore wind farm with 80 turbines with monopile foundations and a substation will annually release 45 tons of Al and 2 tonnes of Zinc (Zn) (assuming 5% Zinc content in Al anodes). Again, use of organic coatings can significantly reduce the material and thus emissions of Al anodes to 19–25 tonnes of Al per year, however coatings themselves bring with them potential environmental impacts of their own (discussed under following pressure section). It is therefore evident that both FLOW and fixed offshore wind developments have potential to act as a considerable local input source of metals into the marine environment.

Zn is the second most abundant metal in Al anodes, contributing 2.5 - 5.75% of total anode mass (Kirchgeorg *et al.,*2018). The fate and impact of Zn anodes on sediment and seawater of Zn has been investigated in various studies, as they are commonly used in harbour sheet piling, ships and ballast water tanks (Rousseau *et al.,* 2009; Caplat *et al.,* 2012).

Seawater tank experiments by Deborde *et al.,* (2015) analysed Al, Zn and Iron (Fe) emitted by Al anodes and demonstrated an increase of the dissolved Zn fraction was only observed in the beginning of the experiment. Decreases were then observed due to absorption to suspended particulate matter and dilution effects in water. Caplat *et al.,* (2010) studied the toxicity of Zn emissions from galvanic anodes on sea urchin embryos and sperm. Results revealed low or no damage compared to the salts of Zn and Al. However, negative impacts of emissions from Zn anodes have been observed in the Pacific oyster (*Crassostrea gigas*) whereby immune system activities were observed to be sensitive to acute Zn toxicity but less impacted by lower Zn concentrations (Mottin *et al.,* 2012). Overall, the expected emissions of Zn from offshore wind farms are expected to be low and exhibit minimal levels of toxicity. Despite this, further research is required to better understand the fate of these emissions from this novel source (Kirchgeorg *et al.,* 2018).

Out of all the chemical elements involved, indium contributes the least to anode material (0.01 - 0.04%). However, given its low environmental occurrence, with just 0.05 ppm in the earth crust, galvanic anodes may present a significant new source of indium to the marine environment (Kirchgeorg *et al.,* 2018). As is the case with Al, indium emissions from galvanic anodes have been observed to accumulate in crustacea which may facilitate their entry to other trophic levels in the food chain (Bell *et al.,* 2020). Despite this, the impact of indium exposure to marine organisms and the environment has seen minimal research and thus further investigations are needed to better understand the potential for any toxicological impacts.

Studies into the potential environmental impacts of Al emissions to sea from galvanic anodes have mainly been restricted to laboratory experiments and harbour environments (Caplat *et al.,* 2010; Mao *et al.,* 2011; Gabelle *et al.,* 2012). A study in a harbour basin in France found that sediment concentrations of Al were significantly increased in the vicinity of anodes, however water concentrations did not exhibit any increases due to dilution effects. Conversely, experiments in seawater filled tanks without sediment showed high Al concentrations in the settled particles and in suspended particulate matter (SPM), which is argued to be of potential relevance to filter feeders (Deborde *et al.,* 2015). Despite this, Deborde *et al.,* (2015) also suspected that dissolved Al in seawater is not of impact to the environment, due to dilution effects.

It is clear that there is potential for a high amount of Al to be emitted by galvanic anodes of turbines. Whether these emissions will increase the dissolved Al concentration in seawater is unclear, due to the high dilution in the open sea. It is currently unknown if these emissions will have an effect on sediment concentrations and on benthos organisms. The total Al content of marine sediments is already high, because it originates from clay minerals and so it is challenging to differentiate natural background Al and the impact of the galvanic anodes on Al concentrations in sediment.

Risk-profiling

While both fixed and FLOW turbines will utilise galvanic anodes, fixed offshore wind farms are likely to have more. The monopiles of fixed offshore wind turbines will go all the to the seabed and will thus require a considerable number of anodes. Comparatively, it is only the floating structures of a FLOW turbine that would require protection from anodes. The studies discussed have also revealed that anode derived Al concentrations in the seawater are likely to have negligible impacts due to dilution. However, sediment concentrations of Al have been proven to increase in the vicinity of anodes. As a result, sediments in the area surrounding fixed turbine monopiles may therefore exhibit increased Al concentrations.

Overall, the number of anodes utilised by FLOW developments is therefore likely to be less. Anodes on FLOW turbines will also be considerably further from sediments than that of fixed turbines making it unlikely for sediments to be impacted. Consequently, this report suggests that the risk ranking should remain unchanged i.e., “**Low**” risk for all project lifecycle phases.

Mitigation measures

As stated previously, organic coatings can reduce the number of galvanic anodes required for corrosion protection, but coatings bring with them potential environmental impacts of their own.

Evidence gaps

Studies of Al emissions from galvanic anodes exist but are limited to laboratory experiments and harbour environments (Caplat *et al.,* 2010; Mao *et al.,* 2011; Gabelle *et al.,* 2012). While these studies can provide inferences as to what may occur in the vicinity of a FLOW development, there is need for FLOW-specific case studies into these potential emissions. In line with this need for research, there is a requirement for FLOW developments to state the likely number of galvanic anodes to be used on their structures to enable application of this necessary research.

Introduction of other substances (solid, liquid or gas)

Seawater is highly corrosive and as a result forms a major challenge for the construction and duration of FLOW infrastructure, which are mainly made of steel (Kirchgeorg *et al.,* 2018). Corrosion increases with salinity of seawater, but parameters such as oxygen concentration, pH (seawater 7.8 – 8.3), and temperature also affect corrosion processes (Sato, 2011; Adedipe *et al.,* 2016). Additionally, wind and waves, but also microbes, can act as a catalyst corrosion (Dinh *et al.,* 2004; Adedipe *et al.,* 2016; Price & Figueira, 2017).

Organic coatings such as epoxied (EP) resins and polyurethane (PUR) are novel corrosion protection techniques used in a variety of marine applications including parts of offshore turbines in contact with the seawater. These coatings provide an artificial barrier to separate the steel from seawater induced corrosion (Price & Figueira, 2017). During wind farm operations, weathering and leaching processes may result in the release of the organic compounds within these coatings into the seawater.

Bisphenol A (BPA) is a common starting product of EP resins and is omnipresent in the environment although not naturally occurring and as such it is under discussion as a substance of environmental concern (European Commission, 2010; Corrales *et al.,* 2015). BPA is also on the OSPAR list of substances of potential concern. Further to this, different reaction products of EP resins are currently under evaluation as suspected potential endocrine disrupters (Kirchgeorg *et al.,* 2018). Experiments on several fish species have shown that low concentrations of BPA can slow body growth, accelerate embryonic development as well as advancing reproductive maturation and hatching times (Ramakrishnan & Wayne, 2008). In addition, BPA has been found to negatively impact the development of the bivalve *Mytilus galloprovincialis* (Balbi *et al*., 2016). The impacts on life history traits associated with BPA may therefore bring negative individual and population impacts on marine species.

Risk-profiling

Fixed foundation and FLOW developments are both exposed to the same erosive processes, and both utilise organic coatings as protection. The environmental impacts of leached and weather coatings are therefore likely to be similar for both types of wind farms. Consequently, this report suggests that the risk ranking should remain unchanged i.e., “**Low**” risk for all project lifecycle phases.

Mitigation measures

Studies investigating the environmental concentrations of BPA in the North Sea and Baltic Sea have demonstrated low current background concentrations (Stachel *et al.,* 2003; Staniszewska *et al.,* 2014). The contribution of organic coatings, from offshore wind infrastructure, on BPA concentrations in the sea is currently unknown. However, the large number of proposed FLOW developments in the Celtic Sea may result in a new point source of organic chemicals like BPA in the area (Kirchgeorg *et al.,* 2018).

While there are currently limited substitutes for organic coatings, they can be used in combination with galvanic anodes on submerged parts of FLOW turbines. This combination reduces the material required for the anode which can thus reduce potential anode contaminants.

Evidence gaps

Concerns have arisen from surrounding the leaching and weathering of organic coatings from FLOW structures. As a result, there is a need to conduct research to investigate whether FLOW developments may act as a new point source of BPA to the marine environment and whether concerning concentrations may be introduced (Kirchgeorg *et al.,* 2018).

Synthetic compound contamination (including pesticides, antifoulants, and pharmaceuticals)

One of the principal advantages of FLOW developments are the opportunities they open for exploiting offshore areas, however increased distance from shore also leads to economic challenges of maintenance. According to the European Marine Energy Centre (EMEC), the biggest challenge will be dealing with biofouling, during operations, which involves the settlement and growth of marine biota on submerged structures (EMEC, 2018). When not maintained biofouling can lead to lowered operational lifespans of offshore assets and increased maintenance costs due to the distance of structures offshore. Additionally, it is in the best interest of developers to effectively manage biofouling given the likelihood that increased marine growth there will lead to increased snagging risk for fishing gear, as structures become increasingly textured (Maxwell *et al.,* 2022). It is therefore likely that, although in its infancy, FLOW developers consider implementing measures to prevent biofouling, since maintenance of offshore structures, especially those far from shore, is difficult and expensive.

In 2008, organotin-based antifouling paints were banned from use in the marine environment due to their highly toxic nature having been found to have damaging consequences on non-target species (Nurioglu *et al.,* 2015). Since then, biofouling protection throughout many marine industries has focussed on the use of zinc and/or copper based conventional or self-polishing copolymer antifouling paints (Ciriminna *et al.,* 2015). Booster biocides, such as copper pyrithione and zinc pyrithione, are being incorporating into these coatings to increase their longevity, despite the need for further research into their potential chronic impacts on the marine environment (Chambers *et al.,* 2006). For example, dissolved copper concentrations exceeding the US federal standard of 3.1 μg/L has been found to impact the development and survival of several mollusc, fish and echinoderm species (Thomas and Brooks, 2010). Although, it is worth noting that these impacts are generally limited to harbours and ports, which can accumulate elevated copper concentrations due to high boating activity.

Increased environmental concerns surrounding the use of heavy metals and booster biocides in antifouling coatings have instigated further research into alternative approaches to protect structures against biofouling. Developments have been made into the use of non-toxic and non-biocide releasing coatings, biomimetics and acoustic techniques (Chambers *et al.,* 2006; Ciriminna *et al.,* 2015; Nurioglu *et al.,* 2015).

Risk-profiling

The issue of biofouling, although still present, is of less concern for fixed offshore wind developments given that they are restricted to coastal areas where dealing with biofouling is more practical and economical. Novel approaches to preventing biofouling, applicable to both fixed offshore wind and FLOW developments, continue to be developed however the economics of treating versus preventing biofouling is likely to be of greater influence to fixed developments. Consequently, this report suggests that the risk ranking should remain unchanged i.e., "**Low**" risk for all project lifecycle phases.

Mitigation measures

Water quality in the vicinity of FLOW developments will depend on whether the offshore wind energy industry adopts (by choice or regulation) environmentally conscious alternatives to biofouling protection. Despite this, impacts are likely to be minor. Moreover, these challenges are not unique to FLOW developments and have to be addressed in other marine industries, including fixed offshore wind developments.

Evidence gaps

There is a lack of evidence and clarity, from the environmental and technical reports of FLOW developments, into the methods, if any, used to tackle biofouling. Indeed, this clarity also appears to be lacking for traditional fixed offshore wind developments. As with BPA, *in situ* research into potential release of contaminants from antifouling paints is required to establish whether quantities of paint used should be of environmental concern.

5. Conclusions

The findings presented within this report provide indicative risk-profile rankings and receptor sensitivity assessments for a number of pressures considered to be relevant to the development of FLOW. Throughout the report, differences and similarities with traditional fixed foundation offshore wind have been discussed. All lifecycle stages have been considered (construction, operation and maintenance, and decommissioning). In addition, potential mitigation measures have been described for each pressure, and any evidence gaps identified.

Based on a comprehensive literature review of available evidence, the findings of this report indicate that the following pressures are of **lower** risk for FLOW, in comparison to fixed foundation, and thus it is recommended that the risk-profile value should be decreased from “**Medium-High**” to “**Low**”:

- **habitat structure changes - removal of substratum (extraction)** – risk lowered from “**Medium-High**” to “**Low**” for all development lifecycle stages. Removal of substratum from the seabed only occurs for one FLOW anchor type: driven piles. This is only one potential anchor type of many to choose from. Furthermore, it is less likely that pre-sweeping activities will be required for FLOW due to smaller area of seabed required for installation and likely surface-laid inter-array cables.
- **underwater noise changes** – risk lowered from “**Medium-High**” to “**Low**” for all development lifecycle stages. For floating foundations, underwater noise is thought to be less of a risk and less impactful as there is not always pile-driving involved in installation of the turbines (many anchor types to choose from), and when there is, the piles are much smaller (driven pile anchors as opposed to piled foundations). There is also likely to be less vessel activity involved in FLOW construction, maintenance and decommissioning activities as a lot of this takes place at port.
- **above water noise** – risk lowered from “**Medium-High**” to “**Low**” for construction and decommissioning development lifecycle phases. Less above water noise during construction and decommissioning for FLOW, less offshore activity, and less vessel activity. Likely to remain the same during operation and maintenance as noise comes from turbines themselves, as well as maintenance vessels.

Based on a comprehensive literature review of available evidence, the findings of this report indicate that the following pressures are of **greater** risk for FLOW, in comparison to fixed foundation, and thus it is recommended that the risk-profile value should be increased from “**Low**” to “**Medium-High**”:

- **smothering and siltation rate changes (heavy)** – risk increased from “**Low**” to “**Medium-High**” for operation and maintenance lifecycle stage, due to the new source of seabed disturbance for FLOW during operation and maintenance; the movement of mooring lines and anchors on the seabed due to wave and current motion.

- **collision BELOW water with static or moving objects not naturally found in the marine environment (e.g., boats, machinery, and structures)** – risk increased from “**Low**” to “**Medium-High**” for operation and maintenance lifecycle stage. Increased risk during operation due to secondary and tertiary entanglement with fishing gear ensnared on mooring lines and anchors.

In addition to pressures where rankings have changed, two novel pressures were identified to be relevant to FLOW, which are previously ranked “**not relevant**” for fixed foundation offshore wind:

- **electromagnetic changes** – relevant to FLOW due to EMF from inter-array cables. FLOW will require inter-array cables being run across the seafloor and/or suspended in the water column, increasing the potential of impacts over fixed-foundation pile-driven turbines.
- **temperature increase** – relevant to FLOW due to temperature increase from inter-array cables. FLOW will require cables being run across the seafloor and/or suspended in the water column, increasing the potential of impacts over fixed-foundation pile-driven turbines.

Given that a number of differences have been identified in the impact of several pressures from FLOW development, as opposed to fixed foundation wind farm development, as well as the fact that two novel pressures have been considered relevant to FLOW that were previously assessed as “**not relevant**” for fixed foundation, this report recommends that Natural England add FLOW as a new and separate operation under the “electricity from renewable energy sources” drop down menu, with separate assessments in relation to sensitivity of features at benchmarks.

6. Recommendations

During the literature review and in-depth research undertaken as part of writing this report, a number of general recommendations have been identified.

Based on the overall objectives of this project, the most significant evidence gaps are considered to be:

- the lack of information relating to the impact of seabed disturbance pressures on specific habitats or sediment types
- information unable to be obtained relating to the design envelope for below water elements of wind turbines, specifically, quantitative figures for the seabed footprints of different anchor / mooring line types, penetration depth of different anchor types, and scour protection requirements

As the evidence gaps identified impact the robustness of this report, it is recommended that they are prioritised in further scopes of work.

Further stakeholder engagement activities would be likely to provide more detailed information relating to further refining the design envelope. As the UK FLOW market develops and projects formulate and finalise potential above and below water design envelopes, it may be possible to narrow and redefine the design envelope as considered within this report. From this, considerations of potential environmental impact assessment based on worst-case design scenarios could also be further refined.

To obtain information more easily on the environmental impacts of FLOW, an international repository could be developed for all FLOW project EIA and monitoring reports. This would allow national collaboration, data and lessons learnt sharing. As part of the literature review, a number of international developers who have commissioned and operated FLOW designs at a trial and precommercial scale were contacted in order to gain access to environmental reports to inform this study. Access to the reports was not always easily accessible as each country has its own permitting and regulating requirements. As we move towards commercial scale roll-out of FLOW internationally, it is recommended that the establishment of an international repository with the aim of information sharing would be beneficial. Moreover, as the UK aims to bring forward up to 5 GW of FLOW by 2030, as part of the British Energy Security Strategy, this report suggests that a UK repository specifically for FLOW would also be beneficial to data sharing and lessons learnt. The Crown Estate’s proposed Offshore Wind Evidence and Knowledge Hub (OWEKH) may provide a suitable platform for this.

Pressures that were not included in the Natural England Advice on Operations tool have not been assessed in this report. However, upon review of research, available information and evidence contained within FLOW case studies, a number of other pressures have been identified that could potentially be relevant (in addition to those already included in the tool). It is recommended that consideration be given to adding these pressures to the Natural England Advice on Operations tool for assessing the impacts of FLOW.

Additional pressures identified include:

- air quality
- impacts to climate change (carbon footprint)
- materials and waste
- socio-economic impacts (i.e., colocation and coexistence with commercial fisheries, shipping, cultural heritage, and other sea users)
- accidental events

In addition to this, it is recognised that the Advice on Operations tool is a useful resource for assessing the potential impacts of included pressures on protected areas in the vicinity of a wind farm site, however, there is no means to assess the impacts on species and habitats that exist in the area and are important (but are not necessarily a qualifying feature of a protected area).

An example of this is that all cetaceans are legally protected throughout Europe under the Habitats Directive, and specifically in the UK under the Wildlife and Countryside Act 1981 (as well as having EPS status). Section 3 demonstrates that many cetacean species are present throughout the Refined Areas of Search, and throughout the Celtic Sea in general. Despite this, the Bristol Channel Approaches / Dynesfeydd Môr Hafren SAC is the only protected area in the vicinity that lists a cetacean species (specifically, Harbour porpoise) as a designated feature. This means that for any other protected area in the vicinity of the Refined Areas of Search, impacts to marine mammals and cetaceans as a receptor would be considered not applicable. However, as there are cetacean species distributed throughout the Celtic Sea, impacts to marine mammals should be considered applicable for any location within the Celtic Sea (including in the vicinity of any of the protected areas).

The pressure “physical loss (to land or freshwater habitat)” refers to the physical loss of seabed and marine habitat in the context of this report. The pressure name has been retained as described in Natural England’s Advice on Operations tool for the purposes of consistency, however, it is recommended that the name of this pressure could be altered to reflect a wider range of habitats.

As well as using Natural England’s Advice on Operations tool, as FLOW projects will be located in sites beyond 12 nm of the coastline, the potential environmental impacts of a FLOW development should also be assessed in relation to the JNCC Pressure Activity Database (JNCC, 2022d).

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8. Glossary

Abbreviation	Definition
ACOPS	Advisory Committee on Protection of the Sea
ADDs	Acoustic Deterrent Devices
AFLOWT	Accelerating Market Uptake of Floating Offshore Wind Technology
AFS	Anti Fouling System
APHA	Animal and Plant Health Agency
BOEM	Bureau of Ocean Energy Management
CBD	Convention on Biological Diversity
Cefas	Centre for Environment, Fisheries and Aquaculture Science
CIS	Celtic and Irish Seas
CMID	Common Marine Inspection Document
Defra	Department for Environment, Food & Rural Affairs
EP	Epoxied
EPS	European Protected Species
ESAS	European Seabirds at Sea
ETI	Energy Technology Institute
EU	European Union
EUNIS	European Nature Information System
FADs	Fish Aggregating Devices
Fe	Iron
FLOW	Floating Offshore Wind
GES	Good Environmental Status
HF	High Frequency

Abbreviation	Definition
HPMAs	Highly Protected Marine Areas
HRA	Habitats Regulation Assessment
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IEMA	Institute of Environmental Management and Assessment
IMMAs	Important Marine Mammal Areas
IMO	International Maritime Organisation
INIS	Invasive non-indigenous species
IUCN	International Union for Conservation of Nature
JNCC	Joint Nature Conservation Committee
KBAs	Key Biodiversity Areas
KOWL	Kincardine Offshore Wind Farm Ltd
LF	Low Frequency
LiDAR	Light Detection and Ranging
MarESA	Marine Evidence based Sensitivity Assessment
MARPOL	International Convention for the Prevention of Pollution from Ships
MCA	Maritime and Coastguard Agency
MCZ	Marine Conservation Zones
MMO	Marine Management Organisation
MMOs	Marine Mammal Observers
MoD	Ministry of Defence
MPA	Marine Protected Areas
MU	Management Units
NCMPAs	Nature Conservation Marine Protected Areas
NOAA	National Oceanic and Atmospheric Administration

Abbreviation	Definition
NSTA	North Sea Transition Authority
OESEA4	UK Offshore Energy Strategic Environmental Assessment
OSC	Ocean Science Consulting
OSPAR	Oslo and Paris Convention
OWEC	Offshore Wind Evidence and Change Programme
OWEKH	Offshore Wind Evidence and Knowledge Hub
PAH	Polycyclic Aromatic Hydrocarbons
PMS	Planned Maintenance System
POSEIDON	Planning Offshore Wind Strategic Environmental Impact Decisions
PSSAs	Particularly Sensitive Sea Areas
PTS	Permanent Threshold Shift
PUR	Polyurethane
RNAS	Royal Navy Air Service
ROV	Remotely Operated Vehicle
RPP	Risk Profiling of Pressures
RSPB	The Royal Society for the Protection of Birds
SAC	Special Areas of Conservation
SAMS	Scottish Association for Marine Science
SAMS	Scottish Association for Marine Science
SCANS	Small Cetacean Abundance in the North Sea
SCUBA	Self-Contained Underwater Breathing Apparatus
SD	Standard Deviation
SDG	Sustainable Development Goal
SEL	Sound Exposure Level
SPA	Special Protection Area

Abbreviation	Definition
SPL	Sound Pressure Level
SPM	Suspended Particulate Matter
SSSIs	Sites of Special Scientific Interest
TBT	Tributyltin
TLP	Tension Leg Platform
TTS	Temporary Threshold Shift
UK	United Kingdom
UKHO	United Kingdom Hydrographic Office
UKMMAS	UK Marine Monitoring and Assessment Strategy Community
UN	United Nations
VHF	Very High Frequency
VMS	Vessel Monitoring System
Zn	Zinc

9. Appendix 1: Summary of risk-profiling and receptor sensitivity

Table 9-1 presents a summary of all risk-profiling, receptor sensitivity and FLOW design envelope recommendations discussed for each environmental impact throughout Section 4.

Table 9-1. Summary of risk-profiling, receptor sensitivity, and technical design envelope recommendations for FLOW

Pressure	Risk-profiling [note 1]	Comparison with fixed foundation	Justification	Sensitive receptors	Technical design envelope recommendations
Abrasion/disturbance of the substrate on the surface of the seabed	C - MH O&M - L D - MH	Remains the same	• Anchor/mooring line/cable abrasion on seabed during operation is a novel source of impact for FLOW. • Reduced impacts of scour for FLOW. • Smaller overall footprint on the seabed for FLOW.	• Epiflora and epifauna living on or at the surface of the substratum. • Sediments such as sand, mixed sediment, muddy sand, and sandy mud. • Biogenic reefs • Sandbanks	• TLP foundation type (smallest mooring footprint on seabed) • Taut mooring lines • Suction caisson anchors
Penetration and/or disturbance of the substratum below the surface of the seabed, including abrasion	C - MH O&M - MH D - MH	Remains the same	• Not always piling activities involved in FLOW. • Smaller penetration depth and footprint on the seabed for driven pile anchors compared to piled foundations.	• Macrofauna and near-surface infauna of the sediment. • Sediments such as sand, mixed sediment, coarse sediment, muddy sand and sandy mud. • Biogenic reefs • Sandbanks	• Gravity anchors (as they penetrate the seabed least)

Pressure	Risk-profiling [note 1]	Comparison with fixed foundation	Justification	Sensitive receptors	Technical design envelope recommendations
Habitat structure changes - removal of substratum (extraction)	C - L O&M - L D - L	Risk lowered from “MH” to “L” for all development lifecycle stages for FLOW	• Removal of substratum from the seabed only occurs for one FLOW anchor type - driven piles. • This is only one potential anchor type of many other available. • Unlikely for pre-sweeping to be required.	• Soft rocks (clays, peats, chalks). • Sediments such as sand, mixed sediment, coarse sediment, muddy sand, and sandy mud. • Biogenic reefs • Sandbanks	• Avoid using the driven pile anchor type.
Physical change (to another seabed type)	C - MH O&M - MH D - MH	Remains the same	• Both fixed and floating foundations result in physical change to seabed type in different ways • Similar artificial reef effect	• All types of substratum. • Sediments such as sand, mixed sediment, and coarse sediment. • Biogenic reefs • Sandbanks	• Selection of infrastructure that introduces minimal hard substrate to the seabed e.g., designs with less surface area and those which are less susceptible to scour effects and thus require little to no scour protection. • Bury inter-array cables where possible (so that they do not require rock dump for protection).
Physical change (to another sediment type)	C - MH O&M - MH D - MH	Remains the same	• See physical change (to another seabed type)	• All types of substratum, except hard substratum habitats. • Sediments such as sand, mixed sediment,	• See physical change (to another seabed type)

Pressure	Risk-profiling [note 1]	Comparison with fixed foundation	Justification	Sensitive receptors	Technical design envelope recommendations
				coarse sediment, muddy sand and sandy mud. • Biogenic reefs • Sandbanks	
Physical loss (to land or freshwater habitat)	C - MH O&M - MH D - MH	Remains the same	• Lower impact overall for FLOW due to the smaller footprint on the seabed, however, still considerable habitat loss associated with FLOW anchors and mooring lines.	• Receptors within the direct spatial footprint of this pressure are considered to be highly sensitive. • Most benthic species will be sensitive and their resistance dependent on their ability to relocate.	• Selection of infrastructure that has the smallest footprint on the seabed. • TLP foundation type (smallest mooring footprint on seabed) • Taut mooring lines • Suction caisson anchors
Smothering and siltation rate changes (Light)	C - MH O&M - MH D - MH	Remains the same	• Anchor/mooring line/cable abrasion on seabed during operation is a novel source of impact for FLOW. • Reduced impacts of scour for FLOW.	• Benthic organisms that have a low tolerance to burial / hypoxic conditions. • Sediments such as mixed sediment, muddy sand and sandy mud. • Biogenic reefs • Sandbanks	• Taut or semi-taut mooring lines (to reduce the length of mooring chain resting on the seafloor).
Smothering and siltation rate changes (Heavy)	C - L O&M - MH D - N/A	Risk increased from “L” to “MH” during O&M phase for FLOW	• Anchor/mooring line/cable abrasion on seabed during operation is a novel source of impact for FLOW.	• Benthic organisms that have a low tolerance to burial / hypoxic conditions.	• See smothering and siltation rate changes (Light)

Pressure	Risk-profiling [note 1]	Comparison with fixed foundation	Justification	Sensitive receptors	Technical design envelope recommendations
		🟥		• Sediments such as sand, mixed sediment, coarse sediment, muddy sand and sandy mud. • Biogenic reefs • Sandbanks	
Changes in suspended solids (water clarity)	C - L O&M - L D - L	Remains the same	• See Smothering and siltation rate changes (Light).	• Light-dependant algae and other photosynthetic marine organisms • Suspension-feeding organisms • Sediments such as mixed sediment, coarse sediment, muddy sand, and sandy mud.	• See smothering and siltation rate changes (Light)
Visual disturbance	C - MH O&M - MH D - MH	Remains the same	• Above water structures remain largely unchanged. • Avoidance effects from visual disturbances are not expected to differ across foundation types except that floating foundations have relatively less infrastructure extending throughout the entire water column.	• Visual disturbance is only relevant to species that respond to visual cues, for hunting, behavioural responses, or predator avoidance, and that have the visual range to perceive cues at distance. • It is particularly relevant to fish, birds,	• Consideration of turbine size, height, number, material, and colour during design. • Smaller foundation types may have less of a visual impact.

Pressure	Risk-profiling [note 1]	Comparison with fixed foundation	Justification	Sensitive receptors	Technical design envelope recommendations
				reptiles, and mammals.	
Barrier to species movement	C - L O&M - MH D - L	Remains the same	• No significant difference between FLOW and fixed foundation offshore wind.	• Mobile species such as fish, birds, reptiles, and mammals. • Macrofauna such as crabs, which undertake migrations to over-winter or to breed, and where populations are dependent on larval or other propagule supply from outside the area.	• Increased spacing between turbines.
Collision ABOVE water with static or moving objects not naturally found in the marine environment (e.g., boats, machinery, and structures)	C - L O&M - MH D - L	Remains the same	• Above water structures remain largely unchanged. • Bird abundance lower offshore, bird flight style / flight height is different offshore (gliding movements more vulnerable to collision). • Turbines are dynamically moving, so may present slightly higher collision risk.	• Only relevant to mobile species. • The main receptor for this pressure is seabirds.	• Paint rotor blades in contrasting colours. • Raising wind turbine hub height and using fewer and larger turbines.
Collision BELOW water with static or moving objects not naturally found in the marine environment (e.g., boats, machinery, and structures)	C - MH O&M - MH D - MH	Risk increased from “L” to “MH” during all phases for FLOW	• Lower risk of vessel collision due to less vessel movement / offshore activities involved in FLOW. • Increased risk during operation due to secondary entanglement with fishing gear ensnared on mooring lines.	• Only relevant to mobile species. • The main receptors for this pressure are diving seabirds, marine mammals and possibly fish.	• Bury inter-array cables where possible. • High contrast mooring line colour. • Lower number and taut mooring lines.

Pressure	Risk-profiling [note 1]	Comparison with fixed foundation	Justification	Sensitive receptors	Technical design envelope recommendations
		🟥			• Consideration of materials used to construct mooring lines i.e., chains and nylon ropes are thought to have a higher snagging potential.
Water flow (tidal current) changes, including sediment transport considerations	C - L O&M - MH D - L	Remains the same	• No evidence to suggest it would be different. • Potentially lower risk as FLOW occupies less space in water column.	• Biotopes which occur in weak to negligible tidal streams, e.g. very deep waters, where currents are typically weak near the seabed. • Sediments such as sand, mixed sediment, muddy sand, sandy mud. • Biogenic reefs	• Selection of infrastructure that has the smallest surface area.
Wave exposure changes	C - N/A O&M - L D - N/A	Remains the same	• No evidence to suggest it would be different. • Potentially lower risk as FLOW occupies less space in water column.	• Habitats (biotopes) or species that require sheltered conditions or substrata that depend on sheltered conditions. • Biogenic reefs	• See water flow (tidal current) changes.
Underwater noise changes	C - MH O&M - MH D - MH	Remains the same	• Not always piling activities involved in FLOW (only during installation of driven pile anchor type) and when there is, the piles are likely to be smaller.	• Mobile species, in particular, fish, marine reptiles, and mammals that respond to sound and/or use sound for	• Selection of technology types which are quieter to install.

Pressure	Risk-profiling [note 1]	Comparison with fixed foundation	Justification	Sensitive receptors	Technical design envelope recommendations
			• Less vessel movement / offshore activities involved in FLOW. • Insufficient evidence to know how frequently piling activities will take place as part of FLOW construction, thus ranking remains the same.	echolocation, communication or hunting.	• Avoid driven pile anchor types. • Select suction caissons, drag, dead-weight, or embedded anchors
Above water noise	C - L O&M - L D - L	Risk lowered from “MH” to “L” during C and D phases for FLOW.	• Less vessel movement / offshore activities involved in FLOW. • Above water structures remain largely unchanged. • Same aerodynamic noise from the blades, and mechanical noise associated with machinery housed in the nacelle of the turbine.	• The main receptor for this pressure is seabirds.	• No technical design envelope recommendations have been identified.
Vibration	C - L O&M - L D - L	Remains the same	• See underwater / above water noise.	• Benthic invertebrates (and, hence their communities).	• Selection of designs with minimal contact with the seabed.
Electromagnetic changes	C - L O&M - L D - L	Novel pressure added for FLOW, as considered “not relevant” to fixed foundation.	• EMF from inter-array cables. • Cables run across the seafloor, as well as suspended in the water column for FLOW, increasing the potential of impacts over fixed foundation turbines. • Ranked the same as “power cable: operation and maintenance”.	• Species sensitivity depends on the ability of the species to sense the EMF and the degree to which this affects the species. • Fish species, elasmobranchs (i.e., sharks, skates, and	• Bury inter-array cables where possible.

Pressure	Risk-profiling [note 1]	Comparison with fixed foundation	Justification	Sensitive receptors	Technical design envelope recommendations
				rays), cetaceans (i.e., whales and dolphins), some sea turtles, and invertebrates (i.e., some snails, lobsters, and crabs) are all considered sensitive. • Elasmobranch fish species considered most sensitive due to highly sensitive electro-sensory system.	
Temperature increase	C - L O&M - L D - L	Novel pressure added for FLOW, as considered "not relevant" to fixed foundation.	• Temperature increase from inter-array cables. • Cables run across the seafloor, as well as suspended in the water column for FLOW, increasing the potential of impacts over fixed foundation turbines. • Ranked the same as "power cable: operation and maintenance".	• Species with a restricted distribution, those that only occur in isolated areas or thermally stable environments (e.g. deep water), or those that are at their southern or northern limits in UK waters.	• Design inter-array cables to minimise thermal loss.
Introduction of light	C - L O&M - L D - L	Remains the same	• Less vessel movement / offshore activities involved in FLOW. • Above water structures remain largely unchanged. • Same light sources.	• Birds and sea turtles are the receptors most sensitive to introduction of light, but also other marine species e.g. possibly plants and algae.	• No technical design envelope recommendations have been identified.

Pressure	Risk-profiling [note 1]	Comparison with fixed foundation	Justification	Sensitive receptors	Technical design envelope recommendations
Introduction or spread of invasive non-indigenous species (INIS)	C - L O&M - L D - L	Remains the same	• Increased risk of INIS spread for FLOW due to construction at port and towing out to site, as well as towing to port and back for maintenance. • Not considered significant enough to change ranking.	• Native species that INIS compete with.	• Selection of floating foundations that are constructed at the offshore site instead of in port.
Litter	C - L O&M - L D - L	Remains the same	• Normal shipping rules apply to both fixed and floating foundation wind farms.	• Large macrofauna such as fish, birds, and mammals.	• No technical design envelope recommendations have been identified.
Hydrocarbon & PAH contamination	C - L O&M - L D - L	Remains the same	• Lower potential for vessel collision and subsequent hydrocarbon spills for FLOW due to less vessel activity.	• Seabirds are particularly sensitive to the effects of surface oil pollution. • Marine mammals. • Fish spawning and nursery areas.	• No technical design envelope recommendations have been identified.
Transition elements & organo-metal (e.g., TBT) contamination	C - L O&M - L D - L	Remains the same	• Number of anodes utilised by FLOW likely to be less than fixed foundation. • Anodes on FLOW turbines further from sediments than that of fixed turbines, making it less likely for sediments to be impacted.	• Benthic organisms.	• No technical design envelope recommendations have been identified.
Introduction of other substances (solid, liquid or gas)	C - L O&M - L D - L	Remains the same	• FLOW and fixed foundation developments both exposed to the same erosive processes, and both utilise organic coatings as protection.	• Fish and bivalves.	• No technical design envelope recommendations have been identified.

Pressure	Risk-profiling [note 1]	Comparison with fixed foundation	Justification	Sensitive receptors	Technical design envelope recommendations
Synthetic compound contamination (including pesticides, antifoulants, pharmaceuticals)	C - L O&M - L D - L	Remains the same	• Biofouling of increased concern for FLOW given location further offshore where dealing with biofouling may be less practical / economical. • Prevention mitigation measures more likely than treating biofouling for FLOW.	• Mollusc, fish and echinoderm species.	• No technical design envelope recommendations have been identified.

[note 1] Separate risk rankings are provided for each lifecycle phase of FLOW (e.g., construction, operation and maintenance, and decommissioning).

Key:
C - Construction
O&M - Operation and Maintenance
D - Decommissioning
L - Low
MH - Medium-High
N/A - Not applicable

10. Appendix 2: Summary of mitigation measures

Table 10-1 presents a summary of all mitigation measures identified for each environmental impact throughout Section 4.

Table 10-1. Summary of mitigation measures identified for each pressure relevant to FLOW

Pressure	Mitigation measures identified
Abrasion/disturbance of the substrate on the surface of the seabed	• Placing anchors and mooring lines in areas of lower ecological importance, avoiding important benthic habitats (i.e., structure forming organisms such as corals and sponges). • Designated or directed anchoring, whereby anchors are guided during anchor fall to direct exactly where the anchor will land on the seabed. • Reducing the length of the mooring chain, ensuring that any excess length of chain that is needed to adjust for drift does not rest on the seabed. • 'Nature inclusive design' options, such as the use of reef balls or additional rocks to reduce scour from mooring lines or cables.
Penetration and/or disturbance of the substratum below the surface of the seabed, including abrasion	• Selection of an anchor design with a smaller penetration depth, such as gravity anchors which have a high seabed footprint due to larger surface area but can be installed on thin substrate layers.
Habitat structure changes - removal of substratum (extraction)	• Selection of an anchor design with a smaller footprint on the seabed, as well as a smaller penetration depth. Suction caisson anchors have the smallest seabed footprint of the anchor types considered in this report, however, a trade-off exists between seabed footprint and seabed penetration depth.
Physical change (to another seabed type)	• Burying inter-array cables where possible, so that they do not require the addition of rock dump for protection. • A suitable trenching route for inter-array cables should also be selected (if possible), which does not pass through rocky areas where burial may be challenging. This will minimise sections of particularly exposed cable / spans and reduce the requirement for spot rock dump. • In terms of the artificial reef effect, foundations with a larger surface area on the seabed and in the water column provide the most habitat for species to colonise and become established. The spar buoy floating foundation type can extend to approximately 100 m deep, which could provide greater amounts of habitat opportunities. Thus, a suitable mitigation measure may be to select a smaller foundation type. • The nature of scour protection used for a structure also contributes to the magnitude of an artificial reef effect. An appropriate mitigation measure would be selection of infrastructure that introduces minimal hard

Pressure	Mitigation measures identified
	substrate to the seabed e.g., designs which are less susceptible to scour effects and thus require little to no scour protection.
Physical change (to another sediment type)	• As above for physical change (to another seabed type).
Physical loss (to land or freshwater habitat)	• Reduce the overall area or footprint of the turbine anchor, mooring line and cable array. • Use a low footprint mooring line configuration such as taut or semi-taut moorings, and a less impactful anchor type (e.g., suction or gravity anchors).
Smothering and siltation rate changes (Light)	• Potential mitigation could include restricting or avoiding operations during key species spawning seasons (e.g.,herring) to limit disturbance to adult fish, eggs and hatching larvae from increased turbidity and sediment deposition. • Taut or semi-taut mooring lines as the selected technology type.
Smothering and siltation rate changes (Heavy)	• As above for smothering and siltation rate changes (Light).
Changes in suspended solids (water clarity)	• As the impacts associated with changes in suspended solids relate closely to smothering and siltation rate changes, no specific mitigation measures have been identified for changes in suspended solids. • See above for mitigation measures related to smothering and siltation rate changes.
Visual disturbance	• Consideration of turbine characteristics such as the turbines size, height, number, material, and colour during design. • In addition, different floating foundation types have a different visual impact due to size and presence in the water column. Smaller foundation types may have less of a visual impact. Spar buoys tend to be the largest foundation type in terms of how far they extend into the water column, with a typical draft of up to 100 m. However, semi-submersible and barge foundation types have a comparably large surface area (40-50 m length/width for barge and 60-80 m length/width for semi-submersible).
Barrier to species movement	• Placing turbines in low-impact areas, or “smart siting”, particularly avoiding areas high in biodiversity. • Spacing turbines further apart. • Adjusting wind farm configuration to suit bird major flight or migration routes.
Collision ABOVE water with static or moving objects not naturally found in the marine environment (e.g., boats, machinery, and structures)	• Vision-based wind turbine mitigation measures i.e., painting rotor blades in contrasting colours. • Installing auditory deterrent devices. • Restricting wind turbine operation at certain times, seasons, or during specific weather conditions. • Raising wind turbine hub height and using fewer and larger turbines. • Careful siting of FLOW farms to ensure minimal overlap with important habitats, protected areas, migration corridors, and large populations of high-risk species.

Pressure	Mitigation measures identified
	• Reducing vessel activities i.e., number of vessels and number of transits. • Reducing vessel speed to 10 knots or less. • Training vessel crew as lookouts. • Using dynamic management techniques for vessels.
Collision BELOW water with static or moving objects not naturally found in the marine environment (e.g., boats, machinery, and structures)	• Burying inter-array cables where possible. • Regularly cleaning lines and cables. • Applying mitigation measures used to reduce biofouling. • Conducting routine inspections of submerged structures. • Acoustic deterrent devices, pingers. • Selection of a high contrast mooring line colour that may be more easily observed by receptor species. • Selection of a lower number and greater tautness of mooring lines. Taut mooring configurations are preferable because less slack in lines is likely to reduce entanglement potential. • Consideration of materials used to construct mooring lines i.e., chains and nylon ropes are thought to have a higher snagging potential. • Siting FLOW farms in areas that reduce overlap with biologically important areas, such as feeding grounds and migration corridors.
Water flow (tidal current) changes, including sediment transport considerations	• Wake redirection, whereby wind turbine rotors are statically yawed to divert the wake away from downstream turbines. • Pitching the floating foundation using ballast in the buoys. As the platform is pitched, the wake is either deflected upwards or downwards, depending on the pitch angle. • Dynamic induction control, increasing the mixing in the wake. • The Helix approach, where each of the blades is individually pitched in a sinusoidal manner resulting in a non-uniform loading of the turbine.
Wave exposure changes	• As the impacts associated with wave exposure changes relate closely to water flow (tidal current) changes, no specific mitigation measures have been identified for wave exposure changes. • See above for mitigation measures related to water flow (tidal current) changes.
Underwater noise changes	• Employing standard noise mitigation measures implemented in the UK (i.e., soft start piling (for both fixed foundations and FLOW driven anchor piles), ADDs and MMOs. • Modified construction methods. • Schedule restrictions to time-sensitive windows if the area is within a breeding range, avoiding siting within migration corridors and coastal pinniped resting areas. • Vessel speed restrictions.

Pressure	Mitigation measures identified
	• Selecting technology types which are quieter to install. Fewer noise-emitting activities occur during installation of floating foundations that use suction caissons, drag, dead-weight, or embedded anchors. • Reduction of sound sources to minimise noise levels i.e., bubble curtains, casing-based systems, and encapsulated resonator systems. Encapsulated resonator systems likely to be most effective for FLOW due to depth restrictions associated with other techniques.
Above water noise	• Reducing the noise levels at the source (e.g., operating equipment at the lowest practicable noise level). • Spatially and/or temporally separating the noise-producing activity from the sensitive species e.g., for migratory species, impacts can be reduced by limiting construction activities to seasons when fewer animals are present or when animals are not engaging in biologically important activities.
Vibration	• As the impacts associated with vibration relate closely to underwater and above water noise, no specific mitigation measures have been identified for vibration. • See above for mitigation measures related to underwater/ above water noise.
Electromagnetic changes	• Monitoring cables for wear and tear, especially dynamic cables, as they are more vulnerable to wear through hydrodynamic stress. • Burying cables where possible. Field strength dissipates quickly, and burial of cables increases distance between source and species receptors, so is an effective mitigation.
Temperature increase	• Designing inter-array cables to minimise thermal loss.
Introduction of light	• The use of blue and green lighting may reduce disorientation in nocturnally migrating birds more than red and white lighting. • Lighting should be minimised whenever and wherever possible, including number, intensity, and duration. • Flashing lights should be used instead of steady burning lights whenever practicable, and the lowest flash rate practicable should be used (BOEM recommends 30 flashes per minute). • Direct lighting should be avoided, and indirect lighting of the water surface should be minimised. • Lighting should be directed to where it is needed, and general area “floodlighting” should be avoided. • Area and work lighting should be limited to the amount and intensity necessary to maintain worker safety. • Using automatic timers or motion-activated shutoffs for all lights not related to aviation obstruction lighting or marine navigation lighting should be considered. • Aviation obstruction lighting that is most conspicuous to aviators, with minimal lighting spread below the horizontal plane of the light.
Introduction or spread of invasive non-indigenous species (INIS)	• Regularly cleaning structures so they are free of biofouling. • Construct floating foundations in situ at the offshore site instead of in port (however, this is likely not the most practical option and would form a trade-off with a number of other pressures).

Pressure	Mitigation measures identified
	• Have a biosecurity plan in place. • Population level control or eradication of INIS, if detected during monitoring, by methods such as removal/air drying, chemical treatment, smothering, mechanical scouring, or freshwater pulses.
Litter	• Complying with normal shipping rules, legislation, codes of conduct and best practice. • Marine litter survey and assessment prior to decommissioning could be carried out.
Hydrocarbon & PAH contamination	• Notifications to mariners and Kingfisher Bulletin prior to operations. • Compliance with MGN 654 and providing appropriate markings on UKHO Admiralty charts. • Establishment of a buoyed construction area and application of exclusion zones up to 500 m during construction.
Transition elements & organo-metal (e.g., TBT) contamination	• Organic coatings can reduce the number of galvanic anodes required for corrosion protection.
Introduction of other substances (solid, liquid or gas)	• Use organic coatings in combination with galvanic anodes on submerged parts of FLOW turbines. This combination reduces the material required for the anode which can thus reduce potential anode contaminants.
Synthetic compound contamination (including pesticides, antifoulants, pharmaceuticals)	• Adopting environmentally conscious alternatives to biofouling protection.

11. Appendix 3: Summary of evidence gaps

Table 11-1 presents a summary of any evidence gaps identified and described for the environmental impacts in Section 4.

Table 11-1. Summary of evidence gaps identified for each pressure relevant to FLOW

Pressure	Evidence gaps identified
Seabed disturbance [note 1]	• In general, seabed disturbance pressures were understood for the majority of marine activities involved with FLOW. • Evidence gaps have been identified regarding the impacts of all seabed disturbance pressures (i.e., abrasion, penetration, introduction of hard substrate, suspended sediment and smothering) on specific sediment and habitat types (e.g., EUNIS habitat types such as offshore circalittoral coarse sediment). • To improve the understanding of seabed disturbance impacts on specific sediment/habitat types, monitoring surveys should be conducted, or numerical modelling carried out to predict potential impacts of various scenarios on these sediment/habitat types.
Abrasion/disturbance of the substrate on the surface of the seabed	• As abrasion to the surface of the seabed encompasses all footprints on the seabed from FLOW activities (both permanent and temporary), quantitative figures estimating the resultant footprints from all of these activities (including different anchor / mooring line / inter-array cable configurations) would be useful in assessment of associated impacts. • The seabed footprint of the various FLOW subsea infrastructure presents an evidence gap currently. • In addition, information relating to quantities of scour protection required for the various anchor and mooring line designs was also unable to be found. • Further to this, it is not yet known to what extent temporary seabed disturbance during FLOW turbine installation may occur, as well as the likely footprint for dynamic movement of mooring lines/anchors on the seabed during operation. • There is no evidence from existing FLOW developments to support the conclusion that erosional impacts of scour during the operational phase are likely to be reduced in FLOW compared to fixed foundation offshore wind.
Penetration and/or disturbance of the substratum below the	• In order to fully assess the impact on seabed penetration for FLOW developments, more detailed information is required on the penetration depth for the various anchor technology types. Each anchor type

Pressure	Evidence gaps identified
surface of the seabed, including abrasion	penetrates the seabed to differing degrees, however, specific quantitative figures (i.e., depth of penetration in metres) were unable to be found for each anchor type.
Habitat structure changes - removal of substratum (extraction)	• As use of the driven pile anchor type is likely to be the only source of removal of substratum from the seabed for FLOW activities, specific quantities of sediment likely to be removed during the use of these anchors would have been beneficial to the assessment of this impact. It is known that driven pile anchors are smaller than piled foundations, however, quantitative figures for volume of material removed from the seabed would make this comparison (as well as relative seabed disturbance impacts) clearer.
Physical change (to another seabed type)	• Information on the extent of scour protection / rockdump required for different FLOW anchor and mooring line designs was unable to be obtained. This information would be useful in assessing the possible extent of the artificial reef effect at a FLOW farm. • In addition, further quantification of the seabed footprint for different anchor and mooring line designs would be beneficial in assessment of this impact.
Physical change (to another sediment type)	• As above for physical change (to another seabed type).
Physical loss (to land or freshwater habitat)	• As habitat loss is directly related to the permanent footprint of structures placed on the seabed, quantitative information regarding the footprint on the seabed of different anchor and mooring line arrangements, as well as inter-array cables and possible scour protection is key to its assessment. • The seabed footprint of the various FLOW subsea infrastructure presents an evidence gap currently.
Smothering and siltation rate changes (Light)	• As above for penetration of the seabed and habitat change (removal of substratum), the volume of sediment that may become suspended in the water column during operation (and thus the area that may be impacted by smothering) depends on penetration depth and volume of substratum removed for the various anchor types. • In addition, as with the impacts of abrasion to the seabed, it would depend on the level of movement taking place in mooring lines on the seabed during operation (i.e., how much sediment they are disturbing due to continual action by waves and currents). For this reason, these evidence gaps are also relevant to smothering and siltation rate changes (light/heavy). • Further to the evidence gaps already identified for other pressures, more research into the scour potential of FLOW infrastructure would be useful to inform this section, as structures with decreased scour potential will experience fewer effects of suspended sediment / sediment deposition.
Smothering and siltation rate changes (Heavy)	• As above for smothering and siltation rate changes (Light).

Pressure	Evidence gaps identified
Changes in suspended solids (water clarity)	• As the impacts associated with changes in suspended solids relate closely to smothering and siltation rate changes, no specific evidence gaps have been identified for changes in suspended solids. • See above for evidence gaps related to smothering and siltation rate changes.
Visual disturbance	• Visual disturbance impacts are linked to various activities, however, quantification of this was found to be extremely difficult, and thus should be identified on a case-by-case basis for FLOW developments. • Use of helicopter landing pads on FLOW turbines.
Barrier to species movement [note 1]	• To be able to assess the occurrence of barrier effects of offshore wind farms on birds, and the extent of these barrier effects, more information is required on species-specific avoidance rates. • Subject matter experts with relevant ornithological expertise on offshore distribution should be engaged to appraise the questions of barrier effects and attraction of birds in further detail. • The emerging range of ornithological evidence further offshore from survey effort in other industries should be used to inform potential impacts of FLOW (for example, the increasing body of ornithological evidence associated with decommissioning of North Sea oil and gas assets). • Identify and assess any challenges related to the development of FLOW farms at unprecedented distances from shore (as FLOW farms are generally located further offshore than fixed foundation wind farms, where bird species abundance is different).
Collision ABOVE water with static or moving objects not naturally found in the marine environment (e.g., boats, machinery, and structures) [note 1]	• Whilst there has been considerable research and discussion about collision risks for turbines broadly, there are significant gaps in the current understanding of seabird and floating turbine specific collision risk. • More qualitative data is required on the number of collision victims among birds, as well as more field data on attraction / avoidance rates. • Further study of bird flight height, flight behaviour, and floating turbine motion. • Bats and offshore wind are also identified as a data gap where further research should be prioritised to identify bat distribution, migration routes, and collision risk with offshore wind turbines.
Collision BELOW water with static or moving objects not naturally found in the marine environment (e.g., boats, machinery, and structures) [note 1]	• More information on the frequency and occurrence of entanglement events. As FLOW develops and if entanglement is physically observed and monitored, more information will become available. • Develop more effective technologies for monitoring, detecting, and removing marine debris snagged on FLOW cable systems. • NOAA, supported by BOEM are currently developing a modelling tool to evaluate the risk of whale species and leatherback sea turtles in deep water becoming entangled in derelict fishing gear snagged on FLOW cable systems. • As well as entanglement, documentation of ship strikes on different species is variable e.g., in the case of porpoises is very low.

Pressure	Evidence gaps identified
	• The likelihood of marine megafauna being able to break a suspended inter-array cable if they became entangled in it. • The possibility that marine mammal echolocation may be able to detect some mooring line designs (i.e., material and configuration) better than others, and could this be a suitable mitigation measure to reduce risk of entanglement.
Water flow (tidal current) changes, including sediment transport considerations	• Very limited studies available on the impacts on water flow resulting from offshore wind farms, and in particular there were no studies describing differences between fixed and floating foundations. • Further research into how and to what degree the development of increasingly extensive offshore wind farms will have an impact on atmospheric / oceanic changes, and how this may impact marine ecosystem productivity.
Wave exposure changes	• Available literature on the topic of wave exposure tends to be grouped with water flow (tidal current) changes to describe changes in hydrogeology/ ocean dynamics in a more general sense, as opposed to specifically describing impacts on wave exposure or nearshore significant wave height. The impacts of FLOW on nearshore significant wave height is an evidence gap. • Instead, wake effects in water have been discussed in this section.
Underwater noise changes [note 1]	• Whilst there is significant data on hearing in pinnipeds and cetaceans, there are significant data gaps in our understanding of how underwater noise affects fish and invertebrates. Collection of improved data and information on the behavioural effect of noise on fish and invertebrates is necessary. • Establish thresholds for assessing behavioural disturbance to fish. • Development of audiograms for key species using behavioural analysis. • Strategic research to investigate the scale of the effect of noise exposure on fish and invertebrates that may result in population level impact on economic impact to fisheries. • Development of detailed guidance to help the assessment of behavioural effects on fish. • Provision of guidance on the approach to be taken for assessment of impacts on invertebrates in the absence of standard noise exposure criteria for this group. • Testing of noise abatement methods at wind farms during construction and their effectiveness in mitigating impacts on fish (given that most standard underwater noise mitigation measures are designed to minimise impacts on marine mammals, not fish). • Further research on underwater noise impacts on turtles. • Testing and monitoring the use and success of underwater noise mitigation measures for FLOW, as opposed to fixed foundation offshore wind. Most technologies have been tried and tested for fixed

Pressure	Evidence gaps identified
	foundation offshore wind farms, but not for FLOW, and thus more research is required to determine if similar mitigation measures are applicable to the different offshore wind farm designs.
Above water noise	• More baseline data on above water noise levels in offshore wind farm areas is needed, particularly studies that estimate noise at various distances from turbines to determine baseline levels prior to construction, installation, and operation of FLOW turbines, with control sites for future monitoring. • Further research on hearing abilities and sensitivity to noise in seabirds.
Vibration	• As the impacts associated with vibration relate closely to underwater and above water noise, no specific evidence gaps have been identified for vibration. • See above for evidence gaps related to underwater/ above water noise.
Electromagnetic changes [note 1]	• It is well-recognised that the impact of EMF presents an evidence gap as a whole. • Currently, conclusive evidence is insufficient and additional knowledge about receptor species' (both benthic and pelagic, and at different life stages) exposure to different EMFs (i.e., sources, intensities), and the determination of the EMF environment, is needed. • More laboratory and field experiments should be conducted to test EMF effects on different groups of species. • Further targeted physiological and behavioural free-ranging studies are also required to determine the energy and time costs associated with the impacts on species from EMFs. • Most studies to date (although limited) tend to focus on one single cable, however, consideration should be given to studies which allow the collection of evidence on repeated exposure due to the encounter of multiple cables (as would be the configuration of wind fam inter-array cables). This would facilitate the evidence in respect of cumulative impacts, which is currently lacking. • While field studies have been conducted on the effects of EMF from cables buried in the seabed, there is an even more limited understanding of the EMF impacts of dynamic cables suspended in the water column. More work needs to be done to understand attraction or aversion effects of suspended cables, particularly on pelagic species (but also demersal). • In situ monitoring of dynamic FLOW inter-array cables would be valuable to addressing this knowledge gap and substantiating any current predictions.
Temperature increase	• Whilst there was some information on temperature increase associated with wind farm export cables, an evidence gap exists whereby there is a lack of research into the temperature increased caused by inter-array cables specifically. • Lack of research investigating the environmental impact of temperature increase resulting from subsea cables generally (on benthic communities or other marine life).

Pressure	Evidence gaps identified
	• Limited information on potential mitigation measures that could be used to reduce the impacts of temperature increase associated with subsea cables.
Introduction of light	• The impacts of introducing artificial light to the marine environment is generally well-studied as it is an impact which is common to most offshore marine activities i.e., oil and gas. However, evidence specific to offshore wind farms and FLOW in particular, is lacking. • Lack of available evidence on whether it is possible introduction of light could interfere with benthic invertebrates and/or spawning cues. • Lack of evidence to prove claims that the introduction of light could potentially be beneficial for immersed plants or lead to increased algal growth. • As introduction of light can be a cause of the barrier effect, further research is needed to quantify attraction/ avoidance effects of FLOW on birds.
Introduction or spread of invasive non-indigenous species (INIS)	• There is a wealth of literature and guidance available on the topic of mitigation measures for managing introduction or spread of INIS in the marine environment for offshore sites generally, however, an evidence gap has been identified in that there are no studies focussing on practical application of these mitigation measures to FLOW farms, or evidence of their use and success in practise. • No case studies with examples of FLOW developments where INIS have been identified were available at the time of writing. Noted that in 2017, a number of articles were published stating that research had begun by SAMS to examine how FLOW farms could provide a new route for invasive species to spread across the oceans, with Hywind Scotland FLOW to be used as an example. However, no published papers on the topic are available as of yet.
Contamination	• In general, pollution/contamination pressures were identified for a number of activities, especially in the case of marine litter, synthetic compounds, transition elements and organo-metal contamination. However, quantification was often not available and literature raised some concerns on the lack of information on interaction of pollutants arising from different activities.
Litter	• Marine litter was reported to be produced by a number of marine activities in literature. However, it was often difficult to identify the source of litter, and evidence was usually not accompanied by quantification. • There was no evidence available for documented marine litter from FLOW developments specifically. • Further research is required to assess the potential for microplastic pollution from turbines utilising various materials and under different environmental conditions.
Hydrocarbon & PAH contamination	• Although there is an abundance of information into the impacts of hydrocarbon spills to the marine environment there is little attention paid to this in the environmental and technical reports of FLOW

Pressure	Evidence gaps identified
	developments. In order to capture all aspects of environmental concerns FLOW developments should incorporate worst-case spill modelling, arising from vessel collisions and/or equipment malfunctions, into their environmental assessments.
Transition elements & organo-metal (e.g., TBT) contamination	• Studies of Al emissions from galvanic anodes exist but are limited to laboratory experiments and harbour environments. While these studies can provide inferences as to what may occur in the vicinity of a FLOW development, there is need for FLOW-specific case studies into these potential emissions. • In line with this need for research, there is a requirement for FLOW developments to state the likely number of galvanic anodes to be used on their structures to enable application of this necessary research.
Introduction of other substances (solid, liquid or gas)	• Concerns have arisen from surrounding the leaching and weathering of organic coatings from FLOW structures. As a result, there is a need to conduct research to investigate whether FLOW developments may act as a new point source of BPA to the marine environment and whether concerning concentrations may be introduced.
Synthetic compound contamination (including pesticides, antifoulants, pharmaceuticals)	• There is a lack of evidence and clarity, from the environmental and technical reports of FLOW developments, into the methods, if any, used to tackle biofouling. Indeed, this clarity also appears to be lacking for traditional fixed offshore wind developments. As with BPA, in situ research into potential release of contaminants from antifouling paints is required to establish whether quantities of paint used should be of environmental concern.
[note 1] Indicates those pressures for which a large volume of literature was available. For these pressures, it may seem that there are more evidence gaps in some cases. However, the opposite is true, whereby the number of evidence gaps reflects the level of detail available in literature, allowing more specific evidence gaps to be identified for those pressures. For pressures where there is less literature available on the topic (and thus topics where less research has been conducted), evidence gaps are broader and more all-encompassing as current research and evidence is not sufficient to refine them further. For this reason, caution should be taken not to assume that more evidence gaps mean that an impact has been studied less.	

12. Appendix 4: Case studies of FLOW developments

Table 12-1 presents a summary of some of the operational FLOW developments, some of which are referred to in this report.

Table 12-1. Case studies of FLOW developments

Name	Operator	Location	Number of turbines	Water depth (m)	Foundation type	Mooring system type	Anchor type	Status
WindFloat Atlantic [a]	Principle Power	Viana do Castelo, Portugal	3	100	Semi-submersible	Catenary (3 per turbine)	Drag-embedment	Fully Commissioned (in operation since 2019)
Kincardine [b][c]	Principle Power	Aberdeen Scotland	6	60 - 80	Triangular semi-submersible, steel (WindFloat foundation)	Catenary (4 per turbine)	Drag-embedment (4 per turbine)	Fully Commissioned (in operation since 2021)
VolturnUS [d]	University of Maine	USA	1	200	Semi-submersible, concrete	Three-line chain catenary	Drag-embedment	Reference wind turbine, designed to support the International Energy Agency (IEA) reference wind turbine
Hywind Scotland Pilot Park [b]	Equinor	Buchan Deep Scotland	5	95 - 129	Spar buoy, steel	Catenary (3 per turbine)	Suction caisson (3 per turbine)	Fully Commissioned (in operation since 2017)
Hywind Tampen [b]	Equinor	Tampen Area Norway	11	260 - 300	Spar buoy, concrete	Catenary (3 per turbine)	Shared suction caissons (1.73 per turbine)	Under Construction (Power produced from first turbine in 2022)

Name	Operator	Location	Number of turbines	Water depth (m)	Foundation type	Mooring system type	Anchor type	Status
GICON-SOF Pilot Floating Wind Farm [e]	GICON	Germany	Concept	18-500	TLP	Taut	Gravity	Prototype in development since 2009. Fabrication of first full-scale prototype in 2014.
PelaStar [f]	Glosten	No locations as of yet	Concept	55-100	TLP	Taut (5 per turbine)	No data	Idea first conceived in 2006. Now developing 15 MW PelaStar designs for the US Northeast Coast, Scotland and the US West Coast.
Fukushima FORWARD Demonstration Project Phase 1 [g]	Marubeni	Japan	1	65	Compact semi-submersible	Catenary (6 per turbine)	No data	Prototype turbine completed in 2013, decommissioned in 2021.
Fukushima FORWARD Demonstration Project Phase 2 [g]	Marubeni	Japan	2	No data	Advanced spar and V-shape semi-submersible	Catenary (8 per turbine)	No data	Installed in 2016, decommissioned in 2021.

Name	Operator	Location	Number of turbines	Water depth (m)	Foundation type	Mooring system type	Anchor type	Status
Sakiyama [h]	Haenkaze Toda Corporation / Goto Floating Wind Power LLC	Kabashima Goto, Japan	1	76	Hybrid spar (lower part concrete, upper part steel)	Three-point Catenary (steel chains)	No data	Two-year demonstration project installed in 2013 off the coast of Kabashima Goto, then transferred to Skiyama Fuke Island. Fully Commissioned
TwinHub [i]	Hexicon	Celtic Sea (at the WaveHub site)	2	50 - 60	Semi-submersible (2 turbines on one foundation)	Catenary	Driven anchor piles	Fully consented, currently at pre-Final Investment Decision phase. A couple of years away from start of construction.
Pentland [j]	Highland Wind Limited	Caithness, Scotland	6-10	66-102	To be determined (All types in consideration)	3-6 per turbine	To be determined (gravity, drag-embedment, vertical load, drilled piles, suction bucket or screw piles in consideration). 3-6 per turbine.	Offshore application submitted to Marine Scotland in August 2022. Commencement of construction would be 2024, completion 2026.

Name	Operator	Location	Number of turbines	Water depth (m)	Foundation type	Mooring system type	Anchor type	Status
European FLOTANT project [k]	Oceanic Platform of the Canary Islands PLOCAN	Canary Islands	Concept	100 - 600	Cylindric concrete structure with reinforced plastic bags	New dynamic cables and mooring lines with sensors integrated	Anchoring system with active heave compensation	3-year project to develop the concept
Floatgen [l]	BW Ideol	Sem-Rev test site (off Le Croisic) France	1	33	Semi-submersible	Catenary	Drag-embedment (6 per turbine)	Fully Commissioned (operational since 2019)
Hibiki [m]	BW Ideol	Kitakyushu City, Japan	1	55	Barge	No data	No data	Demonstrator turbine, operational since 2018
TELWIND [n]	ESTEYCO	No locations as of yet	1	Over 50	Multi-body floating platform with a wide cylindrical platform and a cylindrical ballast body	Catenary	No data	Development began in 2016

Sources:
[a] Banister, (2017)
[b] Lunde *et al.*, (2021)
[c] Kincardine Offshore Wind Ltd, (2018)
[d] Allen *et al.*, (2020)
[e] GICON, (2023)
[f] Glosten, (2014)

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