OFFSHORE RENEWABLES JOINT INDUSTRY PROGRAMME (ORJIP) FOR OFFSHORE WIND

ORJIP BenCH: Benthic habitat changes post-construction of offshore wind

(Final report)

ORJIP BenCH – Benthic habitat changes post-construction of offshore wind

September 2025

working to accelerate offshore consenting

ORJIP Offshore Wind

The Offshore Renewables Joint Industry Programme (ORJIP) for Offshore Wind is a collaborative initiative that aims to:

- Fund research to improve our understanding of the effects of offshore wind on the marine environment.
- Reduce the risk of not getting, or delaying consent for, offshore wind developments.
- Reduce the risk of getting consent with conditions that reduce viability of the project.

The programme pools resources from the private sector and public sector bodies to fund projects that provide empirical data to support consenting authorities in evaluating the environmental risk of offshore wind. Projects are prioritised and informed by the ORJIP Advisory Network which includes key stakeholders, including statutory nature conservation bodies, academics, non-governmental organisations and others.

The current stage is a collaboration between the Carbon Trust, EDF Energy Renewables Limited, Ocean Winds UK Limited, Equinor ASA, Ørsted Power (UK) Limited, RWE Offshore Wind GmbH, SSE Renewables Services (UK) Limited, TotalEnergies OneTech, Crown Estate Scotland, Scottish Government (acting through the Offshore Wind Directorate and the Marine Directorate) and The Crown Estate Commissioners. For further information regarding the ORJIP Offshore Wind programme, please refer to the Carbon Trust website, or contact Ivan Savitsky (ivan.savitsky@carbontrust.com) and Žilvinas Valantiejus (zilvinas.valantiejus@carbontrust.com).

Acknowledgements

This document was produced on behalf of ORJIP Offshore Wind by APEM Group, the National Oceanography Centre (NOC) and Bangor University. The report was authored by Dr Marc Hubble, Nick O'Brien, Ambar Villanueva-Brackley, Alexander Meadows, Kelly Greener, Soren Pears, Dr Talicia Pillay, Dr Lisa Skein, Dr James Strong & Professor Katrien Van Landeghem.

The project was advised by the ORJIP Offshore Wind Steering Group and the Project Expert Panel. We would like to thank the following organisations for their advice and support of the project via participation on the Project Expert Panel:

- Joint Nature Conservation Committee (JNCC)
- Natural England
- Department for Environment, Food & Rural Affairs (Defra)
- NatureScot
- Scottish Government's Marine Directorate

This report was sponsored by the ORJIP Offshore Wind programme. For the avoidance of doubt, this report expresses the independent views of the authors.

Who we are

Our mission is to accelerate the move to a decarbonised future. We have been climate pioneers for more than 20 years, partnering with leading businesses, governments and financial institutions globally. From strategic planning and target setting to activation and communication - we are your expert guide to turn your climate ambition into impact.

We are one global network of 400 experts with offices in the UK, the Netherlands, Germany, South Africa, Singapore and Mexico. To date, we have helped set 200+ science-based targets and guided 3,000+ organisations in 70 countries on their route to Net Zero.

Contents

Tables

Executive summary

The UK Government has committed to delivering 50 gigawatts (GW) of offshore wind by 2030, with 13.9 GW currently operational and another 77 GW in development. As this sector rapidly expands, understanding the environmental impacts on benthic communities becomes increasingly important. This project, undertaken as part of the Offshore Renewables Joint Industry Programme for Offshore Wind (ORJIP Offshore Wind), aimed to strengthen the evidence base on how offshore wind farms affect benthic habitats and species post-construction.

The primary aim of the project was to evaluate five research questions, developed by the ORJIP steering group, relating to post-construction benthic habitat change and recovery:

- RQ1: Are there suitable metrics to detect changes in benthic habitats that could be applied to offshore wind assessments?
- RQ2: Is there a measurable change (increase/decrease) in biodiversity and/or species composition?
- RQ3: Are there localised and regional ecological effects around the infrastructure?
- RQ4: Is there change in ecological function (e.g. functional groups) as a result of biological changes?
- RQ5: Can recovery and/or enhancement be demonstrated and in what timeframe?

The project was delivered through several work packages:

- WP1: Literature review covering all five research questions.
- WP2: Data mapping and collation of benthic monitoring datasets.
- WP3: Interim workshop with the project steering group to decide which questions could be further investigated in WP4.
- WP4: Benthic analyses using AMBI (AZTI Marine Biotic Index) and biological traits analysis on a subset of UK offshore wind farm datasets to further investigate research questions one, two and four.
- WP5: Final reporting

The literature review included a comprehensive review of scientific and grey literature including benthic monitoring reports from 18 OWF monitoring programmes. The main findings of the literature review included:

RQ1: Existing metrics such as abundance, diversity indices and multivariate analyses are widely used and appropriate for detecting changes in benthic habitats. However, the review recommended exploring supplementary metrics, such as AMBI and biological trait-based approaches, to enhance ecological interpretation and potentially detect changes in ecological function that may not be detected by traditional approaches.

RQ2: Changes in biodiversity and species composition were observed in the reviewed OWF monitoring reports. However, these were attributed to natural variability rather than OWF impacts across all 18 monitoring reports. This contrasts with findings from the scientific literature, which reports measurable OWF-related impacts on benthic communities. This difference highlights the need for evaluation of monitoring design and approaches, spatial resolution and duration to ensure that potential effects are not masked by natural variability in benthic communities.

RQ3: The literature review found that localised ecological changes are evident in close proximity to turbine structures, regional-scale impacts are less well understood and underrepresented in existing monitoring programmes and datasets. This aspect remains a knowledge gap requiring further investigation.

RQ4: Few studies directly link benthic habitat changes to functional ecological shifts in benthic communities. The review highlighted the value of trait-based approaches in understanding potential changes in ecological function that may not be evident where diversity and abundance metrics remain the same. Changes in functional traits of benthic communities may interfere with normal ecosystem functioning by disrupting processes such as bioturbation and nutrient cycling. The review recommended investigating RQ4 further through conducting biological traits analysis in WP4.

RQ5: Recovery timelines for benthic communities vary by habitat and exposure, with soft-sediment communities often recovering within 2–3 years. However, the absence of long-term monitoring limits understanding of enhancement potential and the direction of post-construction changes.

Following confirmation from the steering group during the mid-project workshop, AMBI and biological traits analyses were used to analyse collated OWF benthic datasets as part of WP4 to further investigate research questions RQ1, RQ2 and RQ4.

The AMBI analysis was undertaken across four OWF sites and found no significant spatial differences between array areas and reference stations, supporting the conclusion of the monitoring reports that natural variability was the primary driver of observed changes. Traditional diversity and abundance related approaches typically used in analysis of benthic communities can detect change and identify where changes in community structure are associated with environmental variables, but do not readily explain the nature of such changes. The advantage of AMBI is that it also identifies the ecological response to changes, identifying shifts from disturbance sensitive to disturbance tolerant or opportunistic taxa and providing a standardised disturbance classification. This means that AMBI can both detect change and also identify the type of change that has taken place within the benthic community within a readily accessible single metric. This is important for understanding the ecological implications of impacts to benthic habitats and communities.

Similarly, biological traits analyses at three sites revealed no significant influence of OWF construction on the functional composition of benthic communities. Community structure remained consistent across traits including size distribution, lifespan categories, feeding modes and bioturbation activities, with observed variability attributed to natural factors rather than OWF presence. This suggests that while species composition may vary, ecosystem functions were maintained. The metrics currently used in benthic analysis are not designed to indicate potential disturbance of the benthic communities beyond structural changes (relative abundances, diversity and dominance of species) and do not consider the functional aspects of benthic communities. A trait-based approach can address a range of ecological issues and reveal how altered communities influence ecosystem processes, such as nutrient cycling, sediment bioturbation or organic matter decomposition.

It should be noted that the testing of these two approaches was undertaken using datasets that were not specifically designed for these analyses and from areas where other analyses had concluded no significant impact from OWF construction. As such, it is difficult to draw firm conclusions on the potential value of these metrics in benthic monitoring assessments. However, given the advantages detailed above, it is considered that their use in benthic monitoring, to complement traditional analyses, warrants further investigation.

The project findings have informed a series of policy considerations including:

- Improving environmental impact assessments (EIA) processes and monitoring frameworks.
- Supporting licensing and mitigation standards.

- Informing compensation strategies and marine spatial planning.
- Contributing to the development of marine net gain approaches.

In addition, the project has contributed to recommendations across research, planning, environmental assessment and monitoring practices. These recommendations emphasise the need for enhanced research, planning and monitoring approaches that go beyond traditional analyses and assessments to include functional ecology assessments and ecosystem services. Key recommendations include conducting longer-term studies on benthic community succession and ecosystem functioning, the inclusion of trait-based approaches to more fully understand ecological effects and developing standardised monitoring protocols with adequate statistical power using BACI designs. The recommendations suggest improved spatial planning tools that integrate predicted ecological changes with biodiversity indicators, consideration of cumulative regional effects across multiple OWFs, and the incorporation of nature-positive infrastructure such as reef-forming scour protection and restoration zones. Benthic community analyses and the environmental impact assessment process should include functional group composition metrics and comprehensive cumulative assessments, while monitoring programmes should be extended with standardised methodologies, appropriate reference stations, and apply the consistent use of centralised data repositories to facilitate cross-site comparisons.

1. Introduction

1.1. Background

Urgent calls have been made to ramp up the production of renewable energy worldwide. In particular, the UK Government has made commitments to deliver 50 gigawatts (GW) of offshore wind (OW) by 2030. Currently, 13.9 GW of OW is fully commissioned, with another 77 GW in some phase of development or set aside for upcoming seabed lease auctions (Department of Business and Trade, 2024).

This project has been undertaken as part of the Offshore Renewables Joint Industry Programme for Offshore Wind ("ORJIP Offshore Wind") research and development programme, which aims to reduce consenting risk for OW, under the management of the Carbon Trust. The primary objective of ORJIP Offshore Wind is to strengthen the evidence base on the environmental impacts of OW projects, supporting informed decision-making by regulators, developers, and stakeholders. To achieve this, ORJIP provides a framework for identifying and delivering targeted research and development projects that reduce consenting risk, project timelines, costs and environmental impact. This project will contribute to the 'Impacts on Benthic Ecology' priority focus area of the wider ORJIP programme.

The aim of this project has been to investigate five research questions developed by the ORJIP steering group and project expert panel through a literature review and a multi-site analysis of benthic monitoring data from existing OWF sites.

The five research questions evaluated are:

- RQ1: Are there suitable metrics to detect changes in benthic habitats that could be applied to offshore wind assessments?
- RQ2: Is there a measurable change (increase/decrease) in biodiversity and/or species composition?
- RQ3: Are there localised and regional ecological effects around the infrastructure?
- RQ4: Is there change in ecological function (e.g. functional groups) as a result of biological changes?
- RQ5: Can recovery and/or enhancement be demonstrated and in what timeframe?

Existing data reviews have covered numerous aspects of offshore wind farms (OWFs), and specific considerations for benthic ecology include temporary and permanent environmental impacts associated with the installation and physical presence of structures in the water column and on the seabed (including the presence of turbine foundations, substation/converter platform foundations, scour protection and cable protection); changes to hydrodynamic regime and sediment transport; changes to the underwater soundscape; the presence of submarine cables and associated electromagnetic fields (EMF); and a number of other effects which have been considered in this review. Additionally, the nature and extent of these impacts can vary across the construction, operation and decommissioning phases, depending on the specific technologies and methods employed. Furthermore, emerging floating offshore wind (FLOW) technologies introduce some distinct potential effects, particularly in deeper and seasonally stratified waters, where larger anchoring systems and dynamic cables may alter seabed and water column conditions differently. Due to the limited number of current deployments, no monitoring data are yet available for FLOW, although significant expansion is planned, underscoring the need to anticipate and address these differences through future monitoring and research.

A substantial amount of monitoring data has been accumulated in recent years along with the rapid expansion of this industry, resulting in several publications aimed at documenting potential impacts. A recent review of literature on the environmental impacts of wind energy devices found that benthic invertebrates were relatively less represented compared to other receptors such as birds, fish, and marine mammals (Galparsoro *et al.*, 2022). Most research aimed at documenting impacts is based on short-term datasets, 1 – 5 years after construction (Zucco *et al.*, 2006; Jak & Glorius, 2017), hindering our understanding of many of the potential effects of OWFs including the succession and changes in fouling communities on turbines and scour protection (artificial reef effects), impacts on soft sediment communities owing to altered hydrodynamics and nutrient enrichment (Coates *et al.*, 2014; Lefaible *et al.*, 2023).

In evaluating the research questions, this project has collated available information relating to a number of potential impacts of OWFs on benthic habitats and species, including reviewing the findings of post-construction monitoring programmes for multiple wind farms. It provides an up-to-date indication of currently available data and information and highlights current knowledge gaps and limitations.

1.2. Purpose and scope

This project will serve to identify key knowledge gaps to ensure potential effects of OWFs on benthic habitats and species post-construction are sufficiently understood in the context of the OW Environmental Impact Assessment (EIA) and consenting process.

The main outputs of the project are:

- A literature review outlining responses to research questions 1-5 (Appendix 1)
- A data mapping summary report (Appendix 2)
- Presentation at an interim workshop to the ORJIP OSW (Offshore wind) Steering Group and Project Expert Panel
- Data analysis reports (Appendix 3 and 4)
- Final report outlining previous project outputs and policy recommendations (this document)

The evaluation of the research questions aims to inform the following policy considerations in relation to benthic ecology and habitats across the full lifecycle of OWF development:

- PP1: Inform marine spatial planning
- PP2: Mitigating negative impacts through licensing and design standards
- PP3: Inform potential compensation scope and scale
- PP4: Support the delivery and measurement of marine net gain

This report details the project outcomes, including key results, project learnings, and subsequent recommendations that could be used to form the basis of policy positions regarding benthic ecology and habitats across an OWF's lifecycle. Recommendations include roles and responsibilities for key stakeholder groups including:

- Offshore wind farm developers
- Environmental impacts assessment practitioners
- Statutory Nature Conservation Body's (SNCBs) and other interested environmental bodies
- Regulators

2. Project team

This project has been coordinated and delivered by APEM Ltd with extensive literature review contributions by Dr Talicia Pillay and Dr Lisa Skein of the National Oceanography Centre. Reviews have been provided by Prof Katrien Van Landeghem of Bangor University who is the Principal Investigator for the ECOWind-ACCELERATE project and Dr James Strong of the National Oceanography Centre.

3. Project outcomes

3.1. Methodology summary

There were two main approaches to obtaining the information for this review:

- Collation and review of pre- and post-construction benthic monitoring reports and data for OWFs; and
- Wider review of published literature and grey literature.

3.1.1. Collation of pre- and post-construction monitoring reports

The following data sources were used to obtain OWF monitoring reports:

- The Marine Data Exchange (MDE);
- Marine Environmental Data Information Networks (MEDIN); and
- Direct requests to developers.

For RQ1 and RQ2 in particular, data from the pre- and post-construction environmental monitoring reports has been key to providing the information to inform the review, and they have also been referred to for aspects of the responses to RQs 3-5, as appropriate. A total of 47 wind farms were identified to try to obtain pre- and post-construction benthic monitoring reports and associated raw datasets.

Based on the timeframe available it was necessary to focus on a sub-section of available wind farm reports, so 17 UK wind farms were selected and one Dutch site was also included, as it is located within the North Sea with similar communities to UK sites and the post-construction monitoring extended over a longer period compared to average monitoring programmes in the UK (15 years post-construction).

Partial sets of monitoring reports were available for the majority of the 47 OWFs, however, a full set of pre-construction and post-construction[1] monitoring reports was only available for 12 of these and for a further six, sufficiently detailed reference to the pre-construction data was made in the post-construction monitoring reports to include them in the review. In total, 18 OWFs were thus included in the review (Appendix 1). These were developed across Crown Estate leasing rounds 1, 2, and 3, as well as one from the Dutch leasing system. Most UK OWFs were leased under rounds 1 and 2 between 2001 and 2003, with one round 3 development. Princess Amalia, the only non-UK OWF, was developed in 2006. Geographically, the OWFs are located around the UK, including the Irish Sea (six sites), the North Sea (11 sites from the outer Thames Estuary to the Moray Firth), with Princess Amalia situated in the Dutch sector of the North

[1] For six OWFs the pre-construction report was not available but sufficiently detailed reference to the pre-construction data was made in the post-construction monitoring reports to include them in the review.

Sea. To maintain the anonymity of the OWF sites assessed, their exact locations are not presented in this report. The monitoring reports reviewed for these sites ranged between 2002 and 2023.

3.1.2. Literature review

For RQ3-5, there was limited information available in the OWF monitoring reports, and a wider literature review was conducted.

Peer-reviewed journal articles were reviewed (~ 200 in total) as well as other literature produced outside of traditional publishing and distribution channels (“grey literature”) (~50 in total).

The following sections provide a summary of the findings of the review of OWF monitoring reports and the literature review for each research question.

3.2. Literature review summary

3.2.1. RQ1: Are there suitable metrics to detect changes in benthic habitats that could be applied to offshore wind assessments?

Numerous metrics are available to detect changes in benthic habitats and communities (e.g. Pinto *et al.*, 2008; Borja *et al.*, 2000) and these metrics can be used to provide understanding of community structure, biodiversity and ecosystem health and determine changes over time.

The literature review undertaken in Work Package 1 involved reviewing the monitoring reports for 18 OWFs to identify the metrics used to assess benthic habitats and communities in OWF monitoring programmes. The review found that the most frequently used metrics included: abundance, species/taxon richness, Particle Size Analysis (PSA), habitat extent and composition (applied across all 18 monitoring programmes), followed by cluster analysis/ non-metric multidimensional scaling (nMDS), diversity indices (Shannon-Weiner and Pielou’s evenness), SIMPER analysis, and correlation analyses such as RELATE and BIOEnv (the analysis of metrics is presented in Appendix 1). Semi-quantitative approaches such as SACFOR abundance were applied less frequently (primarily for video survey data analysis). Invasive Non-Native Species (INNS) were only referenced (presence or absence) in seven of the 18 monitoring reports.

The most frequently applied metrics in OWF monitoring programmes are not unique to the sector. The use of these metrics represents standard best practice in benthic ecology assessments across various marine industries and are routinely employed in monitoring programmes for aggregate extraction, oil and gas, dredging activities and other marine infrastructure projects. Similarly, diversity indices, species richness measures and multivariate community analyses are not limited to marine environments but also represent key ecological assessment tools used across terrestrial and freshwater environments too. This widespread use across ecosystems and industries reflects their established scientific use and wide-ranging applicability for detecting changes in biological habitats and communities.

The review concluded that the metrics frequently applied are suitable and effective at determining changes in benthic communities and habitats (biotopes) at OWF sites and associated cable corridors.

Although the range of metrics frequently applied are generally recognised as being effective at demonstrating changes in benthic communities/habitats, there is a relative lack of information relating to the effects of such changes on ecological function at a community/habitat level (this is also highlighted in the response for RQ4). The metrics currently are also not designed to indicate potential disturbance of the benthic communities beyond changes in relative abundances of species and provide an indication of dominance of specific taxa. Consequently, the review recommended that the current suite of frequently applied metrics is retained, but supplementary metrics could also be calculated from the benthic ecology datasets to examine the potential for this additional information to better inform the understanding of wider ecosystem level changes at a local and regional scale. The review identified additional biotic metrics that have not, to date, routinely been applied in OWF monitoring programmes but have been applied previously to benthic ecology studies and could be considered for OWFs. These metrics included: the Infaunal Trophic Index (ITI), AZTI Marine Biotic Index (AMBI), Infaunal Quality Index (IQI) and the Benthic Ecosystem Quality Index (BEQI). Further detail on how these metrics can be applied to OWF data is presented in the Data Mapping Summary Report (Appendix 2).

Of those metrics above, this review considers that there is scope for further investigation into the effectiveness of AMBI to detect changes in environmental conditions along a gradient of disturbance (undisturbed to disturbed) associated with organic enrichment. This may be particularly applicable at OWF sites where colonisation of fixed foundation turbines can result in localised increases in the level of deposition of organic compounds around the turbine foundations (for example where there are high levels of colonisation by blue mussels). Traditional analyses, such as the PRIMER functions RELATE and BIO-ENV, can detect where changes in community structure are associated with environmental variables (e.g. organic enrichment), but cannot explain the nature or ecological significance of those changes. The advantage of AMBI is that it also identifies the ecological response, showing where communities are shifting from disturbance sensitive to disturbance tolerant or opportunistic taxa and providing a standardised disturbance classification. This means that AMBI can both detect change and also identify the type of change that has taken place within the benthic community.

The application of a biological trait analysis approach to investigate functional changes in benthic communities was also considered and is explained in further detail in the response to RQ4 and in the Data Mapping Summary Report (Appendix 2).

3.2.2. RQ2: Is there a measurable change (increase/decrease) in biodiversity and/or species composition?

For this research question, the focus was on identifying where measurable change has been recorded in sediment composition or species/community composition post-construction at OWF developments, and how data were evaluated to determine such changes.

As mentioned for RQ1, a combination of univariate and multivariate analysis methods has often been used to detect potential changes in benthic habitats, identifying shifts in community composition (change in biotope allocation), habitat extent change and changes in species abundance for specific habitat types (Indicator species or species of conservation importance).

Assessment criteria were used to examine consistency in approach across different monitoring reports. The assessment focused on four main aspects applicable to the design of benthic ecology surveys and the relevance of the OWF post-construction monitoring. The assessment criteria were: Survey design and statistical approach, Methodology, Correlation analysis and Power analysis. The main findings of the review of consistency of approach included that all 18 OWF monitoring programmes used reference and impact zone sampling stations, with reference stations typically comprising 15-25% of total stations. Statistical significance testing (ANOVA or ANOSIM) was performed in 14 of the 18 monitoring programmes and 11 programmes investigated correlations between benthic community changes and environmental variables. However, none of the programmes reported using power analysis to determine statistically appropriate sample numbers.

According to the monitoring reports reviewed, there were measurable changes in sediment composition and / or species composition (abundance and / or taxon richness) recorded at 17 of the 18 OWF sites. For sediment composition, 11 sites showed changes between pre- and first post-construction surveys with seven sites showing no change. Across multiple post-construction surveys, only four sites showed consistent directional changes. For species abundance, 13 sites showed changes between the pre- and first post-construction surveys with nine of these showing increases in abundances. Five sites showed no initial changes in abundance. Of the 13 that did show initial changes, only five of these maintained consistent trends across the duration of the monitoring programmes. For taxon richness, 12 sites showed changes between the pre- and first post-construction surveys with nine of these showing increases in taxon richness and three sites showing a decrease. Six of the 12 sites showed consistent directional trends over the duration of those monitoring programmes.

In all instances, however, any changes identified outside of the immediate footprint of the turbine infrastructure (>50m from turbine structures), were attributed to natural variability in the monitoring reports. This conclusion was based on similar trends being observed at reference stations located beyond the predicted zone of influence; inconsistent directions of change across multiple post-construction surveys and; statistical tests (such as ANOVA/ANOSIM) being used to compare temporal changes between impact and reference stations (although this was not undertaken at all sites).

Changes attributed directly to the presence of OWFs were primarily documented within foundation colonisation reports, which surveyed fouling communities on OWF subsea structures. Biological zonation patterns were observed on turbine monopiles, with green algae and barnacles in the shallow water zones of monopile structures, dense mussel aggregations in mid-water zones and diverse epifaunal assemblages including anemones and hydroids in deeper water zones towards the base of monopiles. It was proposed that for OWF sites where a complete dataset is available (comprising all data from pre- and post-construction surveys), data could be re-analysed to perform a multi-site analysis to identify and compare potential trends in benthic community structure after the construction of multiple OWF sites. However, a number of potentially confounding sources of variation between OWF datasets would need to be considered when considering this analysis. The options for further analysis are discussed further in the Data Mapping Summary Report (Appendix 2).

3.2.3. RQ3: Are there localised and regional ecological effects around the OWF infrastructure?

There was limited information available in the OWF monitoring reports to investigate RQ3, and a wider literature review was conducted. In the context of this project, "local" refers to the area within and a few miles or kilometres outside the wind farm. The term "regional" refers to the broader geographical area several miles away. Regional impacts could be driven by factors such as, for example, altered broad scale hydrodynamic conditions, increased suspended sediment concentrations (SSC) and sediment deposition (sediment plumes are strongly influenced by tidal cycles), the introduction and spread of non-native species, and the creation of new ecological connections between different marine habitats. The extent and ecological implications of this connectivity remain site-specific and require further investigation.

The literature review found that OWFs alter the localised physical environment and disturb existing benthic communities. These can lead to permanent habitat loss (of the areas of seabed where the infrastructure is placed) or more temporary habitat disturbance (for example from seabed dredging for foundation installation (and associated sediment deposition), cable laying activities and vessel anchoring/jacking up).

The introduction of artificial hard substrates, such as turbine foundations and scour protection, provide habitats for colonisation by hard-substrate species including mussels (*Mytilus* spp.), anemones, polychaetes, and sea urchins. This can lead to replacement of the soft-sediment species in the immediate footprint of the infrastructure, potentially driving localised shifts in community composition. The extent of which primarily depends on the sediment type, water depth, infrastructure, and foundation type and surrounding flow regimes.

The review highlighted that while more evidence is available on the localised effects of OWFs, particularly in close proximity to turbines, leaving gaps in understanding regional-scale effects. Some dedicated research programmes have been referred to in the Literature Review, for example the ECOWind Programme (Appendix 1), which aim to fill some of these data gaps to address the research question in more detail. The OWF post-construction monitoring datasets collated for post-Stage Gate analyses were not considered to provide sufficient resolution to form a basis for fully investigating this research question further, primarily due to a lack of regional-scale data. Consequently, no further investigation of this research question was proposed beyond Stage Gate. However, elements of it, particularly those concerning localised effects, overlap with analyses conducted for other research questions.

3.2.4. RQ4: Is there change in ecological function (e.g. functional groups) as a result of biological changes?

This literature review section explored how changes in benthic communities induced by OWFs affect ecological function, focusing on biological changes and their implications for functional group dynamics. In particular, it examines how shifts in benthic community composition could influence key ecosystem processes such as nutrient cycling, sediment bioturbation, and organic matter decomposition, with attention to transitions within functional groups such as deposit feeders, scavengers, and filter feeders. Similar to RQ3, there was limited information available in the OWF monitoring reports and a wider literature review was conducted.

The review found that, overall, there are very few studies that directly examine how changes to soft sediments around OWFs (and other marine infrastructure such as oil and gas installations) affect functional groups and ecological functioning. However, OWF installation has the potential to alter pre-existing habitats and, specifically, creates additional hard substrate in typically soft substrate (sandy sediment) environments, which has the potential to act as an artificial reef, likely affecting locally ecosystem diversity and the relative abundance of organisms belonging to different benthic functional groups.

While many studies focus on traditional metrics such as species richness and diversity, there remains a need to explore changes in functional traits and roles to better understand how these communities support ecosystem functioning in OWF environments. A biological traits analysis was identified and proposed in order to investigate this research question further beyond Stage Gate.

3.2.5. RQ5: Can recovery and/or enhancement be demonstrated and in what timeframe?

The literature review found that recovery of soft-sediment benthic communities following OWF construction is influenced by multiple factors with recovery times typically occurring within a few years. In frequently disturbed environments, benthic communities demonstrate rapid recovery, with infauna at some North Sea OWF sites returning to pre-construction states within two years, which is similar to recovery timelines reported for sediment communities after dredging activity.

The review indicated that environments with strong currents and storm events create naturally dynamic benthic communities that are better adapted to disturbance, which potentially facilitates faster recovery after disturbance. However, this same environmental variability can make it challenging to distinguish between natural fluctuations and OWF-related impacts. Long-term pre-impact datasets are considered important for understanding natural variability, though such datasets are rarely available.

For epifaunal species, the review found that assessment of recovery is particularly challenging due to less standardised survey methodologies and logistical constraints around surveying in close proximity to turbines. However, some studies demonstrated recovery for long-lived epifaunal species, including the European flat oyster *Ostrea edulis* and hydroid *Sertularia cupressina* at Danish OWFs. The review also noted cases where careful planning based on pre-construction surveys (such as identifying *Sabellaria spinulosa* reefs at Thanet OWF) helped minimise impacts and may have contributed to post-construction increases in reef extent.

Similar to RQ3 and 4, there was limited information available in the OWF monitoring reports. It should be noted, however, that the monitoring reports consistently concluded that natural variability was the main driver of change at OWF sites; therefore, in the absence of measurable effects, there would be no observable recovery to assess. Natural variability was primarily attributed based on similar changes being observed at both impact and reference stations, and inconsistent directions of change across the duration of monitoring programmes. However, the review also identified a number of limitations with the monitoring programmes including how OWF stations and reference stations were compared; the limitations of only having one year of pre-construction baseline data in establishing natural variability; and the challenges of selecting appropriate reference stations with similar environmental conditions and benthic habitats as those within the zone of influence of the OWF.

Similarly, given the challenges of sampling in very close proximity to turbine foundations, it may be the case that effects and subsequent recovery processes close to turbines were not recorded by the monitoring surveys.

Understanding the recovery potential of marine ecosystems post-construction requires comprehensive data related to environmental pressures and associated monitoring over a suitable period of time. Surveys conducted across relevant time scales and spatial scales (locally and regionally) recording species composition, habitat distribution, and ecosystem function are key to tracking changes at OWFs post-construction. Moreover, effective survey design for monitoring programmes, and selection of a sufficient number of suitable reference stations is essential to clarify whether changes evident are due to natural variability or relate to effects of OWFs.

OWFs have not traditionally been designed for ecological enhancement, but there is potential for this to change in the future from the introduction of marine net gain policies. The introduction of OWF structures such as turbine foundations and scour protection can increase biodiversity, aid in species conservation from the re-establishment of rare species and have reserve effects from restricted fishing practices, as highlighted in this review, however contrasting literature does exist. Nevertheless, artificial habitats can differ significantly from natural ones, with increased hard substrate necessitating careful monitoring of ecological impacts.

Overall, the literature review concluded that OWFs can potentially play a positive role in enhancement, particularly through artificial reef effects and fisheries exclusion (where this occurs). However, more long-term studies are needed to understand their full ecological impact and to optimise future developments for biodiversity gains. It was concluded that there were no options to investigate this research question further beyond Stage Gate.

3.3. Data mapping summary

The aim of the data mapping summary report is to indicate which aspects of RQ1-5 can be considered further via analyses of datasets collated during pre- and post-construction monitoring at OWFs. Out of the 18 OWF monitoring programmes reviewed, it was possible to collate a full set of pre- and post-construction benthic datasets for six OWFs (which included at least 2 post-construction surveys). It is notable that none of the sites included in this group were developed for emerging FLOW technology. Instead, they represent earlier-generation, fixed-bottom installations located in relatively shallow (up to 20 m depth), nearshore waters (within 15km from shore). These projects typically feature smaller turbine capacities, reduced hub heights, and lower overall generating output compared to more recent OW developments.

The report summarises five data analysis approaches that could be used to analyse the data collated and potentially provide further information for the benthic community beyond the traditionally used metrics of abundance, taxon richness and diversity statistics. The options proposed for further analysis for RQ1, RQ2 and RQ4 includes ITI, AMBI and ABC Curves, with multi-site analysis proposed as a further analysis option for RQ2. The purpose, benefits, analysis and data requirements, as well as limitations for the proposed options, are detailed in the data mapping summary report (Appendix 2).

3.4. Project stage gate

The findings of the literature review and data mapping summary report were presented at an interim workshop to the ORJIP OSW (offshore wind) Steering Group and Project Expert Panel on the 27th March 2025. The proposals for further analysis of the collated data were put forward for discussion, where it was decided that the following approaches would be progressed post-Stage Gate:

- AMBI; and
- Biological traits analysis

3.5. Data analysis summary

3.5.1. Introduction

Full benthic monitoring data, with at least two post-construction surveys, were available for six of the 18 UK OWFs analysed in the literature review. It was not possible to collect full monitoring data for the remaining 12 OWF sites, either through publicly available portals or requests to stakeholders. All six sets of OWF monitoring data met the criteria to perform AMBI and biological trait analysis, which included benthic fauna and PSA data. Five of the datasets also included total organic carbon (TOC), for analysis of potential organic enrichment near infrastructure.

Prior to using the data analysis approaches chosen during Project Stage Gate, data anonymisation, the appropriate truncation, and data preparation were required for further analysis. Results from analysis are used to contribute to answering research questions 1, 2 and 4, which will then aim to inform policy considerations and recommendations for OWF development.

3.5.2. Anonymisation of OWF sites

All data collated was anonymised to protect the integrity of the initial findings of the OWF monitoring surveys. Non-disclosure agreements were implemented (where required) with developers and members of the ORJIP Steering Group who contributed data for further analysis. Any identifiable information for each OWF was anonymised, including the anonymisation of OWF site names (i.e, to OWF 1, OWF 2 etc.) and survey years were only referred to as pre-construction, construction or post-construction surveys (e.g. 1st, 2nd or 3rd post-construction). The anonymised information of the OWFs used for further analysis is presented in Table 1.

Table 1. Individual site details for analysis

Site	Survey years	Post-construction monitoring duration (yrs)	Location	Foundation	Data collated
OWF 1	**Pre-construction** **1st post-construction** **2nd post-construction**	3	Irish Sea	Monopile	Benthic fauna and PSA for each survey year

Site	Survey years	Post-construction monitoring duration (yrs)	Location	Foundation	Data collated
OWF 2	**Pre-construction** **1st post-construction** **2nd post-construction** **3rd post-construction**	3	North Sea	Monopile	Benthic fauna and PSA for each survey year
OWF 3	**Pre-construction** **1st Construction** **2nd Construction** **1st post-construction** **2nd post-construction**	2	Irish Sea	Monopile	Benthic fauna and PSA for each survey year
OWF 4	**Pre-construction** **1st post-construction** **2nd post-construction**	3	Irish Sea	Monopile	Benthic fauna and PSA for each survey year

3.5.3. AZTI Marine Biotic index

AMBI is an ecological model that investigates the 'health' of benthic communities by classifying disturbance or pollution for a particular interest site and can detect the impact of anthropogenic pressure on the environment (Borja *et al.*, 2000). Disturbance-sensitive taxa are categorised into ecological groups according to taxon dominance along a disturbance gradient providing an insight into the ecological health of benthic communities. The results are in the form of a continuous Biotic Coefficient ranging from 0 to 6 which reflects a gradient from undisturbed (0) to highly disturbed (6) conditions from which subtle changes, both temporally and spatially can be determined. AMBI has been adopted by several European countries as the basis for Water Framework Directive (WFD) benthic assessment in Transitional and Coastal Waters (TraC).

The raw macrofaunal data from four OWFs using a variety of benthic sampling methods was used to apply the AMBI metric for further analysis. To perform the analyses, a set of data truncation rules were utilised (Borja and Muxika, 2005), followed by the distribution of individual abundances of soft-bottom communities into five groups according to sensitivity to an increasing gradient of organic enrichment.

The RELATE function of PRIMER was utilised to find out whether there was a correlation between the environmental metrics including between AMBI scores and the distance from nearest wind turbine and/or TOC. The PERMANOVA test was then used to examine significant differences between AMBI scores, the environmental metrics and survey phases.

The current analysis has been used to investigate AMBI's use as a useful metric for future OWF monitoring. AMBI was applied in the Outer Dowsing Offshore Wind Preliminary Environmental Information Report (GeoXYZ, 2023) but was not applied in any of the 18 reviewed monitoring reports for OWFs. However, the adoption of AMBI for post-construction monitoring was suggested as one option by

Stephenson (2021) and has since been adopted as an assessment tool at an OWF site off the east coast of Denmark (Dahl *et al.*, 2025).

OWF 1 - Main findings and conclusions

For OWF site 1, the PERMANOVA analysis found no significant difference in AMBI scores between the stations located within the OWF array area and reference stations across all survey periods. Similarly, no significant difference in AMBI scores within the array area was observed between the pre- and post-construction surveys. While AMBI scores within the array area showed some fluctuation during the monitoring period, similar patterns of variability were observed at the reference stations, which were located between four and 17 km from the wind farm; similarly, no differences were evident between the AMBI scores at those stations outside the array area but within the zone of influence (ZoI) and the reference stations across the study area. While this temporal variability indicates some level of change at stations within the array, the occurrence of similar patterns at those stations located beyond the zone of influence would indicate that the observed changes are unrelated to influence of the wind farm. Furthermore, it can be concluded that the factors influencing the benthic communities at the reference stations are also likely to be those driving the patterns seen within the wind farm site itself, and as such, it is concluded that natural variability and/or wider regional influencing factors are the main driver of the observed changes across the study area as a whole.

The RELATE analysis found no correlation between AMBI scores and TOC suggesting that TOC was not influencing the AMBI scores. Within the array area, TOC was significantly higher during the pre-construction survey relative to subsequent post-construction surveys, a pattern also evident at reference stations, suggesting that the OWF had no significant influence on TOC and that other factors were driving the observed pattern. As the second post-construction survey was undertaken two years after construction was completed, the colonising communities will still be developing (communities tend to develop over time, typically five to six years from the initial settling of organisms to reach the climax stage (Degraer *et al.*, 2020). As such, it is likely that the inputs of organic material would not have peaked at the time of that survey, although despite this some increased input would be anticipated. Increases in TOC have been reported close to turbine foundations (<50 m) three to six years after installation (Degraer *et al.*, 2020), although increases over more limited spatial extents have also been observed (Leonhard and Pedersen, 2005; Coates *et al.*, 2014). It would appear likely that the location of sample stations relative to turbines at OWF 1 (none within 50 m of a turbine) may have limited the detection of any potential increases of TOC in close proximity to turbines.

Overall, the AMBI analysis seems to support the conclusion of the original benthic analysis conducted during the monitoring programme that concluded changes observed during the survey periods were likely due to natural variability and not the construction of the OWF.

OWF 2 - Main findings and conclusions

Similar to OWF site 1, the PERMANOVA analysis found no significant difference in AMBI scores between the array area and reference stations across all survey periods and no significant difference between the pre-construction survey and first post-construction survey within the array area. Some localised changes were observed, especially at stations 18-20, which shifted from 'undisturbed' to 'slightly disturbed' reflecting a transition from group I (disturbance sensitive) to group III (disturbance tolerant) species. While there were other stations where there was a change in classification, the magnitude of the change in AMBI scores at these sites relative to other sites within the array area and the reference stations may indicate localised influence of the construction of the OWF at these stations. However, the overall absence of significant differences between the array area and the reference stations suggests that widespread effects across the array area were not observed, and that the observed patterns were driven by natural variability.

The RELATE analysis indicated a significant correlation between AMBI scores and TOC within the array area for the entire survey period. This correlation within the array area, where fluctuations in TOC were associated with similar fluctuations in AMBI scores, suggests that faunal patterns are related in part to levels of TOC and that the resultant AMBI score is responding accordingly. However, the PERMANOVA highlighted no significant temporal changes in TOC within the array area, indicating stable sediment organic content across the survey period and no evident organic enrichment associated with the OWF or other potential sources. At the reference stations, levels of TOC were consistent throughout the study, although a significant correlation between AMBI and TOC was only identified during the final post-construction survey which would indicate that TOC is not a key driver in the macrofaunal community patterns at these sites.

Overall, while some localised changes were evident in the post-construction surveys, the AMBI analysis seems to support the conclusion of the original benthic analysis conducted during the monitoring programme that concluded changes observed during the survey periods were likely due to natural variability and not the construction of the OWF.

OWF 3 - Main findings and conclusions

At OWF site 3, the PERMANOVA analysis found no significant effect of site location or survey phase on AMBI scores, indicating no significant differences in AMBI scores between the array area and reference stations across the survey periods. Similar to OWF site 2, some stations within the array area showed larger magnitude changes in AMBI score during the first post-construction survey (stations 3, 4, and 6) shifting from 'undisturbed' to 'moderately disturbed' or 'extremely disturbed'. These changes were temporary, with all stations returning to 'undisturbed' by the second post-construction survey (two years after construction). The reference stations remained largely stable throughout the monitoring period. The absence of statistical significance combined with the temporary nature of the changes, along with recovery of AMBI scores at disturbed stations, suggests that while localised disturbance may have occurred during construction, the benthic communities showed good recoverability and there was no lasting effect on the benthic communities within the array area.

It should be noted that the AMBI software flagged very low abundance or taxa counts at many stations across the array area, suggesting that the AMBI scores and classifications should be treated with a degree of caution.

Analysis of TOC was not possible for this site as TOC concentrations were below the limit of detection at the majority of sites.

OWF 4 - Main findings and conclusions

At OWF 4, PERMANOVA analysis found no significant difference in AMBI scores between all site areas and all survey periods including between the array area and reference stations and between pre- and post-construction surveys in the array area. Similar patterns of variability in AMBI scores were observed at both the array area and reference stations. This suggests that the construction of this OWF did not result in significant changes to the benthic community within the array area.

While TOC within the array area was significantly different from stations outside the array area, export cable route (ECR) and reference stations in the pre-construction survey, these significant differences were not observed in the post-construction survey.

The RELATE analysis identified a correlation between AMBI scores and TOC within the array area in the second post-construction survey only, suggesting that TOC may have influenced the AMBI scores. Additionally, PERMANOVA analysis found significant differences in TOC between the array area and reference sites in the second post-construction phase. This suggests that construction of the OWF may have led to an increase in organic enrichment across the array area as may be expected if colonising epifauna are contributing organic matter to the seabed. However, no significance difference in TOC was identified between survey phases in the array area.

Overall, the AMBI analysis seems to support the conclusion of the original benthic analysis conducted during the monitoring programme that concluded changes observed during the survey periods were likely due to natural variability and not the construction of the OWF. The PERMANOVA results for both site location and survey phase effects on AMBI scores suggests that array and reference areas experienced similar levels of variation, which supports natural variability being the primary driver.

AMBI analysis conclusions

Across the four OWF sites the most notable finding of the AMBI analysis was the absence of significant spatial differences in AMBI scores between array areas and reference stations indicating no measurable spatial influence of the OWFs on the macrobenthic communities sampled. However, some temporal changes were detected between pre- and post-construction surveys, although these could not be attributed to any effects of the OWFs. Overall, the analyses suggest that observed variations in AMBI scores were attributable to natural variability rather than construction-related disturbances, with similar patterns of fluctuation occurring at both array and reference stations. Although localised disturbances were observed at individual stations within some sites, these effects were predominantly temporary, with benthic communities generally demonstrating recovery by the completion of post-construction monitoring (within two to three years after construction).

Some site-specific variations were apparent at OWF sites 2 and 3, which showed more pronounced localised impacts at specific stations, with some locations transitioning from 'undisturbed' to 'moderately disturbed' or 'extremely disturbed' classifications during the first post-construction surveys (one year after construction). At OWF 3 there was a complete reversal of disturbance indicators by the second post-construction survey, although the interpretation of these results should be treated with caution due to very low abundance and species richness at these stations. At OWF 2 there were persistent changes at stations 18-20, characterised by a shift from group I (disturbance sensitive) to group III (disturbance tolerant) taxa throughout the monitoring period.

The relationship between AMBI scores and total organic carbon was variable across sites. At OWF 1 there was no significant correlation, whereas at OWF 2 significant correlations were observed throughout the monitoring period. At OWF 4 a significant correlation was only observed during the second post-construction survey (three years after construction). OWF 1 and 4 had contrasting TOC dynamics across the monitoring period, with OWF 1 showing significant post-construction decreases in organic content, while OWF 4 had significant spatial heterogeneity in TOC without varying across the surveys. These site-specific variations likely reflect differences in local environmental conditions and sediment characteristics.

Limitations

Previous studies have shown that AMBI can be used to detect disturbance from different sources such as hydrocarbon inputs and engineering works. However, limited information is available relating to how useful AMBI might be in naturally stressed and species poor communities such as high energy hydrodynamic environments and subtidal sandbanks (Muniz *et al.*, 2005; Muxikaa *et al.*, 2005). These conditions were more characteristic of the early Round 1 OWF sites and may therefore pose less of a constraint for more recent developments, which are typically located in deeper waters where different environmental conditions may prevail which, in addition to more complex OWF designs, may represent different pressures of variable magnitude to benthic habitats.

Another key limitation in accurately determining the extent of highly localised disturbance, as often predicted during the EIA process, is the lack of targeted post-construction monitoring in close proximity to turbine foundations. Most OWF monitoring programs have not employed spatially explicit sampling designs, such as cruciform or radial layouts, that include stations adjacent to turbine bases and at defined intervals away. Such designs would be particularly valuable for assessing gradients in organic enrichment and benthic community change, using tools such as AMBI, as well as capturing the localised effects of physical disturbances such as sediment scouring around foundations.

The analysis results were grouped based on area (within array, reference etc) and distance from turbines, but the nearest grab stations to turbines for the OWFs analysed are typically at a distance of 50 m or more. Organic matter inputs from colonising fauna may be more restricted to areas much closer to turbines, as elevations of TOC have been reported at distances closer than those of the nearest sampling stations in the datasets considered here (e.g. Coates *et al.*, 2014). This conclusion was reflected in the four-year study at the Block Island OWF (Fonseca in ECO Magazine, 2025) which found that significant changes in benthic composition only occurred in the immediate footprint of the turbines and no evidence was found for a progressive distance-dependent effect on benthic communities. This suggests that enrichment effects may have gone undetected due to sampling distances but also supports the conclusion that such effects are highly localised.

The data from some OWF monitoring programmes may not provide enough statistical power to detect differences if they do exist, especially in terms of the number of overall 'impact' and reference stations that are surveyed. Additionally, monitoring programmes typically only have one pre-construction survey or limited reference stations (if any) which can introduce uncertainty in distinguishing OWF disturbance effects from natural variability of benthic communities.

3.5.4. Biological trait analysis

Summary of the analyses.

Biological traits analysis uses a series of life history, morphological and behavioural characteristics of species present in assemblages to indicate aspects of their ecological functioning. A trait-based approach can address a range of ecological issues and reveal how altered communities influence ecosystem processes, such as nutrient cycling, sediment bioturbation, or organic matter decomposition (Mouillot *et al.,* 2013).

The Cefas data set 'key biological traits of marine benthic invertebrates surveyed in Northwest Europe' (Clare *et al.*, 2022) were used to match the relevant functional traits to the collated benthic species recorded during the OWF monitoring. Species within samples were assigned the following biological traits:

- Maximum size;
- Lifespan;
- Living habitats;
- Sediment position;
- Feeding mode;
- Bioturbation.

Following the assignment of traits, a species and site trait matrix was constructed and subsets of traits (for example those sensitive to disturbance) could then be analysed using univariate and multivariate analyses.

The pre- and post-construction benthic faunal data for OWFs 1, 2 and 3 (Table 1) were analysed using the biological trait approach to help identify spatial and temporal similarities/differences in benthic communities according to biological trait distributions for each OWF site.

OWF 1 - Main findings and conclusions

The biological traits analysis investigated benthic community changes at OWF 1 across pre-construction and three post-construction surveys. Below is a summary of the main findings for each of the six traits and any changes between pre- and post-construction surveys as well as any influence of TOC and sediment fines. The full results of the analysis can be found in Appendix 4.

Maximum Size

Communities were dominated by medium-sized taxa (101-200mm), though smaller organisms (<20mm) increased over the monitoring period, particularly at sites near turbines. Opportunistic species tend to be small, short lived rapidly reproducing species (r-selected) and can be indicative of disturbed conditions, as opposed to the larger, longer lived slow growing less disturbance tolerant k-selected species, which characterise undisturbed conditions (Pianka, 1970). Consequently, an increase in these smaller taxa may be an indication of degradation of environmental conditions, although as this shift occurred across all site groupings including the reference stations, any such changes observed at OWF 1 cannot be attributed to influence of the wind farm.

Lifespan

Taxa with 3-10 yr lifespans, a trait characteristic of k-selected taxa, consistently dominated throughout the study (averaging 53%), with relatively small increases observed post-construction. This pattern, allied to the consistently low proportions of short-lived taxa recorded throughout, would indicate no disturbance-related shifts in this trait in relation to the development of OWF 1.

Living Habitat

Free-living taxa dominated (63% average), while tube-dwelling and burrowing taxa between them represented on average of 30% of individuals.

Sediment Position

Shallow infauna dominated (46-80%) across the survey period and survey areas with typical depth distributions of benthic macrofauna as expected (60-90% of individuals found in the top 5cm), showing no evidence of sediment shallowing that might indicate wide-spread organic enrichment from wind farm structures.

Feeding Mode

Suspension and surface deposit feeders were the most common feeding modes. The average dominance of all feeding mode categories showed little temporal variation across the study.

Bioturbation

Throughout the study period diffusive mixers and surface depositors were the dominant traits at all site groupings between them representing between 80% and 90% of taxa across the whole study with minimal temporal or spatial variation.

Temporal Analysis

The analysis suggested that OWF construction did not significantly influence benthic community traits. While some differences were observed between pre-construction and the second post-construction survey, similar patterns also occurred at reference stations, suggesting natural variability may be the driver behind any observed changes.

Total Organic Carbon

TOC levels decreased across the study area post-construction, including at sites nearest to turbines. While some trait categories showed relationships with TOC levels, particularly for smaller-sized and shorter-lived taxa and higher TOC concentrations, no consistent temporal or spatial patterns were evident suggesting the absence of any connection between TOC patterns and variations in dominance of biological traits in relation to the presence of the OWF infrastructure.

Fine sediments

The proportion of fines (silt and clay i.e. <63μm) generally decreased post-construction except at reference stations where increases were observed, although sediment dispersion modelling indicated that sediment disturbed during construction was unlikely to be deposited at these sites. This indicates that any changes in the proportion of fines in the sediments across the study area are unrelated to the presence of the OWF infrastructure. Furthermore, there was no evidence that sediment characteristics were driving any changes in the distribution of biological traits across the study area.

Conclusions

For OWF 1, there appears to be no influence of the OWF construction in relation to the relative dominance of all benthic traits analysed. No consistent patterns in traits, either spatially or temporally, were observed in relation to the OWF. Where evident, the magnitude of changes are proportionally small and this, combined with the lack of any consistent patterns, would indicate that these are related to natural variability at the OWF site. As such, the traits analysis does not highlight any influence of the OWF development on distribution of traits across the benthic communities. This conclusion is consistent with that of the original benthic study undertaken as part of the post-construction monitoring programme which employed more traditional univariate and multivariate statistical analyses.

OWF 2 - Main findings and conclusions

Below is a summary of the main findings for each of the six traits and any changes between pre- and post-construction surveys as well as any influence of TOC and sediment fines at OWF 2. The full results of the analysis can be found in Appendix 4.

Maximum Size

Small-sized taxa (10-20mm) dominated communities across sites and survey periods, representing 45% of individuals on average. Taxa with a maximum size of <20mm total showed little variation between sites and years with the highest proportion reaching up to 84% at adjacent sites in the third post-construction survey. However, similar proportions occurred at reference stations (71%), suggesting natural variability being the primary driver.

Lifespan

Taxa with 3-10 yr lifespans dominated (53% average), with shorter-lived taxa (<1 year) more prevalent within the array area (22%) compared to other areas. Some temporal shifts occurred between pre-construction and second and third post-construction years, but patterns were inconsistent across site groupings.

Living Habitat

Free-living taxa predominated (63% average) but declined over the monitoring period while burrow dwellers increased, particularly within the array area. However, the combined proportion of these two categories remained consistent (87-91%).

Sediment Position

Mid-depth dwelling taxa consistently dominated (53% average) across survey periods and areas with highest proportions during pre-construction. Shallow infauna increased post-construction at array sites but remained stable elsewhere, indicating localised changes.

Feeding Mode

Surface and sub-surface deposit feeders were consistently the most dominant (32% and 31% respectively) across survey years and site groupings. Similarly, the relative dominance of scavengers and predators remained relatively stable across the study area.

Bioturbation

Diffuse mixing taxa dominated (61% average), particularly at array sites, while surface deposition taxa were more prevalent at sites outside the array area. No clear temporal patterns emerged for any bioturbation category.

Temporal Changes

In general, the analysis found limited evidence that OWF construction influenced benthic community traits. While some variability was observed across the monitoring period, patterns were similar at reference stations, indicating that natural variability is likely the primary driver across the study area.

Total Organic Carbon

TOC levels were generally higher near turbines and increased slightly in the first post-construction survey at sites 100-250m from turbines, potentially indicating organic input from epibenthic colonisers. However, these changes in TOC did not translate into consistent trait responses.

Sediment Fines

Fine sediment proportions were generally higher near turbines but showed no consistent temporal patterns. While some trait categories showed relationships with fines content, these were not clearly linked to OWF presence as similar patterns occurred across all OWF areas including controls.

Conclusions

For OWF 2, some spatial and temporal variability is evident in the traits data with the magnitude of any changes being relatively small and showing no clear correlation with the OWF. Consequently, considering the magnitude of the observed changes and the lack of any clear driver, it is concluded that the spatial or temporal variability in the distribution of biological traits are related to natural factors with no measurable influence of OWF 2. The original monitoring report also concluded that construction and operation had no detectable effect on sediment characteristics or faunal diversity.

OWF 3 - Main findings and conclusions

Below is a summary of the main findings for each of the six traits and any changes between pre- and post-construction surveys as well as any influence of sediment fines at OWF 3. As the majority of results for TOC were below the detection limit, no meaningful patterns could be determined and consequently TOC is not discussed in relation to this site. The full results of the analysis can be found in Appendix 4.

Maximum Size

Taxa with maximum size of between 21 and 200m dominated communities across sites and survey periods, representing on average almost three quarters of individuals across the study. The distribution of maximum size categories remained relatively consistent throughout the study period and across the study area.

Lifespan

Taxa with 1-3 yr lifespans dominated, representing 76% of individuals on average, while longer-lived taxa 3-10 yr) represented 22%. No clear spatial or temporal patterns were evident in the relative dominance represented by any of the lifespan trait categories and while some variation was evident, the magnitude of changes overall were small.

Living Habitat

Free-living taxa predominated representing on average 46% of individuals, while tube dwelling taxa represented on average 43%, while the combined proportion of these two categories remained consistently above 70%.

Sediment Position

Surface dwelling taxa consistently dominated (51% average) across survey periods and areas with shallow dwelling taxa representing 26% on average over the study period. No distinct spatial or temporal patterns were evident.

Feeding Mode

Suspension feeders were consistently the most dominant (37%) across survey years and site groupings. Similarly, the relative dominance of predators represented 24% of individuals and scavengers 22%. No clear spatial temporal patterns were evident in the relative dominance represented by any of the feeding mode trait categories.

Bioturbation

Surface depositing taxa dominated representing on average two thirds of individuals across the study while diffuse mixers represented 22%. No clear spatial or temporal patterns emerged for any bioturbation category.

Temporal Changes

In general, the analysis found limited evidence that OWF 3 construction influenced benthic community traits. While some variability was observed across the monitoring period, patterns were similar at reference stations, indicating that natural variability is likely the primary driver at the site.

Sediment Fines

Some increases in the proportion of fines were observed post-construction across the study area, although levels were consistently higher at sites outside the wind farm array area. While some trait categories showed relationships with fines content, these were not clearly linked to the presence of the OWF as similar patterns occurred across all OWF areas including controls.

(TOC was not considered in the OWF 3 analysis as three quarters of results reported throughout the study were recorded as “less than” values with the result that no meaningful patterns could be determined).

Conclusions

For OWF 3, some spatial and temporal variability is evident in the traits data with the magnitude of any changes being proportionally small and showing no clear correlation with the OWF. Consequently, considering the magnitude of the observed changes and the lack of any clear driver, it s concluded that the spatial and temporal variability in the distribution of biological traits are related to natural factors with no measurable influence of OWF 3 evident. The original monitoring report also concluded that construction and operation had no detectable effect on sediment characteristics or faunal diversity.

Biological traits analysis conclusions

The biological traits analyses at all three OWF sites revealed similar conclusions in that the analyses suggest that OWF construction did not significantly change the biological traits of the benthic communities at the sites with any observed variability attributed to natural factors rather than construction disturbance. Common patterns emerged across various traits, particularly between OWF 1 and OWF 2, where medium to small-sized taxa dominated communities, with organisms possessing 3-10 yr lifespans consistently representing the majority of individuals. Free-living taxa predominated at both locations, while feeding mode distributions remained stable throughout the monitoring periods, with suspension and deposit feeders remaining dominant in both pre- and post-construction phases. Bioturbation communities were similarly structured at both sites, with diffusive mixers and surface depositors co-dominant.

Some differences were evident between the patterns described above for OWF 1 and OWF 2 compared to those observed at OWF 3. At OWF 3, medium sized taxa dominated, while taxa with lifespans of 1-3 years were the most common. While free-living taxa were also important at OWF 3, tube-dwelling taxa were the most abundant, although both groups could be considered as co-dominant. While suspension and deposit feeders remained the most dominant feeding modes, scavengers and predators were slightly more prevalent at OWF 3 than at the other two OWFs. However, these differences are related to natural environmental factors with faunal patterns at OWF 3 driven by the high energy, mobile sandy habitats, characterised by relatively sparse communities of low diversity dominated by taxa such as amphipod crustacea and mobile polychaete species. However, it should be noted that, as with OWF 1 and OWF 2, little spatial or temporal variability was evident and such variability was considered to be related to natural factors rather than any influence of the wind farm.

In general, where temporal or spatial variations in trait composition were detected, these patterns were also observed at reference stations, suggesting that natural variability, rather than OWF-related impacts, was the primary driver of benthic community variability.

Limitations

A key limitation identified across the reviewed OWFs is the lack of robust pre-construction data, with most sites having only a single sampling event prior to construction. This poses challenges for trait-based approaches, which typically require comprehensive baseline datasets to reliably distinguish natural variability from changes induced by OWF development, and to link biological changes to shifts in ecosystem functioning. Given that the acquisition of additional pre-construction data is generally unfeasible due to temporal and financial constraints, alternative strategies must be employed, albeit with important limitations. These include the use of ecologically comparable reference sites, selected based on similarity in key environmental parameters (e.g., depth, substrate, salinity), to serve as proxies for baseline conditions. Furthermore, historical datasets, even if methodologically inconsistent or insufficient for formal statistical analyses, can still offer valuable context. When used cautiously, such data can provide insights into past community structure and trait composition. Trait-based analyses could be applied to historical datasets from the development area, where available, helping to frame observed changes within the broader envelope of natural variability.

Another limitation relates to the nature of the potential effects on benthic communities of changes in sedimentary characteristics associated with changes in fining of the sediment and increases in TOC in relation to potential changes in hydrodynamic regimes and material released by colonising epifauna on OWF infrastructure. In relation to fining of sediments lower grain size has been reported as a result in reduction in current speed close to the OWF (Leonhard and Pedersen, 2005). Similarly, increases in TOC have been reported in the vicinity of OWF foundations (Coates *et al.*, 2014). However, in both cases such observations were recorded within 25 m of the foundations with no significant effects evident at greater distances. It should be noted that for samples considered in the present study none were collected closer than 50 m from a turbine. Other studies have also noted that distant changes of altered current flow on particulate transport and organic enrichment might be difficult to measure, especially within dynamic environments subject to high natural variability (Wilding, 2014; Dannheim *et al.*, 2020). Consequently, it is considered that any significant influence of the OWFs on sediment characteristics in the present study are unlikely to be manifested at the sampling locations and that any observed patterns in the benthic community data will not be driven by OWF related sediment changes. To better assess any such influences, sampling should be undertaken in closer proximity to foundations, ideally within 25 m of any structures.

Furthermore, the Cefas catalogue did not have all potential traits recorded for each taxon within the collated datasets. This may have led to a reduction in reliability and accuracy in analysis results. Other databases were considered to fill any gaps in trait data found in the Cefas catalogue, such as the Biological Traits Information Catalogue (BIOTIC), however, this resource had been discontinued at the time of this analysis. Moreover, the catalogue translates traits to genus level only, so any potential nuances at the species level would not be detected.

4. Contribution to the research questions

This section summarises the findings from the literature review and the benthic analyses to evaluate their contribution to addressing the five research questions. Key conclusions are summarised and knowledge gaps identified including the requirements for future work to fill these gaps. These include practical recommendations relating to planning, impact assessment, construction and operation of OWFs.

4.1. Research Question 1: Are there suitable metrics to detect changes in benthic habitats that could be applied to offshore wind assessments?

Conclusions from literature review

The literature review concluded that there are suitable metrics to detect changes in benthic habitats that can be applied to OW monitoring programmes. The review of 18 constructed OWFs indicated a well-established suite of metrics currently in use, with consistent patterns of use across monitoring programmes. These approaches align closely with those employed in other mature sectors, such as the aggregate extraction industry, particularly within the context of ecological impact assessment. Metrics that achieved 100% use across all reviewed monitoring programmes include habitat distribution and composition, abundance, species/taxon richness, and PSA. These metrics are well established in ecological monitoring and provide the core framework for benthic monitoring at OWF sites.

Other commonly used metrics included multivariate analyses such as cluster analysis, nMDS, and SIMPER analysis, alongside diversity indices including Shannon-Wiener and Pielou's evenness. Less frequently used metrics included phyletic composition, biomass measurements, physico-chemical parameters and statistical tests such as ANOSIM and PERMANOVA. The review concluded that the metrics outlined above are suitable and effective at determining changes in benthic communities and habitats (biotopes) at OWF sites and associated cable corridors, provided there is robust survey design with sufficient sampling stations and consistency in sampling locations over time.

However, it was determined that additional metrics could be implemented on existing data to complement the range of widely used metrics and provide further insight on potential changes in benthic communities beyond changes in relative abundances of species.

The review identified several metrics not currently used in OWF monitoring that have potential applications. These include the ITI for assessing feeding guild changes, the AMBI for detecting disturbance gradients particularly related to organic enrichment, the IQI for ecological quality assessment, the Benthic Ecosystem Quality Index (BEQI) for multilevel ecosystem assessment, ABC Curves for detecting anthropogenic perturbation, and biological trait analysis for understanding functional diversity and ecosystem functioning. The use of such metrics, in combination with the commonly used metrics, has the potential to provide a more holistic view of the effects of OWF construction.

Conclusions from data analyses

Of the potential options for additional metrics identified in the literature review, AMBI and biological traits analysis were used to analyse the collated data in Work Package 4 to further investigate the research question. In discussion with the ORJIP steering group, it was decided that AMBI was one of the preferred options for analysis in Work Package 4 due to its capacity to detect change in benthic communities and also identify the nature of the change in relation to environmental pressures. Similarly, the biological trait analysis approach was adopted to investigate functional changes in the benthic communities, which are not typically investigated through the use of traditional metrics.

The AMBI analysis conducted across four OWFs indicated that while some variability in scores for the index between array areas and reference stations were evident at all OWF sites, these were not considered to be statistically significant in ecological terms. Similarly, no significant temporal changes between pre- and post-construction surveys were evident at any of the four sites. The variations in AMBI scores were generally attributed to natural variability rather than construction-related disturbances given that similar patterns in the fluctuation of AMBI scores were found to occur at both array and reference stations.

The application of AMBI may be particularly useful to understand any effects from organic enrichment associated with colonising fauna in close proximity to turbine infrastructure. However, this would require its use to be considered at the survey design stage to ensure that robust data along a gradient from turbines are collected.

Biological traits analysis also concluded no significant influence of the OWFs construction in relation to the relative dominance for the traits considered. Community structure remained consistent across various traits including size distribution, lifespan categories, feeding modes and bioturbation activities. Similar to the AMBI analysis, any spatial or temporal variability observed was considered to be related to natural variability and not directly attributed to OWF construction.

Both approaches concluded that natural variability was the primary driver behind changes in the benthic communities across all sites. This is in agreement with the findings of the 18 OWF monitoring reports that were reviewed for the literature review, which all also concluded that changes are primarily due to natural variability.

It should be noted that the testing of these two approaches was undertaken using datasets that were not specifically designed for these analyses and from areas where other analyses had concluded no significant impact from OWF construction. This introduces a degree of uncertainty with regard to the conclusions. To properly test the value of specific metrics, dedicated datasets should be collected for this purpose. However, it is considered that both approaches have the potential to provide valuable insights beyond the traditionally used taxonomic metrics, but their use will need to be considered at the survey design stage to ensure the collection of robust data appropriate for use with AMBI and traits analysis. Additionally, it is considered that, beyond survey design, these approaches could be relatively easily incorporated into traditional benthic monitoring programme analysis without undue cost and programme implications.

Knowledge gaps

As discussed in the literature review (Appendix 1), the range of metrics frequently applied are generally effective at demonstrating changes in benthic communities/habitats, however, there is a lack of information relating to the effects of such changes on ecological function at a community/habitat level. This lack of information is applicable to all types of coastal and offshore marine development including OWFs. The metrics currently used are also not designed to indicate potential disturbance of the benthic communities beyond structural changes (relative abundances, diversity and dominance of species) and do not consider the functional aspects of benthic communities.

Non-native species monitoring has historically been a gap in OW environmental practice, with only seven of the 18 reviewed monitoring programmes making specific reference to non-native species presence or absence. It is important to note that at the time these monitoring programmes for OWFs were conducted, such monitoring was not a standard licensing requirement. However, current UK marine licensing regulations now mandate the inclusion of INNS Mitigation Plans for OWFs in UK waters. These plans must detail measures to prevent the introduction and spread of invasive species throughout all project phases. Despite this regulatory shift, the limited consideration of non-native species in earlier programmes highlights a legacy gap in monitoring practices. However, this is not unique to OWF monitoring with INNS monitoring generally historically inadequate and inconsistent across sectors.

The Before-After-Control-Impact (BACI) design is the most rigorous statistical design for detecting environmental impacts (Green, 1979; Underwood, 1994). While this approach was adopted in the studies considered here, the limited baseline data undermines the ability to detect robust temporal patterns and to distinguish natural variability from construction-related impacts. This limitation can also apply, to some extent, when the duration over which post-construction surveys are undertaken is limited to two to three years. Furthermore, as seabed habitat type and its heterogeneity significantly affect natural variability in marine benthic communities (Gray & Elliott, 2009) this should be factored into monitoring programme design (Boyd, 2002; Cefas, 2004; Ware & Kenny, 2011; Judd 2012) with reference stations selected to represent the range of habitats occurring in the potential ZoI of the OWF.

Future work required to fill gaps

The literature review and benthic analyses identify a number of areas for future research and monitoring requirements. Further dedicated testing of the value of additional metrics such as AMBI and biological traits analysis would benefit the analysis as current traditional taxonomic-based approaches may not be sensitive enough to detect ecosystem function changes as a result of OWF development.

For biological traits analysis there is a need to expand the trait catalogues to include species-level information beyond the current genus-level classifications. This would improve the resolution and accuracy of traits analyses and increase the power of the technique to detect change.

Incorporating a robust BACI (Before-After-Control-Impact) design into OWF monitoring programmes is critical for distinguishing project-related impacts from natural variability. Central to this approach is ensuring adequate spatial and temporal replication, particularly through the inclusion of a sufficient number of both reference and impact stations. Expanding the number and geographic spread of these stations to encompass all relevant habitats enhances statistical power, thereby improving the ability to detect ecologically meaningful changes. This, in turn, increases confidence in attributing observed changes to wind farm activities rather than to background environmental fluctuations.

However, collecting additional pre-construction data is often impractical due to temporal and financial constraints. As a result, alternative strategies must be employed, despite their limitations. One such approach involves selecting ecologically comparable reference sites—based on key environmental parameters such as depth, substrate, and salinity, to act as proxies for baseline conditions. Additionally, historical datasets, even if methodologically inconsistent or statistically limited, can still provide valuable context. When used cautiously, these data can offer insights into past community structure and trait composition. In particular, trait-based analyses of historical data from the development area can help place observed changes within the broader scope of natural variability. Unless strategic monitoring at a regional level becomes part of developer responsibilities such approaches may remain the only viable option for establishing ecological baselines.

Furthermore, the inclusion of non-native species analysis and reporting should be recommended in OWF monitoring programmes at sites where site-specific concerns exist as informed by local and regional INNS information, to better assess potential stepping-stone effects and associated ecological risks arising from OWF infrastructure.

4.2. Research Question 2: Is there a measurable change (increase/decrease) in biodiversity and/or species composition?

Conclusions from literature review

The literature review indicated that measurable changes in biodiversity and species composition can occur at OWF sites; however, the nature, magnitude, and ecological significance of these changes are influenced by habitat type, spatial location within the OWF development area, and specific characteristics of the development itself (e.g., construction methods, foundation type, and scale).

For soft sediment habitats, 18 OWF monitoring programmes were reviewed, which found that changes in sediment particle size, invertebrate abundance and taxon richness were observed at multiple sites. However, all monitoring programmes concluded that observed changes in benthic community structure and biodiversity were attributed to natural variability rather than impacts from the construction of the OWFs. These conclusions were underpinned by similar trends being observed at reference stations, inconsistent directions of change between successive surveys and the recognition that these development areas are situated in naturally dynamic marine environments subject to high degree of natural disturbance.

The primary change in biodiversity and species composition at OWF sites is seen in the development of hard substrate communities on turbine foundations. Rapid colonisation of these artificial structures was found to occur within one to three years post-construction, with epifaunal communities developing that differed considerably from the original and surrounding soft sediment habitats. Seven of the 18 OWFs that monitored foundation colonisation documented increased species diversity and biomass on and immediately adjacent to the structures.

The wider literature review also documented instances of localised environmental changes around OWF infrastructure, including increased TOC levels attributed to mussel aggregations causing changes in sediment composition and chemistry, and benthic species assemblages.

Knowledge gaps

Whilst measurable change has been consistently detected within the reviewed monitoring reports for OWFs, all monitoring programmes have concluded that such changes have been as a result of natural variability, with the exception of localised impacts, in certain cases, in the immediate footprint of the OWF from fouling communities. This is contrary to academic literature which indicates that the presence of OWFs has the potential to lead to measurable changes in benthic communities, such as for soft sediment communities, beyond those observed in the footprint of turbine infrastructure (Coates *et al.,* 2014; De Mesel *et al.,* 2015; Degraer *et al.,* 2019; Galparsoro *et al.,* 2022; Lefaible *et al.,* 2023).

Generally, OWF monitoring programmes have been designed to assess potential impacts, with pre-construction monitoring assessing baseline conditions and subsequent monitoring assessing changes in these conditions in response to the construction, presence and operation of an OWF. However, from the monitoring reports reviewed, there is a notable lack of consistency in survey approach between OWF monitoring programmes for detecting such changes in benthic communities. This includes variations in the use of survey methods, monitoring programme duration, and the proportion of reference stations. The proportion of reference stations compared to stations within the OWF impact zones varied greatly between monitoring programs. A benefit to the OWF industry would be to standardize survey design and methodology going forward with a recommendation that sufficient consideration is given to the location and number of reference stations to provide a robust basis for conclusions when considering changes due to natural variability. Similarly, power analysis was not detailed in monitoring reports to determine adequate sample numbers for detecting meaningful biological changes. This may suggest that power analysis was either not applied during the survey design of monitoring programmes to determine sample size to detect a measurable effect size, or it is possible that power analysis was undertaken but not referenced within the survey report methods. If power analysis was not undertaken, the sampling design lacks evidence to support a minimum sample size to detect an effect with a certain degree of confidence (Cohen, 1992). In light of these issues, there is a clear need for the development and implementation of standardised survey designs and methodologies across OWF monitoring programmes. Such standardisation would improve data comparability, strengthen the robustness of impact assessments, and ultimately enhance the ability to detect and interpret ecological changes with greater confidence.

Very few of the monitoring programmes had a dedicated underwater video or imagery element to assess epifaunal communities and broader habitat changes on and in close proximity to the turbine infrastructure. The limited use of complementary survey techniques reduces the comprehensiveness of monitoring programmes and our understanding of changes in biodiversity. However, underwater video monitoring has become a more commonly used technique in more recent OWF developments, enhancing the ability to identify potential changes in benthic communities around turbine infrastructure.

Future work required to fill gaps

Addressing these knowledge gaps requires survey methodology improvements and standardisation and expanded research focus. Where benthic monitoring is deemed necessary it would be beneficial to establish industry-wide standards for survey design that includes the use of power analysis during the planning phase of monitoring programmes. This should include development of clear guidance on minimum statistical power requirements and allocation of reference stations. This would help to ensure consistency and enable meaningful meta-analyses.

As detailed above a benefit to the OWF industry would be to standardise survey design and methodology going forward with a recommendation that sufficient consideration is given to the location and number of reference stations to provide a robust basis for conclusions when considering changes due to natural variability. This, in turn, would improve the effectiveness of monitoring programmes in distinguishing between natural variability and disturbances associated with OWF development. Additionally, ensuring consistent public availability of monitoring data via established data platforms, such as the Marine Data Exchange and OneBenthic, would support broader regional and site-specific analyses of OWF related impacts.

Consistency in the use of underwater video and imagery in monitoring programmes would benefit our understanding of changes on and in close proximity to turbines, particularly in areas where traditional grab sampling is inappropriate or challenging. This would allow a wider spectrum of changes to be consistently observed, including the development of epifaunal communities on hard structures. While it is recognised that underwater video was not consistently applied in earlier monitoring efforts, it is increasingly becoming standard practice in more recent OWF developments, enhancing the ability to detect and interpret any potential changes.

Future research may increasingly shift focus beyond biodiversity and species-level metrics to incorporate ecosystem-level assessments. Such assessments evaluate changes across multiple dimensions of ecosystem structure and function, including functional diversity, trophic interactions, and energy flow through food webs.

4.3. Research Question 3: Are there localised and regional ecological effects around the infrastructure?

Conclusions from literature review

OWFs are known to produce both localised and regional-scale ecological effects, particularly on benthic communities. Locally, the introduction of artificial structures, such as monopile foundations, scour protection and cable protection can change areas of the seafloor from predominantly soft-sediment habitats to hard-substrate environments. These new substrates can act as artificial reefs, promoting colonisation by sessile species such as mussels (*Mytilus edulis*), barnacles (*Balanus spp.*), and anemones (*Metridium senile*), which significantly increase habitat complexity and species richness (De Mesel *et al.*, 2015; Vanagt *et al.*, 2013; Degraer *et al.*, 2019). The fouling communities that develop around OWF structures exhibit zonation and successional stages, often stabilising over several years but with variation depending on local conditions (Zupan *et al.*, 2023).

At a broader scale, OWFs may influence regional species distributions, trophic dynamics, and ecosystem connectivity. OWF structures can act as stepping stones, enhancing dispersal of both native and non-native species (Dannheim *et al.*, 2017; Henry *et al.*, 2018). Biofouling communities also enrich sediments in the immediate vicinity of turbines via faecal deposition, leading to organic enrichment, finer sediment textures, and shifts in benthic community composition (Coates *et al.*, 2014; SEER, 2022). This enrichment can attract scavengers and higher trophic levels, as shown by increased presence of crabs, brittle stars, and flatfish near OWF installations (Bunker, 2004; Hutchison *et al.*, 2021).

Regionally, hydrodynamic alterations caused by OWF infrastructure, including changes in water flow, sediment transport, and current velocity, have been documented, in some cases, to affect local sediment composition and stratification (Daewel *et al.*, 2022; Forster, 2018). These changes influence the distribution and structure of benthic communities, with sediment grain size variation driving shifts in dominant macrofaunal species and associated ecosystem processes such as bioturbation and nutrient cycling (Van Hoey *et al.*, 2004; Coates *et al.*, 2015). Looking ahead, the emergence of FLOW technologies is facilitating the expansion into deeper, seasonally stratified shelf seas, necessitating the use of larger and more complex turbine support structures that may further alter local hydrographic and sedimentary regimes.

Furthermore, OWFs pose additional stressors through EMFs emitted by subsea cables, and underwater noise from installation and operation. Although the behavioural and physiological responses of benthic invertebrates to EMFs and noise are still poorly understood, early studies indicate potential sub-lethal effects and alterations in larval development and migration (Scott *et al.*, 2020; Hutchison *et al.*, 2021). Although these impacts are not currently anticipated to be significant in EIA terms, understanding their localized and cumulative effects remains potentially important for effective environmental management and mitigation, if required.

Identified knowledge gaps

There is currently insufficient understanding of how OWFs influence benthic ecosystems at regional spatial scales, particularly beyond the immediate turbine footprint. While localised impacts, such as habitat change and fouling colonisation, are well documented but also, as demonstrated by the monitoring data reviewed in this study, extremely localised to the turbine locations, there is a lack of comprehensive studies quantifying cumulative and far-field effects, including sediment redistribution, biogeochemical cycling, and long-term shifts in community composition, noting also that secondary indirect effects considered in OWF EIAs and based on detailed hydrodynamic and sediment modelling, suggest that such effects are limited to within or nearfield to the OWF array area.

To date, most OWFs have been constructed in shallow, nearshore waters that are typically unstratified and well-mixed, using fixed foundation technologies. However, the development of FLOW technologies is enabling expansion into deeper, seasonally stratified shelf seas, which require larger and more complex turbine support structures (Dorrell *et al.*, 2022). Stratified seas are critical to marine primary production and are closely linked to biogeochemical cycling. The introduction of anthropogenic structures into these environments can enhance vertical mixing, potentially disrupting natural stratification. This increased mixing may elevate nutrient availability, thereby altering productivity patterns and exerting cascading effects on marine ecosystem dynamics. There is therefore a key research gap in this emerging technology and deeper waters.

Another gap lies in the limited data on how OWFs influence species connectivity and dispersal. While OWFs may enhance connectivity among certain benthic species through stepping-stone effects, empirical data confirming whether this does in fact occur at any significant and ecologically meaningful scale are sparse. The role of OWFs, alongside other existing subtidal infrastructure, in facilitating the spread of non-native species is similarly understudied (Kerckhof *et al.*, 2011; De Mesel *et al.*, 2015).

Finally, the ecological consequences of different OWF decommissioning strategies are not fully understood, since no commercial scale OWF have yet been decommissioned. While preliminary evidence suggests that partial removal of infrastructure (e.g., retaining scour protection/cable protection), where permitted by the regulatory framework, may help maintain benthic biodiversity. Studies to confirm these findings are sparse across different sites or turbine designs (Spielmann *et al.*, 2023).

Future work required to fill gaps

To improve understanding of local and regional OWF impacts, site specific monitoring should focus on surveys designed over a suitable period and with sufficient statistical rigor to identify the consequence of OWF development at a particular site. This could include establishing standardised baseline data collection before construction, followed by routine post-construction surveys extending across suitable timescales to appropriately describe the changes to the benthic faunal communities and associated habitats, where required. Furthermore, as indicated in Section 4.4, there is the potential to analyse monitoring data using both taxonomic and functional diversity, using trait-based metrics to evaluate changes in ecological functioning and ecosystem services (Boutin *et al.*, 2023; Coates *et al.*, 2014).

Hydrodynamic and sediment transport modelling should be better integrated with targeted ecological monitoring to assess how OWF-induced alterations in physical conditions translate into biological responses. To ensure robustness, models should be validated using BACI survey designs and calibrated for site-specific environmental contexts (van Berkel *et al.*, 2020). This integrated approach will enhance understanding of the physical thresholds beyond which benthic community structure and ecosystem functioning are significantly affected. FLOW developments will also need to account for potential impacts to deeper, seasonally stratified shelf seas in their environmental monitoring approaches, incorporating ecosystem-level indicators that capture changes in stratification, nutrient dynamics, and associated ecological processes.

Further research is needed to investigate the role of OWFs in species dispersal and connectivity. Academic research conducted at a strategic scale using genetic and tagging studies could, for example, provide insights into the stepping-stone role of turbines for native and non-native species. Similarly, strategic broadscale monitoring of non-native species colonisation patterns on representative OWFs compared to natural reefs and oil platforms are essential to guide management actions and risk assessments (Mineur *et al.*, 2012; Bulleri and Airoldi, 2005).

Furthermore, decommissioning scenarios should be empirically tested through pilot projects that evaluate species retention, habitat integrity, and cost-effectiveness under different infrastructure removal options, subject to any limitations imposed by the regulatory framework and technical and within commercial and technical limits. Studies like those by Spielmann *et al.* (2023) should be expanded across diverse geographic settings and turbine designs to develop evidence-based decommissioning guidelines that maximise ecological benefit while ensuring safety and feasibility.

4.4. Research Question 4: Is there change in ecological function (e.g. functional groups) as a result of biological changes?

Conclusions from literature review

The installation and operation of OWFs have the potential to alter benthic ecosystem functioning by shifting community composition and dominant functional groups. The introduction of artificial hard substrates in previously soft-sediment environments may promote the colonisation of epifaunal suspension feeders, such as mussels and barnacles, in place of infaunal deposit feeders and bioturbators typically associated with soft sediments (Petersen and Malm, 2006; Wilding *et al.*, 2017). While these changes are often predicted to influence key ecosystem processes, including nutrient cycling, organic matter decomposition, and sediment bioturbation (Coates *et al.*, 2014; Krone *et al.*, 2013), empirical evidence remains limited, particularly at larger spatial and temporal scales, likely due to the localized nature of these effects. As a result, such changes are generally addressed within EIAs and incorporated into the consenting process, though additional field-based research is needed to better understand their potential long-term ecological implications.

OWF-induced changes extend beyond immediate community composition to include broader ecosystem-level impacts; however, these are often highly localised. Suspension feeders enhance water column filtration and increase organic matter deposition, potentially leading to opportunistic species proliferation and altered energy flow within the benthic food web (Maar *et al.*, 2009; Coates *et al.*, 2014). Conversely, construction-related disturbance (including dredging, if required) and sediment modification can reduce the abundance of key bioturbators, as evidenced by reductions in sediment oxygen consumption and nutrient fluxes in areas with altered sediment composition (Pratt *et al.*, 2014).

The functional composition of benthic assemblages on OWF infrastructure is dynamic and driven by biological succession. Initial colonisation phases often show high functional richness, which may decline in later successional stages as dominant species like *Mytilus edulis* and *Metridium senile* outcompete other taxa (Boutin *et al.*, 2023). These late-stage communities can influence ecosystem functions differently, providing aspects of possible enhancement in some cases (e.g., water filtration) while potentially suppressing other processes (e.g. larval recruitment or sediment mixing) (De Borger *et al.*, 2021; Ivanov *et al.*, 2021).

Additionally, OWFs may influence ecological function due to hydrodynamic alterations, which can modify sediment transport and larval dispersal. These changes can affect species distributions and trait composition, often favouring sessile, suspension-feeding taxa over mobile, sediment-dependent organisms (Shields *et al.*, 2011; Coates *et al.*, 2014). The resulting shift in trait dominance may contribute to a functional transition from bioturbation and organic matter recycling toward filtration and sediment stabilisation. However, these effects are typically highly localised, with the magnitude and spatial extent of ecological change largely confined to the immediate vicinity of turbine structures.

While changes in biodiversity are often used as proxies for ecosystem health, it is increasingly clear that shifts in functional traits are also of key importance for understanding the ecological consequences of OWFs (Boutin *et al.*, 2023; Hutchison *et al.*, 2020). Therefore, trait-based approaches can be beneficial for evaluating the net effect of OWF developments on benthic ecosystem functioning.

Conclusions from biological traits analysis

The biological traits analyses conducted on datasets from three OWFs did not detect the significant changes in ecological function identified in the literature review. These analyses found no significant influence of OWF construction on the relative dominance of benthic traits. Community structure, and therefore function, remained relatively consistent across various traits including size distribution, lifespan categories, feeding modes and bioturbation activities. While small changes in traits dominance were evident, this would be expected in a highly dynamic environment such as OWF sites, and similar patterns of variability were observed at reference stations suggesting that the primary driver was natural variability.

It should be noted that the datasets analysed were not from surveys that were specifically designed for traits analysis or to detect changes in ecological function of communities in close proximity to OWF infrastructure. Typical grab surveys would usually maintain a safe working distance from turbines to ensure the grab sampler does not interact with the turbine structure or any surrounding scour protection. This means that sampling may not have targeted the primary, but highly localised, area where the most significant changes in benthic communities might have occurred, and therefore potentially ecological function, during post-construction phases.

As such, while the traits analysis concurred with the findings of the original monitoring programme that utilised traditional analysis methods, it may be that changes in traits and ecological function in close proximity to the turbines were missed by this analysis.

Identified knowledge gaps

Despite progress, several critical gaps remain in understanding how OWFs affect ecological function due to changes in benthic communities.

Few long-term studies have tracked how functional group composition evolves over time post-installation. While biodiversity data exist for up to 11–15 years in some cases (e.g., Zupan *et al.*, 2023), functional trait assessments over comparable periods are rare. Without this long-term perspective, it is difficult to determine whether observed changes are temporary successional stages or represent new functional equilibria.

There is a lack of studies explicitly linking physical habitat modifications, such as changes in sediment type or hydrodynamic regime, to alterations in functional processes like nutrient cycling or carbon burial. Although theoretical models predict such links, empirical validation is sparse and typically limited to small spatial scales (Coates *et al.*, 2014; Ivanov *et al.*, 2021).

Trait-based approaches are not yet applied as part of OWF ecological assessments. Functional traits such as feeding type, mobility, and bioturbation capacity are rarely integrated into standard monitoring data analyses, limiting the ability to assess ecosystem function changes comprehensively (Mouillot *et al.*, 2013; Reiss *et al.*, 2009).

Additionally, it remains unclear how cumulative OWF developments influence functional diversity at regional scales. The risk of homogenisation, where similar fouling communities develop across multiple installations, has not been thoroughly evaluated (Langhamer, 2012; Dannheim *et al.*, 2020). This is a knowledge gap in relation to resilience and long-term ecosystem service delivery in heavily developed marine regions.

Furthermore, while the potential for positive functional outcomes such as carbon sequestration or nutrient retention has been noted, these benefits have not been consistently quantified, nor has their spatial extent been established beyond site-specific case studies (Krone *et al.*, 2013; Wilhelmsson *et al.*, 2006).

Future work required to fill gaps

To address these gaps, future research can prioritise the incorporation of biological traits data into OWF monitoring programmes. This includes developing baseline trait profiles for pre-construction communities and tracking shifts through the post-construction phase using metrics such as functional diversity, evenness, and redundancy (Boutin *et al.*, 2023). Elements of monitoring programme survey design could focus specifically on traits analysis to complement the current traditional survey designs for example, collecting data in close proximity to a number of turbines within an array area in addition to across the array area. Establishing national or regional databases of benthic species' functional traits would support this aim and allow for cross-site comparisons.

Studies over a suitable period are essential to understand the full successional trajectory of fouling communities and their impact on ecological function. Extending monitoring across longer timescales and encompassing both natural and artificial hard substrate habitats would be beneficial to understanding and filling this knowledge gap. It is recognised that this may require a collaborative approach between OWF developers and researchers. This will help clarify whether OWF-induced communities converge on stable functional endpoints or continue to evolve under ongoing environmental pressure (Zupan *et al.*, 2023).

Additionally, while predictive modelling is already a key component of EIA, there is scope to expand these efforts through broader-scale, strategic monitoring that integrates hydrodynamic, sediment transport, and ecological data. Such models could help validate anticipated effects of OWF installations at larger spatial scales. Validation through field data, collected via BACI-style surveys, would support a more comprehensive understanding of observed versus predicted changes in response to OWF activities (Smith *et al.*, 1993; van Berkel *et al.*, 2020).

Research could also be conducted to explore the cumulative effects of multiple OWFs on regional functional diversity. This includes mapping functional homogenisation patterns, assessing connectivity between installations, and evaluating the resilience of altered ecosystems to external stressors such as climate change or invasive species (Lindeboom *et al.*, 2015; De Borger *et al.*, 2021).

Furthermore, policy-relevant studies are needed to quantify the functional ecosystem services provided by OWFs, such as water filtration, carbon sequestration, and secondary production (Watson *et al.*, 2024). These services could be incorporated into Marine Net Gain frameworks, allowing for a more holistic valuation of OWF contributions to marine ecosystem functioning.

4.5. Research Question 5: Can recovery and/or enhancement be demonstrated and in what timeframe?

Conclusions from Literature Review

OWFs can exert both temporary and long-lasting influences on benthic habitats and communities. The ability of these ecosystems to recover post-construction or to be enhanced through OWF development varies across habitat types, the species present, and site-specific environmental conditions.

Soft sediment habitats, which are commonly affected during OWF installation, generally indicate a strong capacity for recovery. Several studies have demonstrated that infaunal communities can return to pre-construction conditions within approximately two years, particularly in environments naturally characterised by high disturbance (Coates *et al.*, 2015; van Dalfsen *et al.*, 2000). It should be noted that these findings relate to temporary impacts to infaunal communities, and do not apply to permanent impacts, such as loss of habitat, within the footprint of turbine infrastructure or scour protection.

Recovery patterns of epifaunal species in benthic habitats remain poorly understood, primarily due to the limited application of standardised, long-term monitoring methodologies (Vandendriessche *et al.*, 2014). Although most OWF sites collect epifaunal data using drop-down video surveys, conducting robust quantitative analyses on these data remains challenging due to issues such as variability in image quality, resolution, and observer bias. Some OWFs, such as Princess Amalia, have demonstrated the potential for longer-term data collection (up to 15 years) using trawl surveys to examine epifaunal succession (Leewis and Klink, 2022). The study, however, indicated no significant differences in soft-bottom benthic fauna between areas inside and outside the OWF across this timeframe, with similar species abundance, diversity indices, and community composition (Leewis and Klink, 2022).

Artificial structures such as turbine foundations, scour protection and cable protection have demonstrated ecological enhancement potential by serving as artificial reefs that increase local biodiversity, biomass, and species richness (Degraer *et al.*, 2019; De Mesel *et al.*, 2015; Vanagt *et al.*, 2013). Such effects have included the colonisation of commercially important species like *Ostrea edulis* and crustaceans such as lobsters and edible crabs (Hooper and Austen, 2014; Robertson *et al.*, 2021). However, these changes may not be considered to represent enhancement unless infrastructure has been specifically designed with biodiversity objectives and the local environment in mind (Evans *et al.*, 2019; Firth *et al.*, 2020).

Reserve effects, particularly through exclusion of bottom-trawling around turbine foundations, have been associated with increased abundance of benthic species, yet the long-term persistence and causal mechanisms of such effects remain uncertain (Dunkley and Solandt, 2022; Krone *et al.*, 2017; Isaksson *et* *al.*, 2023). Evidence from repeated mapping at the Thanet OWF, however, provides valuable insights into the potential for habitat recovery from OWF developments. Pearce *et al.* (2014) documented the re-establishment and spatial expansion of *Sabellaria spinulosa* reef structures over multiple years, indicating recovery of this reef at the site potentially facilitated by reduced disturbance from activities such as fishing and the appropriate micro-siting of OWF infrastructure. This case study suggests that, under appropriate conditions, OWFs can contribute positively to the recovery of sensitive reef-building species.

Decommissioning decisions will be pivotal in determining whether the biodiversity associated with hard structures remains, as removal of all OWF infrastructure would be anticipated to return the seabed to pre-OWF conditions over time, reducing localised diversity, especially in terms of epifauna (Spielmann *et al.*, 2023). Whilst decommissioning strategies for OWF infrastructure are relatively novel in the UK, with the earliest OWFs reaching the end of their anticipated operational lifespan in the next few years, examples from other offshore infrastructure industries (e.g. oil and gas) indicate that in many cases not all infrastructure can be removed, often leaving foundations and scour protection permanently in place. Decommissioning plans already submitted for OWF sites currently only include proposals for partial removal, often highlighting that it is not technical feasible to fully remove the buried sections of the wind turbine foundation (RenewableUK, 2025).

Identified knowledge gaps

A critical gap in understanding the ecological impact of OWFs lies in the lack of longer-term monitoring data, although more recent monitoring regimes are already addressing this issue by monitoring over an extended period post construction. The monitoring programmes reviewed typically spanned two to three years post construction, making it difficult to assess if there are any longer-term changes in benthic community structure, function, and stability. This limitation is particularly evident in tracking successional patterns of species colonising turbine infrastructure and their implications for ecosystem functioning over time.

There is also a notable deficiency in data concerning epifaunal recovery. While there have been many studies of infaunal responses to OWF installation based on grab sampling in soft sediments, epifaunal communities, especially those associated with seabed hard structures, remain relatively understudied. This is primarily due to challenges in standardised sampling, restricted access near turbines for safety reasons, and logistical constraints.

Another significant gap pertains to the attribution and definition of ecological enhancement. Many studies report increases in biodiversity or biomass due to artificial substrates, yet few distinguish whether these outcomes result from intentional nature-positive design or passive colonisation. Without this distinction, it is difficult to determine whether observed enhancements can be replicated or scaled, particularly in the context of Marine Net Gain objectives (Evans *et al.*, 2019). In addition, further clarity is required to determine if colonisation following implementation of intentional nature-positive design measures could be considered to represent enhancement at OWFs.

Furthermore, enhancement is often measured using taxonomic metrics such as species richness and abundance. While informative, these do not capture shifts in functional roles or ecosystem processes, which are central to evaluating long-term ecological health. Limited understanding exists about how fouling communities on OWF structures contribute to nutrient cycling, sediment stability, or trophic connectivity, particularly as these communities progress through successional stages (Boutin *et al.*, 2023).

Uncertainties also remain regarding the strength and persistence of reserve effects created by OWF-associated fishing exclusions. While some studies suggest that OWFs act as de facto Marine Protected Areas (MPAs), (Hammar *et al.*, 2016), few have tested the longevity of these effects or disentangled them from other influencing factors like prey availability or habitat complexity. Similarly, decommissioning practices and their effects on long-term benthic enhancement outcomes remain under-researched, especially regarding whether removing infrastructure negates localised increases in biodiversity established over decades (Spielmann *et al.*, 2023).

Future work required to fill gaps

To address these gaps, a key priority is to propose a standardised monitoring programme that collect data on both infaunal and epifaunal communities, using robust sampling methodologies such as drop-down video and Remotely Operated Vehicles (ROVs), to access hard-to-reach turbine areas. High-resolution and consistent data over longer periods are essential to detect trends, understand recovery trajectories and differentiate between natural variability and anthropogenic effects.

Monitoring efforts could also incorporate functional trait-based metrics alongside traditional taxonomic indicators, as indicated in Section 4.1. Developing a suite of functional indicators, particularly tailored to artificial reef habitats, will be essential for assessing the ecological quality of OWF-induced habitats over time (Boutin *et al.*, 2023).

In terms of ecological enhancement, future studies could be used to differentiate between passive and intentional biodiversity gains. Comparative studies of modified versus unmodified infrastructure designs, such as complex scour protection layouts, textured turbine coatings, or integrated reef modules, would help identify which design elements most effectively support desired ecological outcomes (Evans *et al.*, 2019; Firth *et al.*, 2020). These studies should be supported by experimental pilot projects and integrated into future OWF developments, including floating OWF.

Research on reserve effects should include multi-site, long-term studies to determine whether bottom-trawling exclusion from areas in and around OWFs consistently enhances benthic biodiversity and biomass, and whether these effects extend to commercially valuable species like crabs and lobsters. Such work should also examine how reserve effects interact with other OWF-related ecological changes, including increased prey availability and altered habitat structure.

Decommissioning strategies should be empirically tested to understand their ecological consequences. Studies should explore biodiversity retention under different removal scenarios, including, subject to the prevailing regulatory framework, full, partial, or no removal of foundations, scour protection layers and cable protection. Evidence from sites like Horns Rev 1 suggests that selective retention of infrastructure can preserve up to 90% of associated species, underscoring the importance of tailored, ecologically informed decommissioning policies (Spielmann *et al.*, 2023).

Collectively, this future work will be instrumental in refining our understanding of recovery and enhancement within OWFs, informing policy frameworks like Marine Net Gain when it is implemented, and ensuring that OWFs continue to contribute positively to marine biodiversity, resilience, and ecosystem services. The evidence to date indicates that recovery of soft-sediment communities at OWFs is feasible within short to medium timeframes, when disturbances are minimal and habitats are inherently dynamic. However, a robust understanding of recovery and enhancement, especially for epifaunal communities and functional roles, remains limited due to gaps in long-term, standardised monitoring and targeted enhancement design. Addressing these knowledge gaps through extended research and monitoring, supported by clear metrics and adaptive design, is essential to fully understand the ecological trajectory of OWFs and to ensure they contribute meaningfully to marine ecosystem recovery, resilience, and policy goals such as Marine Net Gain.

5. Informing policy positions

5.1. PP1: Inform marine spatial planning

OWFs can modify benthic habitats through the introduction of artificial hard substrates, including turbine foundations, scour and cable protection, and substation or converter platforms. These structures may resemble natural reef features and support colonisation by epifaunal assemblages such as mussels, barnacles, and anemones (Cale and Churn, 2021). While this can locally increase habitat complexity and biodiversity, it may also displace soft-sediment infauna, resulting in changes to community composition and trophic structure. However, such changes are typically not a primary driver in spatial planning decisions. Instead, the presence of designated conservation sites and features, such as MPAs, Special Areas of Conservation (SACs), or other priority habitats, is often used as a proxy for habitat sensitivity in Marine Spatial Planning (MSP) and the EIA processes. These designations highlight areas where benthic communities are of particular ecological importance or vulnerability. Additionally, the introduction of artificial structures may facilitate the spread of non-native species, including invasive barnacles and crabs, raising a further consideration for long-term ecological and management concerns (Cale and Churn, 2021).

Given these ecological implications, MSP could be informed by site-specific assessments of habitat sensitivity and the potential for artificial structures to facilitate non-native species spread. While general benthic data may have limited influence on siting decisions, designated conservation features and protected areas offer a practical proxy for ecological vulnerability. The UK Marine Strategy (Part One), which outlines descriptors for achieving Good Environmental Status (GES), including those related to biodiversity, non-indigenous species, and seafloor integrity, provides a relevant policy framework for assessing and managing such impacts within MSP processes.

Moreover, spatial planning should recognise not just species presence but also broader ecological functions and habitat roles. While functional diversity data are not typically a direct input into planning frameworks, understanding how different habitats and associated communities support key ecosystem processes can help identify areas of higher ecological value or resilience. This perspective is increasingly relevant for strategic environmental assessments and for ensuring that OWF expansion does not contribute to regional ecological homogenisation or compromise ecosystem functioning (Mouillot *et al.*, 2013).

5.2. PP2: Mitigating negative impacts through licensing and design standards

Effective licensing frameworks should incorporate consideration of ecological function, not just species-level diversity. For example, the shift from infaunal to epifaunal dominance, driven by the colonisation of OWF hard structures, can alter benthic ecosystem functions such as sediment bioturbation and nutrient cycling (Coates *et al.*, 2014). Therefore, filtration by mussel beds may increase, while bioturbation by deposit feeders may decline. These localised functional changes are well-documented and routinely assessed through EIAs. However, in most licensing contexts, they are typically considered to be of limited spatial extent and not significant at the regional scale. While such changes may influence ecological processes in the immediate vicinity of structures, they are unlikely to affect broader ecosystem resilience unless developments are clustered, or cumulative impacts intensify across multiple OWF sites.

To address this, trait-based ecological assessments could be embedded in the analysis of data for both pre- and post-consent monitoring (Boutin *et al.*, 2023). This approach aligns with UKMS Part 2 indicators and allows for tracking biodiversity by ecological role rather than just abundance or richness.

Incorporating ecological traits helps to monitor shifts in function, critical for adaptive design and mitigation.

Licensing and EIA processes already incorporate adaptive feedback mechanisms, where monitoring data can inform mitigation through project design, including layout configuration, cable routing, and scour protection strategies (Natural England, 2021). Where significant negative effects are identified, these elements are commonly adjusted to reduce ecological impacts. Continued application of this evidence-based, adaptive approach will be increasingly important as OWF developments scale up and cumulative effects become more likely. In line with Natural England's strategic advice, early consideration of decommissioning and its potential ecological and wider ecosystem effects should also be embedded at the planning stage to support long-term environmental stewardship (Natural England, 2021).

Greater clarity should be provided by stakeholders about how localised increases in biodiversity are viewed due to the installation of structures on the seabed in terms of mitigation/offsetting/compensation measures for OWFs; in particular, clarity around any differences if such colonisation is passive or is actively encouraged via infrastructure design measures which promote epifaunal colonisation. This advice should also carry through to recommendations for decommissioning in relation to any enhancement measures that have been implemented.

5.3. PP3: Inform potential compensation scope and scale

Strategic, scalable compensation measures are required only in cases where adverse effects on designated sites or features, such as SACs (under the Habitats Regulations) or Marine Conservation Zone's (MCZs) (under Marine Environmental Enhancement Baseline (MEEB) principles), cannot be fully mitigated. This is distinct from broader marine net gain ambitions, which are not yet mandatory in the offshore context.

In cases where mitigation alone is insufficient, the Offshore Wind Environmental Improvement Package (OWEIP) and Energy Act 2023 provide a mechanism for implementing Marine Recovery Funds. These funds offer the potential for regional, pre-emptive compensation, maximising ecological return on investment (Ward *et al.*, 2022).

Compensation measures must aim to deliver functional equivalence, not merely replicate habitat type, area, or species presence. Effective compensation should restore key ecological functions, such as bioturbation, nutrient cycling, or organic matter processing, by targeting habitats that are functionally, not just structurally, comparable to those impacted (Natural England, 2021). To support this, developers and SNCBs should draw on existing spatial assessments and ecological data layers to identify suitable habitat and compensation mechanisms capable of sustaining the desired functional outcomes.

Evidence also indicates that compensation delivered strategically, and in advance of impacts, is more likely to succeed (UKMS Part 3). As OWF expansion continues and competition for seabed space intensifies, plan-level compensation may offer a more strategic mechanism for addressing unavoidable impacts, particularly to wide-ranging species such as seabirds, but also in cases where export cabling intersects with designated benthic features and mitigation options are limited.

5.4. PP4: Support delivery and measurement of marine net gain

Marine Net Gain (MNG) is a key policy mechanism for ensuring that OWF development delivers long-term environmental benefits. OWFs must not only avoid ecological damage but proactively enhance biodiversity through habitat creation and restoration. Initiatives such as oyster reef restoration or nature-inclusive design features (e.g., textured turbine bases) can facilitate this (Cale and Churn, 2021).

Monitoring frameworks such as a Regional Ecosystem Monitoring Programme (REMP) should be used to assess recovery and enhancement, as well as ecosystem service delivery. This includes evaluating nutrient cycling, carbon storage, and community resilience across long-term timescales (Catapult Offshore Renewable Energy, 2024). Trait-based data and natural capital metrics should be central to measuring progress toward net gain targets (Boutin *et al.*, 2023).

The Offshore Wind Enabling Actions Programme (OWEAP) is currently defining legal and delivery mechanisms to integrate MNG into marine policy. This includes aligning it with the terrestrial Biodiversity Net Gain system to ensure cross-sector consistency (Howell Marine Consulting, 2023). OWFs that align with these expectations will be better positioned to support MNG approaches and ocean recovery goals.

6. Recommendations

6.1. Research to fill knowledge gaps

Targeted research can help to improve our understanding of how OWFs affect benthic communities and ecosystem functioning. Longer-term studies to assess benthic community succession dynamics could be beneficial and are already an emerging requirement, particularly in relation to ecological functions such as bioturbation, filtration, and nutrient cycling.

Existing data highlight a highly localised shift from soft sediment infaunal communities to epifaunal assemblages on hard substrates on and in the vicinity of turbine foundations and other infrastructure, but when scaled up across multiple turbines, areas of scour protection and cable protection measures the full implications for ecosystem services remain relatively unstudied at OWF sites (Coates *et al.*, 2014; Boutin *et al.*, 2023), partly as a result of challenges in standardised sampling, restricted access near turbines for safety reasons, and logistical constraints. Trait-based approaches should be expanded, supported by comprehensive species functional trait databases that enable ecosystem function modelling at scale (Mouillot *et al.*, 2013; Reiss *et al.*, 2009).

Further research is needed to quantify the effects of EMFs generated by subsea cables on benthic invertebrates, particularly given the mixed findings on behavioural and developmental responses (Scott *et al.*, 2020). Similarly, the impacts of underwater noise from pile driving and operational turbine vibrations on benthic taxa remain poorly understood, highlighting the need for studies that integrate physiological, behavioural, and population-level assessments (Mooney *et al.*, 2020). Although these impacts are not currently anticipated to be significant in EIA terms, understanding their localised effects remains important for effective environmental management and mitigation, if required. Additionally, more work is required to explore the role OWFs play in facilitating species connectivity, including the dispersal of non-native and native species, particularly where artificial substrates can potentially act as stepping stones (De Mesel *et al.*, 2015; Langhamer, 2012).

6.2. OWF planning

Current best practice in OWF planning, particularly as adopted by The Crown Estate (The Crown Estate, 2018; 2022; 2024) and many developers, already incorporates habitat sensitivity mapping to guide site selection, typically avoiding designated sites and ecologically sensitive benthic habitats. Building on this foundation, future spatial planning tools could further enhance decision-making by integrating predicted changes to ecological function alongside biodiversity indicators, with continued focus on areas supporting biogenic reef structures, shellfish beds, and vulnerable soft sediment habitats (Cooper and Barry, 2017). Challenges may still arise in balancing these priorities with increasing demands on marine space.

OWF planning should also consider regional cumulative effects such as sediment redistribution, hydrodynamic change, and species dispersal patterns. This is especially important given the potential for large-scale ecosystem homogenisation if multiple OWFs are sited in close proximity (Daewel *et al.*, 2022).

This review found that OWF infrastructure has not traditionally been designed for ecological enhancement, which may limit its contribution to biodiversity and net gain goals. Where ecological enhancement is a planning objective, the early integration of nature-positive infrastructure, such as reef-forming scour protection, kelp planting, or designated oyster and mussel restoration zones, should be actively encouraged (Robertson *et al.*, 2021). These measures can enhance local biodiversity, support fisheries productivity, and improve ecosystem resilience. Such approaches align with the emerging MNG policy and Defra's broader objectives for ocean recovery and sustainable use of the marine environment, and The Crown Estate's Whole Seabed Programme and Marine Delivery Routemap provide a framework for integrating enhancement and nature recovery activities within marine spatial planning across marine sectors.

6.3. Environmental Impact Assessment (EIA)

Future EIAs should move beyond taxonomic inventories and include functional ecology assessments. Evaluating how OWFs affect functional group composition (e.g. filter feeders vs. deposit feeders) provides better insight into ecosystem health and resilience (Boutin *et al.*, 2023). The review of 18 OWF monitoring reports for this work found that benthic monitoring programmes at OWF sites relied exclusively on diversity and abundance-based analyses (such as species richness, abundance and diversity indices) to assess construction and operational effects. While these traditional diversity metrics are established best practice across marine sectors, they are limited to detecting changes in diversity and abundance. This means that significant functional changes in benthic communities, which regulate ecosystem processes such as bioturbation and nutrient cycling, may remain undetected where diversity metrics remain unchanged. Given this, guidance should recommend the inclusion of metrics such as biological traits analysis and ecological resilience indicators to complement existing approaches.

Baseline studies must be robust, with data providing the foundation to distinguish between natural variability and project-driven change (Coates *et al.*, 2015). The use of a sufficient number of well-matched reference stations is a key consideration and these reference areas should be ecologically similar in sediment type, depth, and community structure to ensure accurate impact detection (Pearce *et al.*, 2014).

Future EIAs must also include comprehensive cumulative assessments, moving beyond isolated project-scale evaluations to consider the landscape-level impacts of multiple OWFs and other marine activities (e.g., commercial fishing, cable installation, and dredging). Particular attention should be given to INNS, which may be introduced or facilitated by OWF infrastructure and vessel traffic.

Looking ahead, the emergence of FLOW technologies is facilitating the expansion into deeper, seasonally stratified shelf seas, necessitating the use of larger and more complex turbine support structures that may further alter local hydrographic and sedimentary regimes. EIA will therefore also need to account for potential impacts to deeper, seasonally stratified shelf seas in their environmental monitoring approaches, incorporating ecosystem-level indicators that capture changes in stratification, nutrient dynamics, and associated ecological processes.

Shared regional data repositories should be developed and maintained, allowing access to standardised benthic and ecological datasets across sites and projects within the same region. Such collaborative platforms would enhance transparency, facilitate comparative analysis, and support more holistic, ecosystem-based planning and regulation.

6.4. Benthic surveys and monitoring

Due to common limitations in pre-construction data (often restricted to a single sampling event), it is recommended that OWF developers consistently adopt the use of ecologically comparable reference sites in benthic monitoring programmes, selected based on environmental parameters such as depth, substrate, habitat type and salinity. Additionally, historical datasets, while sometimes inconsistent, should be considered to contextualise natural variability over time.

To reliably distinguish OWF-related impacts from background variability, monitoring programmes should consistently adopt BACI designs. Adequate spatial and temporal replication, including sufficient and well-distributed reference and impact stations, will increase statistical power and the confidence in attributing observed changes to OWF activities.

The review of monitoring programmes found differences in approaches and survey design. Industry-wide standardisation of survey methods, including consistent application of trait-based approaches and use of underwater video and imagery (especially where traditional sampling is unsuitable), is essential. This will improve comparability across sites and enhance detection of epifaunal and hard-substrate-associated communities. Data should consistently be made publicly available via platforms such as Marine Data Exchange and OneBenthic to support a broader understanding of the seabed and its associated communities.

Survey strategies should align with site-specific hydrodynamic and sediment transport modelling to better understand the links between physical changes (e.g. sediment redistribution) and biological responses. These models should be calibrated and validated using BACI data to support ecosystem-level interpretation of OWF impacts.

In anticipation of more complex OWF deployments (e.g., FLOW in deeper, stratified waters), future surveys should go beyond species counts and include metrics of functional diversity, trophic interactions, and nutrient cycling, to reflect changes in ecosystem structure and function.

It would be beneficial if survey design could incorporate two or more turbine foundations, where sampling is conducted along a distance gradient to greatly facilitate comparisons with TOC levels, PSA data and potentially other parameters with increasing distance from a turbine. This approach would provide data to test more robustly some of the expectations associated with biofouling of infrastructure and potential subsequent ecological effects. It is appreciated that the locations would need to be selected carefully to allow for potentially confounding effects of other neighbouring turbines.

Where feasible, survey designs should incorporate two or more turbine foundations, with sampling carried out along a distance gradient away from each structure. This approach would facilitate comparisons of biological responses with environmental parameters such as TOC and PSA and help to robustly test hypotheses regarding biofouling effects and associated ecological changes. Site selection should be carefully planned to minimise confounding influences from neighbouring turbines or overlapping footprints.

In addition to the use of more traditional metrics, a trait-based approach to data analysis should be conducted across all OWFs, allowing better detection of functional changes in benthic communities. Metrics should include sediment bioturbation, organic matter content, and species' ecological roles in addition to abundance and richness.

A centralised national OWF benthic monitoring database should be established to coordinate data sharing, support cumulative impact assessments, and provide evidence for Marine Net Gain accounting. This would also aid in tracking the outcomes of enhancement measures and inform adaptive licensing and compensation decisions. Ideally, there should be some agreement on the standard types of information that should be provided in pre- and post-construction monitoring reports at OWFs to facilitate comparison of results across different studies.

6.4.1. Monitoring objectives

Benthic monitoring and the specific hypotheses that will be tested should be clearly defined to ensure that meaningful data are collected and that specific evidence gaps or areas of uncertainty are addressed. Selecting the most appropriate indicators is an important step when designing benthic monitoring plans and the choice of metric will determine the methodology, spatio-temporal scales and the required confidence in subsequent assessments (Wilding *et al.*, 2017). Metrics must be assessed at the spatial and temporal scales that are relevant to the question monitoring is seeking to address and effort should be made to select metrics of change that can be linked to ecosystem function or service provision (Wilding *et al.*, 2017).

Given the potential for OWFs to act, in some cases, as de facto MPAs in the sense that bottom trawling pressure can sometimes be reduced from the pre-construction level (and particularly for future floating OWF sites), monitoring for positive 'reserve effects' should also be integrated as an objective. This includes assessing population changes in commercially valuable species such as brown crab and lobster and understanding how OWFs contribute to spatial population connectivity (Krone *et al.*, 2017; Dunkley and Solandt, 2022).

6.4.2. Power analysis

Fit-for-purpose monitoring is required with sufficient statistical power to detect ecologically meaningful changes. The review found that none of the 18 OWF monitoring programmes reported using power analysis to guide survey design. Power analysis can be used to determine the adequate level of sampling effort that allows detection of a real effect (of a set size) with a required power and significance (Green, 1989). Consequently, where possible, power analysis should be undertaken to inform the design of a monitoring programme to ensure its capability to detect meaningful changes (Bennet *et al.*, 2016).

Franco *et al.* (2015) determined that within an OWF there was a high probability of reliably detecting a ≥50% change in mean benthic species richness (S) between areas with a sampling effort of four stations per impact type area and three replicates per station. More stations per impact type area were required to reliably detect a ≥50% change between areas in mean benthic abundance (five stations) and mean biomass (10 stations) due to increased variability for these parameters.

6.4.3. Temporal extent

It has been highlighted that the BACI design is the most rigorous statistical design for detecting environmental impacts (Green, 1979; Underwood, 1994). Consequently, it is recommended that programmes include both pre- and post-construction monitoring to adequately inform the BACI approach.

As environmental impacts may not be immediately apparent, monitoring programmes should be of a suitable duration to understand changes and recovery over time which are likely to be driven by receptor and the monitoring objectives. Monitoring programmes should be designed to incorporate longer term or lasting impacts to validate predictions of significant effects made within the EIA and to improve our understanding of long-term effects and recovery of marine receptors. Longer-term datasets are essential to track community stabilisation and recovery patterns, and monitoring programmes should be extended over longer periods where feasible (Leewis and Klink, 2022).

6.4.4. Number of reference stations

Analysis of benthic monitoring programme reports undertaken during the literature review for RQ1 and RQ2, indicated that the number of reference stations varied considerably between monitoring programmes from two to 18 stations, and this ranged from 3% to 50% of all sampling locations surveyed per OWF. For many of the OWFs the number of reference stations allocated represented 15-25% of the stations.

There is currently no specific guidance to determine the proportion of reference stations that should be applied for OWF monitoring programmes and it would be useful if such guidance could be developed. Noble-James *et al.* (2018) discuss the statistical desirability to incorporate equal numbers of impact and control locations, however, applying such an approach would likely have significant practical, logistical and cost implications. It is understood that at certain OWF sites it can be difficult to find reference stations with similar conditions to the zone of influence of the OWF limiting the options. In some instances, however, with limited additional sampling effort, there may be potential to increase the number of reference stations to help determine if trends identified at the OWF site are attributable to the construction and operation of the OWF or natural variation in benthic sediment or community characteristics.

6.4.5. Spatial extent

Sampling stations should be distributed within and around development sites by distinguishing areas based on the expected distribution of impacts generated by the OWF with sites within the near-field area of the wind turbine and along the export cable corridor, with further sites around the development site within one tidal excursion from it (i.e. within the area affected by sediment transport and deposition). Reference stations should be located beyond the tidal excursion distance. A key limitation identified in the review and benthic analyses was the absence of sampling locations in close proximity to turbine infrastructure where impacts are known to occur. Locating some stations nearer turbines and along a gradient away from the turbines would help determine effects and indicate potential levels of organic enrichment around turbines and how that could be affecting benthic communities on a more local scale in the vicinity of turbine foundations.

6.4.6. Standard methodology

Benthic monitoring sampling design is generally standardised with the use of 0.1 m^2 grabs common practice (Gray and Elliott, 2009), although practicalities have resulted in other sample unit sizes being adopted (Ferraro and Cole, 1990). Other aspects of the survey design (e.g., number of sampling stations, spatial coverage) were case dependent, often due to the variability of site-specific features of the development (Franco *et al.*, 2015).

A strategic, collaborative or joined up approach can deliver monitoring programmes of a greater scale and scope, thereby providing a greater understanding of ecological impacts, sensitivity or recovery. Consequently, while it should be a prerequisite that for an individual monitoring programme consistent sampling techniques are employed throughout the course of the study, it is recommended that wherever possible standard techniques should be adopted for all future OWF monitoring programmes to facilitate multi-site comparisons. Similarly, the suite of samples collected should be consistent and potential aspects for inclusion are:

- Biological samples – grab sampling to provide samples for faunal samples (mean species richness S, total benthic abundance N and biomass B) - a consistent naming convention should also be followed using the World Register of Marine Species (WoRMS) list of accepted scientific names and biotopes should be recorded using the EUNIS classification system;
- Drop-Down Video (DDV)/camera to visually assess benthic habitats and epifaunal communities colonising turbine foundations but also to determine epifaunal communities present on sediment in the vicinity of the turbine foundations and associated habitats;
- Physicochemical samples – sediments collected for granulometric and chemical analyses. Consideration should also be given to continual monitoring during construction using sensors monitoring parameters such as turbidity and dissolved oxygen. Sediment quality could be further assessed by sediment profile imagery and or collection of cores for redox measurement; and
- Geophysical data – mapping of seafloor topography and sediment characteristics to detect changes in during construction and operational phases.

Additional specific explanatory data that could be collected and provided in post-construction monitoring reports have been proposed by Coolen *et al.* (2022) as follows:

- Sampling date;
- Longitude and latitude for each sample;
- Sampling depth;

- Sampling height from seabed for samples on infrastructure;
- Sediment composition (grain size, % fines, total organic carbon content) for seabed samples;
- Seawater temperature at sampling depth;
- Whether fishing is allowed at the sample location in case of seabed samples (If yes: type of fishery);
- Seawater salinity at sampling depth;
- Distance to nearest structure for seabed samples;
- Date of construction of that nearest structure.

It would also be useful if the coordinates of each turbine foundation are provided to facilitate analysis of samples in relation to distance from turbine foundations.

6.4.7. Presentation of information in post-construction monitoring reports

When reviewing the post-construction monitoring reports for multiple OWFs it was evident that there was considerable variation in terms of how data were presented and the clarity of information. It is appreciated that the focus of different post-construction monitoring programmes will vary depending on consent requirements, however, some standardisation of how data should be presented, and which analyses should be conducted would be beneficial. This would be particularly useful in terms of how data for OWF and cable route sites and reference stations are statistically compared for a given year (biota and sediment type), and how data are compared across years (again providing analyses which separate out effects at the OWF and cable route sites and reference stations).

In summary, effective benthic monitoring for OWFs requires a comprehensive, multidisciplinary approach that integrates biological, physical and chemical data. OWF benthic monitoring programmes should be designed with clear objectives, consistent methodologies, sufficient statistical power and an appropriate number of reference stations to properly understand any effects from the construction and operation of OWFs and distinguish any effects from natural variability. Monitoring programmes should be undertaken over sufficient time scales to understand long term or lasting impacts and to validate predictions made during the EIA process, and to improve our understanding of long-term effects and recovery of marine receptors (if adverse effects of an OWF are identified). Moreover, the development of best practice guidance for the selection of reference stations, temporal and spatial sampling extent and standardised reporting would be beneficial.

6.5. Summary

These recommendations for OWF development emphasise the need for enhanced research, planning, and monitoring approaches that go beyond traditional analyses and assessments to include functional ecology assessments and ecosystem services. Key recommendations include conducting longer-term studies on benthic community succession and ecosystem functioning, the inclusion of trait-based approaches to more fully understand ecological effects and developing standardised monitoring protocols with adequate statistical power using BACI designs. The recommendations suggest improved spatial planning tools that integrate predicted ecological changes with biodiversity indicators, consideration of cumulative regional effects across multiple OWFs, and the incorporation of nature-positive infrastructure such as reef-forming scour protection and restoration zones. Benthic community analyses and the environmental impact assessment process should include functional group composition metrics and comprehensive cumulative assessments, while monitoring programmes should be extended with standardised methodologies, appropriate reference stations, and consistent use of centralised data repositories to facilitate cross-site comparisons. These recommendations provide a blueprint for sustainable OWF development, balancing energy needs with biodiversity protection. By integrating functional ecology, adaptive management, and strategic monitoring into each phase of the

OWF lifecycle, developers, regulators, and policymakers can ensure that OW contributes positively to marine ecosystem health and resilience.

7. References

Borja, A.; Franco, J.; Pérez, V. (2000). A Marine Biotic Index to Establish the Ecological Quality of Soft-Bottom Benthos within European Estuarine and Coastal Environments. Marine Pollution Bulletin, 40: 1100–1114.

Borja, A. and Muxika, I. (2005). Guidelines for the use of AMBI (AZTI's Marine Biotic Index) in the assessment of the benthic ecological quality. Marine Pollution Bulletin 50(7):787-9.

Boutin, K., Gaudron, S.M., Denis, J. and Lasram, F.B.R., 2023. Potential marine benthic colonisers of offshore wind farms in the English Channel: A functional trait-based approach. Marine Environmental Research, 190, p.106061.

Boyd, S.E. (2002) Guidelines for the conduct of benthic studies at aggregate dredging sites. CEFAS, Lowestoft.

Bulleri, F., and Airoldi, L. 2005. Artificial marine structures facilitate the spread of a non-indigenous green alga, Codium fragile ssp. tomentosoides, in the North Adriatic Sea. Journal of Applied Ecology, 42(6), 1063–1072.

Bunker, F.St.P.D. 2004. Biology and video surveys of North Hoyle wind turbines, 11–13 August 2004. A report to CMACS Ltd by Marine Seen, Estuary Cottage, Bentlass, Hundleton, Pembs, SA71 5RN.

Cale, H., and Churn, B., 2021. Nature Inclusive Design: Challenges and Opportunities for UK Offshore Wind Farms 80 pp.

Catapult Offshore Renewable Energy, 2024. Accelerating Offshore Wind Developing a Regional Ecosystem Monitoring Programme for The UK Offshore Wind Industry, 21 pp.

Cefas (2004) Offshore Wind Farms: Guidance Note for Environmental Impact Assessment in Respect of FEPA and CPA Requirements. Prepared by the Centre for Environment, Fisheries and Aquaculture Science(Cefas) on behalf of the Marine Consents and Environment Unit.

Coates, D.A., Deschutter, Y., Vincx, M. and Vanaverbeke, J., 2014. Enrichment and shifts in macrobenthic assemblages in an offshore wind farm area in the Belgian part of the North Sea. Marine environmental research, 95, pp.1-12.

Coates, D.A., Van Hoey, G., Colson, L., Vincx, M., and Vanaverbeke, J. 2015. Rapid macrobenthic recovery after dredging activities in an offshore wind farm in the Belgian part of the North Sea. Hydrobiologia, 756, 3–18.

Daewel,U., Akhtar, N., Christiansen, N. and Schrum, C. 2022. Offshore wind farms are projected to impact primary production and bottom water deoxygenation in the North Sea. Communications Earth and Environment (2022) 3:292

Dahl, K., Robinson, B.J.O., Buur, H., Reducha Andersen, K., Reducha Andersen, N., Göke; C. and Hansen, J.L.S. (2025). Anholt wind farm's impact on benthic biodiversity at turbine and wind farm level Aarhus University, DCE – Danish Centre for Environment and Energy, 47 pp. Technical Report No. 330

Dannheim, J., Beermann, J., Lacroix, G., De Mesel, I., Kerckhof, F., Schon, ¨ I., Degraer, S., Birchenough, S., Garcia, C., Coolen, J.W.P., Lindeboom, H.J., (2017). Understanding the Influence of Man-Made Structures on the Ecosystem Functions of the North Sea (UNDINE). Final report revised.

Dannheim, J., Bergström, L., Birchenough, S.N., Brzana, R., Boon, A.R., Coolen, J.W., Dauvin, J.C., De Mesel, I., Derweduwen, J., Gill, A.B. and Hutchison, Z.L. 2020. Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. ICES Journal of Marine Science, 77(3), 1092-1108.

De Borger, E., Ivanov, E., Capet, A., Braeckman, U., Vanaverbeke, J., Grégoire, M., and Soetaert, K. 2021. Offshore wind farm footprint of sediment organic matter mineralization processes. Frontiers in Marine Science, 8, p.632243.

De Mesel, I., Kerckhof, F., Norro, A., Rumes, B., and Degraer, S. 2015. Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. Hydrobiologia, 756, 37–50.

Degraer, S., Brabant, R., Rumes, B., and Vigin, L. 2019. Environmental impacts of offshore wind farms in the Belgian part of the North Sea: making a decade of monitoring, research, and innovation. Brussels: Royal Belgian Institute of Natural Sciences, OD Natural Environment, Marine Ecology and Management, 134 pp.

Degraer, S., Carey, D., Coolen, J. W. P., Hutchison, Z., Kerckhof, F., Rumes, B., and Vanaverbeke, J. 2020. Offshore Wind Farm Artificial Reefs Affect Ecosystem Structure and Functioning: A Synthesis, Oceanography, 33, 48–57.

Department of Business and Trade. 2024. Offshore wind - great.gov.uk international. Available at: https://www.great.gov.uk/international/content/investment/sectors/offshore-wind/ (Accessed: 17 February 2024)

Dorrell, R. M., Lloyd, C. J., Lincoln, B. J., Rippeth, T. P., Taylor, J. R., Caulfield, C. C. P., & Simpson, J. H. 2022. Anthropogenic mixing in seasonally stratified shelf seas by offshore wind farm infrastructure. Frontiers in Marine Science, 9. Available at: https://doi.org/10.3389/fmars.2022.830927 (Accessed: 17 February 2024)

Dunkley, F., and Solandt, J.L. 2022. Wind farms, fishing and benthic recovery: overlaps, risks and opportunities. Marine Policy, 145, p.105262.

Evans, A.J., Firth, L.B., Hawkins, S.J., Hall, A.E., Ironside, J.E., Thompson, R.C., and Moore, P.J. 2019. From ocean sprawl to blue-green infrastructure: a UK perspective on an issue of global significance. Environmental Science & Policy, 91, 60–69.

Firth, L.B., Airoldi, L., Bulleri, F., Challinor, S., Chee, S.Y., Evans, A.J., Hanley, M.E., Knights, A.M., O'Shaughnessy, K., Thompson, R.C., and Hawkins, S.J. 2020. Greening of grey infrastructure should not be used as a Trojan horse to facilitate coastal development. Journal of Applied Ecology, 57(9), 1762–1768.

Fonseca, M. 2025. Examining the foundations of offshore wind. Environment coastal and offshore magazine. Volume 13 issue 2, Summer 2025.

Forster, R.M. 2018. The effect of monopile-induced turbulence on local suspended sediment patterns around UK wind farms: field survey report. An IECS report to The Crown Estate, ISBN 978-1-906410-77-3.

Galparsoro, I., Menchaca, I., Garmendia, J.M., Borja, Á., Maldonado, A.D., Iglesias, G. and Bald, J. 2022. Reviewing the ecological impacts of offshore wind farms. *npj Ocean Sustainability*, *1(1*), pp.1.

Gray, J.S. & Elliott, M. (2009) Ecology of marine sediments. From science to management, 2nd edn. Oxford University Press, Oxford.

Hammar, L., Perry, D. and Gullström, M. 2016. Offshore wind power for marine conservation. Open Journal of Marine Science, 6(1), 66-78.

Hooper, T. and Austen, M. 2014. The co-location of offshore wind farms and decapod fisheries in the UK: Constraints and opportunities. Marine Policy, 43, 295-300.

Howell Marine Consulting 2023- Offshore wind policy and delivery landscape, 2023. A report by the ECOWind Programme Champions for the ECOWind Programme, 38 pp.

Hutchison, Z.L., Gill, A.B., Sigray, P., He, H. and King, J.W. 2021. A modelling evaluation of electromagnetic fields emitted by buried subsea power cables and encountered by marine animals: considerations for marine renewable energy development. Renewable Energy, 177, 72-81.

Isaksson, N., Scott, B.E., Hunt, G.L., Benninghaus, E., Declerck, M., Gormley, K., Harris, C., Sjöstrand, S., Trifonova, N.I., Waggitt, J.J., and Wihsgott, J.U. 2023. A paradigm for understanding whole ecosystem effects of offshore wind farms in shelf seas. ICES Journal of Marine Science, p.fsad194.

Ivanov, E., Capet, A., De Borger, E., Degraer, S., Delhez, E.J., Soetaert, K., Vanaverbeke, J., and Grégoire, M., 2021. Offshore wind farm footprint on organic and mineral particle flux to the bottom. Frontiers in Marine Science, 8, p.631799.

Jak, R. and Glorius, S. 2017. Macrobenthos in offshore wind farms: a review of research, results and relevance for future developments.

Judd, A. (2012) Guidelines for data acquisition to support marine environmental assessments of offshore renewable energy projects. CEFAS, Lowestoft.

Kerckhof, F., Degraer, S., Norro, A., And Rumes, B. 2011. Offshore intertidal hard substrata: a new habitat promoting non-indigenous species in the Southern North Sea: an exploratory study. In Offshore Wind Farms in the Belgian Part of the North Sea: Selected Findings from the Baseline and Targeted Monitoring. Brussels: Royal Belgian Institute of Natural Sciences, Management Unit of the North Sea Mathematical Models, Marine ecosystem management unit. 27–37 pp.

Krone, R., Dederer, G., Kanstinger, P., Krämer, P., Schneider, C., and Schmalenbach, I. 2017. Mobile demersal megafauna at common offshore wind turbine foundations in the German Bight (North Sea) two years after deployment: Increased production rate of Cancer pagurus. Marine Environmental Research, 123, 53–61.

Krone, R., Gutow, L., Joschko, T. J., and Schröder, A. 2013. Epifauna dynamics at an offshore foundation - Implications of future wind power farming in the North Sea. Marine Environmental Research, 85: 1–12.

Langhamer, O., 2012. Artificial reef effect in relation to offshore renewable energy conversion: State of the art. The Scientific World Journal, 2012(1), 386713.

Leewis, L. and Klink, A. 2022. Princess Amalia Windturbine park 2022: Statistical comparison of benthic fauna inside and outside the Princess Amalia Wind Park fifteen years after construction; first analysis. Eurofins Omegam B.V. Amsterdam, 31 pp.

Lefaible, N., Braeckman, U., Degraer, S., Vanaverbeke, J. and Moens, T. 2023. A wind of change for soft-sediment infauna within operational offshore wind farms. Marine Environmental Research, 188, p.106009.

Leonhard, S.B. and Pedersen, J. (2005). Benthic Communities at Horns Rev Before, During and After Construction of Horns Rev Offshore Wind Farm Final Report Annual Report 2005.

Lindeboom, H., Degraer, S., Dannheim, J., Gill, A. B., and Wilhelmsson, D. 2015. Offshore wind park monitoring programmes, lessons learned, and recommendations for the future. Hydrobiologia, 756(1), 169–180.

Maar, M., Bolding, K., Petersen, J.K., Hansen, J.L. and Timmermann, K. 2009. Local effects of blue mussels around turbine foundations in an ecosystem model of Nysted off-shore wind farm, Denmark. Journal of Sea Research, 62(2-3),159-174.

Mineur, F., Cook, E. J., Minchin, D., Bohn, K., Macleod, A., and Maggs, C. A. 2012. Changing coasts: Marine aliens and artificial structures. Oceanography and Marine Biology, 50, 189–234.

Mouillot, D., Graham, N.A., Villéger, S., Mason, N.W. and Bellwood, D.R. 2013. A functional approach reveals community responses to disturbances. Trends in ecology & evolution, 28(3),167-177.

Muniz, P., Venturini, N., Pires-Vanin, A.M.S., Tommasi, L.R. and Borja, A. (2005). Testing the applicability of a Marine Biotic Index (AMBI) to assessing the ecological quality of soft-bottom benthic communities, in the South America Atlantic region. Marine Pollution Bulletin, 50(6), 624-637.

Muxika, I., Borja, A. and Bonne W. (2005). The suitability of the marine benthic index (AMBI) to new impact sources along European coasts. Ecological Indicators, 5, 19-31.

Natural England, 2021. Natural England's Approach to Offshore Wind. Natural England Technical Information Note, TIN181. Natural England, 13 pp.

Parker, J., Fawcett, A., Rowson, T., Allen, S., Hodgkiss, R., Harwood, A., Caldow, R., Ludgate, C., Humphrey, O. and Copley, V. 2022. Offshore Wind Marine Environmental Assessments: Best Practice Advice for Evidence and Data Standards. Phase IV: Expectations for monitoring and environmental requirements at the post-consent phase. Natural England. Version 1.0. 177pp.

Petersen, J. K., and Malm, T., 2006. Offshore windmill farms: Threats to or possibilities for the marine environment. AMBIO: A Journal of the Human Environment, 35(2): 75–80.

Pianka, E.R. (1970) On r and k selection. American Naturalist, 104, 592-597.

Pinto, R., Patricio, J., Baeta, A., Fath, B. D., Neto, J. M. & Marques, J. C. 2008. Review and evaluation of estuarine biotic indices to assess benthic condition. Ecological indicators, 9, pp.1-25.

Pratt, D. R., Pilditch, C. A., Lohrer, A. M., and Thrush, S. F. 2014. The effects of short-term increases in turbidity on sandflat microphytobenthic productivity and nutrient fluxes. Journal of Sea Research, 92: 170–177.

Reiss, J., Bridle, J.R., Montoya, J.M., Woodward, G. 2009. Emerging horizons in biodiversity and ecosystem functioning research. Trends in Ecology and Evolution 24, 505–514.

RenewableUK, 2025. Developing effective end-of-life policy frameworks for UK offshore wind. February 2025. 6-27.

Robertson, M., Locke, S., Uttley, M., Helmer, L. and Kean-Hammerson, J. 2021. Exploring the role of offshore wind in restoring priority marine habitats. Blue Marine Foundation, United Kingdom 26 pp.

Scott, K., Piper, A.J.R. Chapman, E.C.N. & Rochas, C.M.V., 2020. Review of the effects of underwater sound, vibration and electromagnetic fields on crustaceans. Seafish Report.

SEER. 2022. Benthic Disturbance from Offshore Wind Foundations, Anchors, and Cables. U.S. Offshore Wind Synthesis of Environmental Effects Research, 15 pp.

Shields, M. A., Woolf, D. K., Grist, E. P. M., Kerr, S. A., Jackson, A. C., Harris, R. E., Bell, M. C., *et al.* 2011. Marine renewable energy: The ecological implications of altering the hydrodynamics of the marine environment. Elsevier Ltd.

Smith, E.P., D.R. Orvos, and J. Cairns Jr. 1993. Impact assessment using the before-after- control- impact (BACI) model: Concerns and comments. Canadian Journal of Fisheries and Aquatic Sciences 50(3):627–637.

Spielmann, V., Dannheim, J., Brey, T. and Coolen, J. W. 2023. Decommissioning of offshore wind farms and its impact on benthic ecology. Journal of Environmental Management, 347, 119022.

Stephenson, P.J. (2021). A Review of Biodiversity Data Needs and Monitoring Protocols for the Offshore Wind Energy Sector in the Baltic Sea and North Sea. Report for the Renewables Grid Initiative, Berlin, Germany.

The Crown Estate. (2018) Offshore Wind Leasing Round 4: Resource and Constraints Assessment Methodology. London: The Crown Estate. Available at:

https://www.thecrownestate.co.uk/media/3331/tce-r4-resource-and-constraints-assessment-methodology-report.pdf (Accessed: February 2025).

The Crown Estate. (2022) Celtic Sea Floating Wind Site Selection Methodology. London: The Crown Estate. Available at: https://www.thecrownestate.co.uk/media/4150/2022-floating-wind-site-selection-methodology-report.pdf (Accessed: February 2025).

The Crown Estate. (2024) Cable Route Identification and Leasing Guidelines. London: The Crown Estate. Available at: https://www.thecrownestate.co.uk/media/3994/the-crown-estate-cable-route-identification-leasing-guidelines.pdf (Accessed: February 2025).

Underwood, A.J. (1994) On Beyond BACI: Sampling Designs that Might Reliably Detect Environmental Disturbances. Ecological Applications, 4, 4-15.

van Berkel, J., Burchard, H., Christensen, A., Mortensen, L. O., Petersen, O. S., and Thomsen, F. 2020. The effects of offshore wind farms on hydrodynamics and implications for fishes. Oceanography, 33, 108–117.

van Dalfsen, J. A., Essink, K., Madsen, H. T., Birklund, J., Romero, J., and Manzanera, M. 2000. Differential response of macrozoobenthos to marine sand extraction in the North Sea and the Western Mediterranean. ICES Journal of Marine Science, 57, 1439–1445.

Van Hoey, G., Degraer, S., Vincx, M., 2004. Macrobenthic community structure of soft-bottom sediments at the Belgian Continental Shelf. Estuarine Coast Shelf Science 59:599–613.

Vanagt, T., Van de Moortel, L., and Faasse, M. 2013. Development of hard substrate fauna in the Princess Amalia Wind Farm: Monitoring 3.5 years after construction. eCOAST report 2011036.

Vandendriessche, S., Derweduwen, J., and Hostens, K. 2014. Equivocal effects of offshore wind farms in Belgium on soft substrate epibenthos and fish assemblages. Hydrobiologia, 756, 19–35.

Ward, O., Aberson, M., Kirby, D., Chaverra, A., Roberts, A., Cross, K., Warner, I., And Reach, I. 2022. Spatial assessment of benthic compensatory habitats for offshore wind farm impacts. NECR443. Natural England, 131 pp.

Ware, S.J. & Kenny, A.J. (2011) Guidelines for the Conduct of Benthic Studies at Marine Aggregate Extraction Sites, 2nd edn. Marine Aggregate Levy Sustainability Fund (MALSF).

Watson, S., Somerfield, P., Lemasson, A., Knights, A., Edwards-Jones, A., Nunes, J., Pascoe, C., McNeill, C., Schratzberger, M., Thompson, M., Couce, E., Szostek, C., Baxter, H., and Beaumont, N., 2024. *The global impact of offshore wind farms on ecosystem services*. Ocean and Coastal Management, 249, 107023.

Wilding, T.A. (2014). Effects of man-made structures on sedimentary oxygenation: extent, seasonality and implications for offshore renewables. Marine Environmental Research, 97, 39-47.

Wilding, T., A.B. Gill, A. Boon, E. Sheehan, J.-C. Dauvin, J.-P. Pezy, F.X. O’Beirn, U. Janas, L. Rostin, and I. De Mesel. 2017. Turning off the DRIP (‘Data-rich, information-poor’)— rationalising monitoring with a focus on marine renewable energy developments and the benthos. Renewable and Sustainable Energy Reviews 74, 848–859.

Wilhelmsson, D., Malm, T. and Öhman, M.C. 2006. The influence of offshore windpower on demersal fish. ICES Journal of Marine Science, 63(5),775-784

Zucco, C., Wende, W., Merck, T., Köchling, I., & Köppel, J. 2006. Ecological research on offshore wind farms: International exchange of experiences. *Part A: assessment of ecological impacts. BfN-Skripten*.

Zupan, M., Rumes, B., Vanaverbeke, J., Degraer, S., and Kerckhof, F. 2023. Long-term succession on offshore wind farms and the role of species interactions. Diversity 15 (2), 288

Appendix 1 – WP 1: Literature Review

(External document)

Appendix 2 – WP2: Data Summary Report

(External document)

Appendix 3 – WP4: AMBI Analysis Report

(External document)

Appendix 4 – WP4: Biological Traits Analysis Report

(External document)

carbontrust.com

+44 (0) 20 7170 7000

The Carbon Trust is a company limited by guarantee and registered in England and Wales under Company number 04190230 with its Registered Office at: Level 5, Arbor, 255 Blackfriars Road, London SE1 9AX, UK.

Published in the UK: 2025