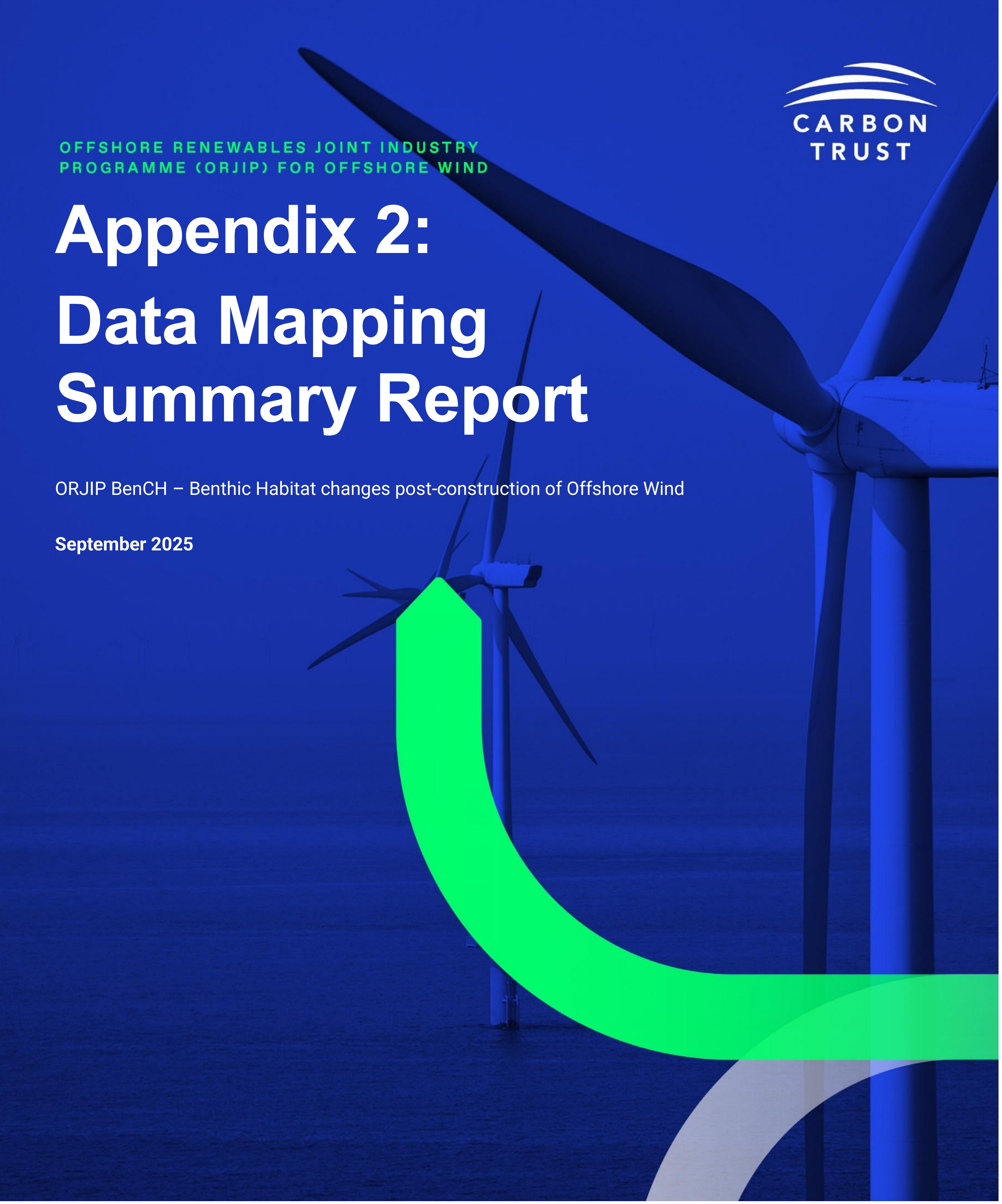

CARBON TRUST

OFFSHORE RENEWABLES JOINT INDUSTRY PROGRAMME (ORJIP) FOR OFFSHORE WIND

Appendix 2: Data Mapping Summary Report

ORJIP BenCH – Benthic Habitat changes post-construction of Offshore Wind

September 2025

orjip 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).

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- 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

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1. Introduction

1.1 Background

This report forms part of the deliverables for a wider Offshore Renewables Joint Industry Programme for Offshore Wind ("ORJIP Offshore Wind") research and development project known as BenCH (Benthic habitat changes post-construction of offshore wind).

This report accompanies APEM (2025a) and APEM (2025b) which have outlined responses to the following key questions investigated during the BenCH project:

- 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?

Part of the project is a Stage Gate at which it will be determined whether there was sufficient evidence to address these questions, and to highlight where the knowledge gaps are and which aspects could be considered further as part of the BenCH project.

The aim of this report is to summarise some of the key findings of APEM (2025a and b) and indicate which aspects of these questions can be considered further via analyses of benthic data sets collated during post-construction monitoring at offshore wind farms (OWFs). Where requirements are considered to be beyond the scope of this project, some recommendations for further investigation have been put forward.

The information and proposals for additional work in this report will be considered further at a workshop with the ORJIP OSW (Offshore wind) Steering Group and Project Expert Panel to determine which aspects could be progressed post Stage Gate.

2. Data collation methodology

2.1 Data requirements

To adequately address the research questions RQ1-5, benthic ecology pre-construction and post-construction monitoring reports and data sets were collated for OWFs located in UK waters (and one EU OWF).

For the purposes of any analyses post-Stage Gate it was necessary to obtain raw data as well as reports and it was considered that focus should be on OWFs where pre-construction data and at least two years of post-construction monitoring data were available.

The sources from which OWF pre and post-construction monitoring benthic data sets were collated are indicated in Table 1.

Table 1 Relevant source types for addressing research questions.

Source type	Description of Source type
Online data sources/portals	
Marine Data Exchange (https://www.marinedataexchange.co.uk/)	Digital platform of industry marine survey data, research and evidence created by the Crown Estate. Documents downloaded for analysis included: Pre-construction and post-construction benthic survey reports and data.
Marine Environmental Data and Information Networks (MEDIN) (https://medin.org.uk/)	Digital platform which collated marine environmental data recorded by multiple organisations in the UK. Documents downloaded included: Pre-construction and post-construction benthic survey reports and data.
Direct requests to developers	For wind farms for which data could not be obtained via the MDE or Medin, direct requests were sent to developers, primarily via the Carbon Trust.

3. Summary of data collated

A total of 47 wind farms were identified, primarily in UK waters, to investigate data availability, particularly pre- and post-construction monitoring reports and associated raw data sets. The data sources identified in Section 2.1 were systematically investigated to collate as much data as possible for each OWF. The following sections summarise the collated data and availability of data for further analyses beyond Stage Gate.

Out of the 47 OWFs identified, a set of pre- and post-construction monitoring reports were collated for 18 OWF sites (Table 2) and these formed the basis of the literature review for RQ1 and RQ2 (APEM, 2025a) and where appropriate RQ3-RQ5 (APEM, 2025b).

Table 2. Offshore wind farms for which a complete set of monitoring reports were collated.

OWF site (Owner)	Commissioned	Sampling technique(s)	Survey reports collated
Barrow OWF* (Ørsted)	2006	Grab, Divers (foundation colonisation survey), Trawl	Post-construction (Year 1, Year 2 and Year 3)
Beatrice OWF (SSE Renewables)	2019	Grab, DDV, ROV (foundation colonisation survey)	Pre-construction Post-construction (Year 1 and Year 2)
Blyth Demo OWF (EDF Renewables)	2018	Grab, DDV, Trawl	Pre-construction Post-construction (Year 1)
Burbo Bank OWF (Ørsted A/S)	2007	Grab, Divers (foundation colonisation survey), Trawl (pre-construction only)	Pre-construction Post-construction (Year 1 and Year 3)
Greater Gabbard OWF* (SSE; RWE Npower Renewables)	2012	Grab, DDV, Trawl, ROV (foundation colonisation survey)	Post-construction (Year 1, Year 5 and Year 10)
Gunfleet Sands I&II OWF (Ørsted A/S)	2010	Grab	Pre-construction Post-construction (Year 1, Year 2, Year 3)
Kentish Flats OWF* (Vattenfall)	2005	Grab, Divers (foundation colonisation survey)	Post-construction (Year 1, Year 2, Year 3)
London Array OWF* (Orsted A/S; E.ON Climate & Renewables UK Ltd; Masdar)	2013	Grab, Trawl	Post-construction (Year 1)
Lynn and Inner Dowsing OWF	2009	Grab, DDV, Trawl	Pre-construction Post-construction (Year 2, Year 3, Year 4)

OWF site (Owner)	Commissioned	Sampling technique(s)	Survey reports collated
(Macquarie Asset Management)			
North Hoyle OWF (Greencoat UK Wind)	2004	Grab, Trawl, Divers (foundation colonisation survey)	Pre-construction Post-construction (Year 1 and Year 2)
Ormonde OWF (Vattenfall)	2012	Grab, DDV, Trawl	Pre-construction Post-construction (Year 1 and 2)
Princess Amalia	2008	Dredge/trawl, Box core, Divers (foundation colonisation survey)	Pre-construction Post-construction (Year 4, Year 5, Year 9 and Year 15)
Robin Rigg East & West OWF (RWE Renewables)	2010	Grab, DDV, Trawl	Pre-construction Post-construction (Year 1, Year 2 and Year 3)
Scroby Sands OWF (RWE Renewables)	2004	Grab	Pre-construction Post-construction (Year 1)
Sheringham Shoal OWF (Equinor)	2012	Grab, DDV/Video transect, Trawl	Pre-construction Post-construction (Year 2)
Thanet OWF* (Vattenfall)	2010	Grab, DDV, Trawl	Post-construction (Year 1)
Walney 1&2 OWF* (Ørsted; Greencoat UK; PGGM)	2011	Grab, DDV	Post-construction (Year 3)
Westermost Rough OWF (Orsted A/S)	2015	Grab, DDV	Pre-construction Post-construction (Year 1, Year 2 and Year 3)

*Pre-construction data and results only available in post-construction reports.

For six of these OWFs it was possible to collate a full set of pre-and post-construction benthic data sets with at least two post-construction surveys, to enable potential further analyses beyond Stage Gate.

Possible options for analyses of data beyond Stage Gate are discussed in Section 4. It is noted that the pre- and post-construction monitoring reports and analyses considered for this project have been subject to stakeholder review and outputs have been finalised and agreed to discharge consent conditions. Potential sensitivities associated with presentation of new information relating to potential effects of a specific OWF are well understood. Consequently, although any analyses proposed post-Stage Gate differ from those conducted in the original post-construction monitoring reports, the decision has been taken to anonymise the OWF data sets utilised for any additional analyses.

The intention is that results of the proposed analyses and potential benefits, or not, of conducting the indicated analyses as part of the broader suite of post-construction monitoring data analyses going forward, can be readily presented and discussed without providing the identities of the OWFs involved.

4. Potential for future data analysis

Following the investigations for RQ1-5 as outlined in APEM (2025a and b), knowledge gaps relating to the potential effects of OWF development on benthic communities were identified and a summary is provided in Annex 2a.

The following proposals for data analysis post-Stage Gate are relevant to addressing 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?', and RQ4 'Is there change in ecological function (e.g. functional groups) as a result of biological changes?'.

For RQ3 'Are there localised and regional ecological effects around the infrastructure?' it was determined in APEM (2025b) that there are a range of data gaps in relation to localised and regional effects of OWFs which would require a dedicated research programme to address. The collated data for the reviewed OWFs are not considered to be of sufficient resolution to support further investigation for this research question. Therefore, no options to investigate this research question further are proposed beyond Stage Gate (APEM, 2025b). Of particular consideration for RQ3, there are clear localised changes at OWFs due to the colonisation of OWF infrastructure by epifaunal organisms as indicated in 4.14.1 are reliant on the availability of suitable quantitative data including data from the OWF and reference stations. Consequently, there is little potential to reanalyse the turbine colonisation data as part of the post-Stage Gate analyses. Consequently, the post-Stage Gate investigations outlined below are focussed on the benthic grab monitoring data sets characterising the infaunal seabed communities in and around the OWFs.

For RQ5 'Can recovery and/or enhancement be demonstrated and in what timeframe' the conclusion was that there are no proposals to investigate this research question further beyond Stage Gate, as indicated in APEM (2025b). In the context of the question the term 'recovery' was defined as 'a scenario where an adverse impact has been identified due to construction or operation of an OWF (e.g. in year one post-construction monitoring such as a change in benthic community parameters) and recovery is the shift back towards the pre-construction baseline conditions (Nature Scot, 2024a)'. However, for all the OWF monitoring reports reviewed it was concluded that the OWF was not having an adverse effect on any aspects of benthic ecology, consequently it was not possible to investigate recovery rates. Similarly, none of the reports reviewed considered enhancement for the associated benthic habitats.

4.1 Options for further analysis for RQ1, RQ2 and RQ4: Application of additional metrics

For OWF sites where a complete data set is available, it is proposed that data could be analysed to provide further information for the benthic invertebrate community beyond the traditionally used metrics of abundance, taxon richness and diversity statistics. The additional metrics that can be applied can provide further ecosystem/population level information e.g. changes in different benthic feeding groups and changes in the proportion of disturbance-sensitive species.

4.1.1 Infaunal Trophic Index (ITI)

Purpose and benefits

The Infaunal Trophic Index (ITI) is a marine benthic invertebrate-based index that categorises benthic species based on their feeding strategies and can identify changes in community structure and composition based on these strategies (Codling and Ashley, 1992). More specifically, the ITI analysis has the potential to indicate whether there are notable changes in the dominance of particular types of feeding class (e.g. filter feeders, deposit feeders, suspension feeders and scavengers) associated with changes in community composition. Unlike traditional metrics that focus on changes in taxon abundance, richness and diversity, the ITI provides insight into shifts in ecological function within benthic communities, which may indicate disturbance even where diversity and abundance metrics remain relatively stable. The focus on functional changes in benthic communities means the ITI is also a suitable metric for investigating RQ4.

The ITI generates a numerical representation (0 - 100) of the relative abundance of the most dominant infaunal organisms found within benthic samples based on their trophic category (Pinto *et al.,* 2008).

Although ITI was not applied within any of the reviewed post-construction monitoring reports for OWFs, the Outer Dowsing Offshore Wind Preliminary Environmental Information Report (GeoXYZ, 2023) applied ITI to complement traditional analyses and indicate the relative proportion of individuals belonging to different feeding groups within the main community types identified via cluster analysis. The same methodology could be applied to the collated OWF data, and results statistically compared between years to identify the potential for temporal variation.

Analysis and data requirements

Raw macrofaunal data using a variety of benthic sampling methods can be used to apply ITI for further analysis. The following data truncation rules should be utilised prior to analysis (Word, 1978):

- Application of the index is commonly restricted to soft-sediment communities;
- The surface area of samples considered must be at least 0.1 m^2; and
- The sample must be screened through 1.0- or 0.7-mm mesh.

The above truncation rules are commonly adopted as standard protocol during benthic sampling of soft sediment communities using grab sampling techniques, consequently they have been adhered to for the post-construction monitoring data sets collated for this project.

Infaunal macrofauna found within samples would then be organised into four main feeding classes (GeoXYZ, 2023; Pinto *et al.,* 2008):

1) suspension detritus (or filter) feeders;
2) interface feeders (facultative filter and deposit feeders);
3) deposit feeders; and
4) subsurface deposit feeders.

When organisms in a sample are divided into the above categories, the trophic structure can be calculated using the following formula:

$$ITI = 100 - \frac{100}{3}\left(\frac{N_2 + 2N_3 + 3N_4}{N_1 + N_2 + N_3 + N_4}\right)$$

*N_n is the number of individuals within the respective feeding group.

The results from the ITI approach would produce a numerical value which is categorised into four grading classifications; degraded conditions (0-30), intermediate conditions (30-60), normal conditions (60-80), and reference conditions (80-100) (Pinto *et al.,* 2008).

Limitations

It should be noted that ITI is not a measure of ecological status as it simply provides a scale of values devised from the dominance of specific infaunal species (Word, 1978; Gamito and Furtado, 2009). The maximum ITI value is attained when the community is composed entirely of suspension feeders, while a more balanced community of feeding types would result in a lower quality classification.

The ITI categorises species into broad trophic groups, which may overlook nuances in feeding strategies and variations in feeding behaviour of individual species.

Similar to traditionally used diversity metrics, the ITI may be influenced by natural changes in ecological communities making it difficult to distinguish between effects of OWFs and natural variability.

4.1.2 AZTI Marine Biotic Index (AMBI)

Purpose and benefits

AZTI's 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.,* 2011). Disturbance-sensitive taxa are categorised into ecological groups according to taxon dominance along a gradient of organic enrichment, providing an insight into the ecological health of benthic communities (WFD-UKTAG, 2014).

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. AMBI could be a useful index to apply to post-construction monitoring, noting potential localised increases in the level of deposition of organic compounds around turbine foundations addressed in APEM (2025a and b).

Analysis and data requirements

Raw macrofaunal data using a variety of benthic sampling methods could be used to apply the AMBI metric for further analysis. To perform this, the following data truncation rules should be utilised (Borja and Muxika, 2005):

- Use of data restricted to soft bottom communities only; and
- Removal of the following taxa from data:
    - non-benthic invertebrates;
    - freshwater taxa;
    - In salinity >10 remove insecta;
    - Remove juveniles when the species are not identified;
    - Remove non-soft sediment taxa ;
    - Remove epifaunal taxa;
    - Remove planktonic taxa;
    - Certain taxa should be grouped together (e.g. certain genus types); and
    - Never use high taxonomic levels (e.g. Bivalvia, Gastropoda), except those included in the taxon list (e.g. Nemertea etc.).

The AMBI index relies on the distribution of individual abundances of macrofaunal soft-bottom communities into five groups according to sensitivity to an increasing gradient of enrichment of organic matter (Pinto *et al.,* 2008):

I. Species with high sensitivity to organic enrichment and present under unpolluted conditions;
II. Species always present in low densities with little variation in abundance over time, exhibiting indifference to enrichment;

III. Species present in normal conditions; however, populations are stimulated by organic enrichment, tolerant to excess organic matter enrichment;
IV. Second-order opportunistic species, adapted to slight to pronounced imbalances of environmental conditions; and
V. First-order opportunistic species, adapted to pronounced unbalanced environmental conditions.

The AMBI value ranges from 0 (unpolluted) to 6 (heavily polluted) and 7 represents azoic conditions (extremely polluted) (WFD-UKTAG, 2014). The AMBI scores are effectively a ratio between the proportion of disturbance sensitive and tolerant taxa within a sample (Borja and Muxika, 2005). The scores are based on the percentage of abundance of each group of one site, given by the Biotic coefficient.

$$\text{Biotic coefficient} = \left\{ \frac{(0 \times \%G_{I}) + (1.5 \times \%G_{II}) + (3 \times \%G_{III}) + (4.5 \times \%G_{IV}) + (6 \times \%G_{V})}{100} \right\}$$

Multivariate AMBI (M-AMBI) could also be applied by combining the AMBI score, Shannon-Wiener Diversity (H') and species richness (S), (Fitch *et al.*, 2014). This method has shown to be effective for determining reference conditions for different environmental conditions of discreet habitats.

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 hydrodynamic energy areas and subtidal sandbanks (Muniz *et al.*, 2005; Muxikaa *et al.*, 2005). Furthermore, this approach does not take into account within-habitat variability and, due to the removal of all epifaunal and non-soft sediment taxa from the data sets to perform AMBI, results are restricted to infaunal, soft sediment communities.

A key limitation is that the OWF post-construction monitoring does not usually include stations in close proximity to turbine foundations and then at set distances away from the foundations which would be beneficial in determining any potential gradient of organic matter from turbines using AMBI. The analysis results could be grouped based on distance from turbines, but the nearest grab stations to turbines are anticipated to likely be at a distance of 50 m or more and this approach requires obtaining the locations of turbines for the OWFs being investigated.

4.1.3 ABC Curves

Purpose and benefits

Abundance–Biomass Comparison (ABC) models are tools for detecting the effects of anthropogenic perturbation of biological communities (Warwick, 1986). ABC models are underpinned by the r- and K-selection theories and involve plotting *k*-dominance curves (Lambshead *et al.*, 1983) along with *k*-biomass curves on the same graph for comparative purposes.

Analysis and data requirements

Taxa are ranked on a logarithmic scale on the *x*-axis, with cumulative percentage dominance (in terms of abundance and biomass) displayed on the *y*-axis. Taxa are displayed in a different order on the *x*-axis for the abundance and biomass curves. Hence, taxa identities do not match up and the model should be read by separately considering the dominance structure of the community captured for abundance and biomass (Warwick, 1986).

As biomass data should relate to tissue weight only, influence of shell material in bivalves and gastropods will need to be considered. Consequently, it is recommended that wet weight biomass data is converted to dry weight for all biota and to shell free dry weight for bivalves and gastropods. This can be achieved by reference to conversion table such as those provided by Rumohr *et al*. (1987).

Under undisturbed conditions, the biomass curve will lie above the abundance curve, a pattern shaped primarily by biomass (Figure 1). In pristine environments, the benthic community is generally dominated by one or two K-selected (conservative) taxa, which are large in size but not dominant in numbers. While *r*-selected (opportunist) taxa are also present, they are not dominant in terms of biomass or abundance.

When a disturbance alters the community, the biomass curve intercepts that of abundance. In case of severe disturbance, the biomass curve even lies beneath that of abundance, indicating a drastic alteration of the community structure. The two latter patterns are determined by K-selected species, which usually decrease in numbers, whereas *r*-selected taxa are not affected or might even thrive under disturbance. The result is that the two curves intermingle under an intermediate disturbance, or the biomass curve lies beneath the abundance one if there is gross disturbance (Figure 1).

The contention is that these three conditions (termed undisturbed, moderately disturbed and grossly disturbed) should be recognisable in a community without reference to control samples in time or space, the two curves acting as an 'internal control' against each other. Reference to spatial or temporal control samples is, however, still desirable. Adequate replication of sampling is a prerequisite of the method, since the large biomass dominants are often represented by few individuals, which will be liable to a higher sampling error than the numerical dominants.

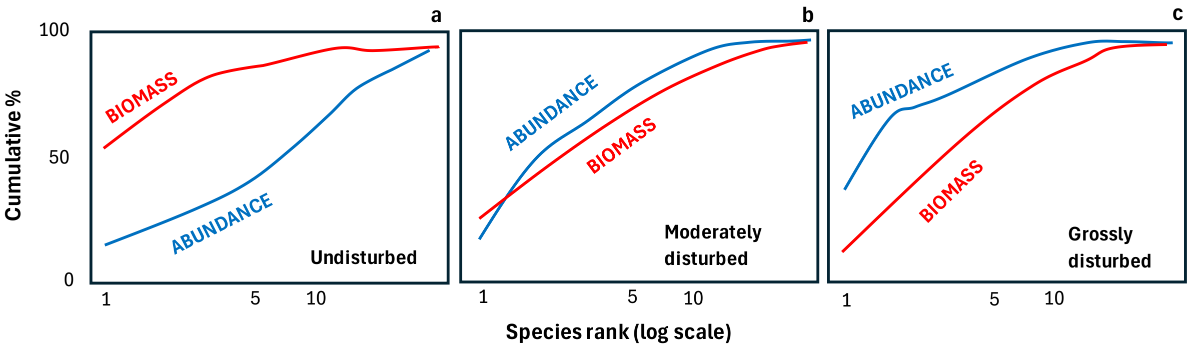

Figure 1. Hypothetical k-dominance curves for species biomass and abundance, showing 'undisturbed', 'moderately disturbed' and 'grossly disturbed' conditions.

When the number of sites, times or replicates is large, presenting ABC plots for every sample can be cumbersome, and it would be convenient to reduce each plot to a single summary statistic. Warwick (1986) contends that the biomass and abundance curves increasingly overlap with moderate disturbance, and transpose altogether for the grossly disturbed condition, which, as a unidirectional hypothesis, is amenable to quantification by a single summary statistic. Clarke (1990) proposes the W statistic which is produced by subtracting the abundance from the biomass value for each species rank in an ABC curve. If the biomass curve is above the abundance curve throughout its length the sum of these values across all ranks will be strongly positive. In contrast, where biomass is below the abundance curve this sum will be strongly negative. To enable comparisons to be made between samples standardisation is required with the following standardised sum proposed by Clarke (1990):

$$W = \sum_{i=1}^{S} (B_i - A_i)/[50\,(S - 1)]$$

Where B_i = Biomass, A_i = Abundance and S = number of taxa.

The resultant values for W range from –1 to 1 where increasing negative values reflect increasing disturbance and increasing positive values reflecting increasing stability in the communities assessed.

Limitations

The key limitation for this approach is that a full set of biomass data for pre-construction and at least two post-construction monitoring surveys in only available for one of the 18 OWFs indicated in Table 2 (despite anonymisation, as only one OWF would be involved, it is suggested that permission would be required from the developer to use this data set for this analysis). Options to apply it to additional OWFs could be expanded by considering OWFs with pre-construction biomass data and just one set of post-construction biomass data.

In addition, a potential problem with the cumulative nature of the curves is that the visual information presented is over-dependent on the single most dominant species. The unpredictable presence of large numbers of a species with small biomass, perhaps an influx of the juveniles of one species, may give a false impression of disturbance. With genuine disturbance, one might expect patterns of ABC curves to be unaffected by successive removal of the one or two most dominant species in terms of abundance, or biomass disturbance effects are not just seen in changes to a few dominant species but are evidence across the complete suite of species in the community. Consequently, where patterns may be masked by influence of single dominants, Clarke (1990) recommends the use of partial dominance curves which compute the dominance of the second ranked species over the remainder i.e. ignoring the first ranked species. It is proposed that a comparison of the results with the two approaches could potentially be undertaken for this metric.

4.1.4 Biological trait analysis

Purpose and benefits

A Biological trait approach to data analysis has the potential to identify the impact that colonising species and shifts in benthic community composition may have on biological diversity and ecosystem functioning (Boutin *et al.,* 2023). 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. Changes in the patterns of trait expression within benthic assemblages, for example changes in the relative abundance of taxa exhibiting the traits, can be used to indicate the effects of disturbance on ecological functioning (Bremner *et al.,* 2006).

The strength of this approach is that it can be tailored to detect specific functional changes that are reflective of potential disturbance impacts, which may not be as apparent when using traditional diversity-based metrics.

Analysis and data requirements

The Cefas data set 'key biological traits of marine benthic invertebrates surveyed in Northwest Europe' (Clare *et al.,* 2022) would be used to match the relevant functional traits to the collated benthic species recorded during the OWF monitoring. Species within samples would be assigned the following biological traits according to their behavioural, morphological and reproductive characteristics (further detailed is provided in Annex 2b).

- Maximum size;
- Morphology;
- Lifespan;
- Egg development location;
- Larva development location;
- Living habitats;
- Sediment position;
- Feeding mode;
- Mobility; and
- Bioturbation.

Following the assignment of traits, a species and site trait matrix would be constructed and subsets of traits (for example those sensitive to disturbance) could then be analysed using univariate and multivariate analyses. Euclidean distance could be performed to quantify the dissimilarity between sites and monitoring years based on their traits. Dendrograms and Multi-Dimensional Scaling (MDS) plots can be produced based on Bray-Curtis similarity coefficients (Bray and Curtis, 1957) to help visualise spatial and temporal similarities in benthic communities according to biological trait distributions. The relationship between environmental variables and biological traits between survey years could also be analysed using correlation tests such as Bio-Env (BEST) and Relate tests.

Limitations

The Cefas catalogue may not have all potential traits recorded for each taxa within the collated data sets. This may lead to a reduction in reliability and accuracy in analysis results. In addition, the catalogue translates traits to genus level only, so any potential nuances at the species level would not be detected.

4.2 Potential for further analysis for RQ2: Multi-site analysis

It is proposed that to further investigate RQ2: Is there a measurable change (increase/decrease) in biodiversity and/or species composition?, a multi-site analysis could be performed to identify and compare trends in benthic community structure of multiple OWF sites.

4.2.1 Multi-site analysis

Purpose and benefits

The multi-site analysis represents the adoption of a meta-analysis approach, being the statistical combination of results from two or more separate studies. This approach, using species data with other environmental variables as explanatory factors can highlight consistent patterns in species diversity and abundance and also physical changes to benthic habitats. Compared to the analysis of single site studies the simultaneous analysis of data from multiple sites can increase the statistical power of any analyses, thereby providing a more robust indication and understanding of potential effects of OWF development on benthic ecosystems. This enhanced understanding of patterns can then be incorporated in the design of future monitoring programmes and better inform future Environmental Impact Assessments (EIAs).

Future multi-site analysis could involve a comparison of changes pooled across multiple sets of reference stations with respective OWF data sets, to determine if trends observed at individual OWFs are replicated when multiple data sets are analysed together.

Such analyses have been conducted previously such as Coolen *et al*. (2022) who investigated benthic community biodiversity changes across six wind farms sites in the southern North Sea, highlighting the influence of factors such as depth, seasonality and proximity to introduced infrastructure. The results demonstrated that multi-site analysis may provide an improved level of understanding of ecological patterns on large-scale effects of anthropogenic structures on marine biodiversity which may not be highlighted by the analysis of data from single monitoring studies. Similarly, a multi-site analysis of the effects that wind farm structures have on fish populations was undertaken by Methratta and Dardick (2019) who noted that pelagic fish species are particularly difficult to monitor in relation to OWFs and impact data are scarce. Methratta and Dardick (2019) highlighted the need for regional, national, and international collaboration on monitoring approaches and data sharing to develop a more holistic understanding of how offshore wind farms affect living marine resources.

Analysis and data requirements

Multi-site analysis can improve the understanding into the structure and function of benthic populations and communities by employing a number of techniques. The data required can include the standard array of information routinely collected during benthic studies relating to community structure, environmental factors and geographical information.

- Community diversity and abundance
- Taxon biomass
- Particle size data and contextual sediment descriptions
- Water depth
- Sediment chemistry
- Site location

Where variation in sampling and processing techniques occur between data sets, some form of standardisation of data may be required such as conversion to standard density measures (including consideration of variation in number of replicates) and conversion of biomass to standard measure (e.g. dry weight). Similarly, seasonal factors should be considered as this can influence populations, particularly in relation to reproductive cycle (e.g. recruitment, loss of mature spawning cohorts). Depending on the nature of the sites included in the analysis other environmental explanatory factors could be considered and accounted for where possible.

Standard analytical techniques will be applied to more traditional metrics used for post-construction monitoring as outlined in APEM (2025a) to facilitate the identification of spatial and temporal patterns. In addition, PERMANOVA (Permutational Multivariate Analysis of Variance) could be employed which is a statistical method which tests for differences between groups based on multivariate data allowing comparison of community composition across different locations, environmental gradients and temporal gradients. As the technique relies on a similarity matrix produced from macrobenthic data collected routinely during benthic surveys, existing data can be utilised and no additional aspects of survey design are required in future surveys.

Limitations

There are a number of limitations associated with the multi-site analysis by which the potential increased power of the approach to detect ecological patterns is lost and are not discernible against natural variation. These include:

Number of studies: the selection and inclusion of a limited set of studies may bias the analytical outcome - as indicated in Section 0,

- Summary of data collated it is considered six OWF data sets are available with more than one year of post-construction data, but the number of OWFs included could be increased if those with only one set of post-construction data were included.
- Data quality: the validity of conclusions drawn from multi-site analysis depends on the quality of the individual studies included in the analysis – for instance (a) are the individual studies designed to be truly representative of the habitats investigated; and (b) are the inferences made from each of the individual studies included in the analysis valid.
- Heterogeneity of methods: use of dissimilar sampling methods in individual studies can result in data consistency being compromised which can increase the risk of making erroneous inferences from the data. It will be ensured as far as possible that consistent sampling methods have been used for the data sets included in the analyses.

4.3 Recommendations for the future of Offshore Wind monitoring

Many studies have shown that changes in benthic habitats can directly affect the structure and function of macrofaunal communities and that the spatial distribution of macrofauna is closely related to a number of factors such as water temperature, water depth, hydrodynamic conditions, dissolved oxygen content, and sediment types (e.g. Mancinelli *et al*., 1998; Ysebaert and Herman, 2002; Como and Magni, 2009). Consequently, monitoring programmes should follow a multidisciplinary design which integrates physical, biological and chemical parameters. Furthermore, a long-term monitoring strategy should be established to assess both the immediate and long-term effects of construction, operation and decommissioning (as applicable) of OWFs and which are able to detect changes that may signal environmental degradation. Consequently, the use of a single index for assessment is limiting and with a multiple methods approach there can be an increased likelihood of accurately identify the overall environmental impact of a development on the benthic environment (Lu *et al*., 2021).

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. Surveys are planned in consultation with regulatory authorities and are designed with reference to relevant guidance (e.g. Boyd, 2002; Cefas, 2004; Ware & Kenny, 2011; Judd, 2012) along with any conditions and recommendations stated in the licence required to construct and operate the OWF.

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).

Power analysis: Fit-for-purpose monitoring is required with sufficient statistical power to detect ecologically meaningful changes. 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 analyses 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. Franco *et al*. (2015) did stress that an impact removing 50% of the species in an area would likely be regarded unacceptable by regulators and other stakeholders. The authors indicated that adoption of a 10% effects threshold would require greater sampling effort of 10 to 15 stations per area to assess 10% changes in species richness, with 15 to 20 stations required for abundance and 20 to 50 stations required for biomass (Franco *et al*. 2015).

Temporal extent: It has been highlighted that the Before-After-Control-Impact (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 long term or lasting impacts to validate predictions made within the Environmental Statement (ES) and to improve our understanding of long-term effects and recovery of marine receptors. Clearly defined criteria for when and how decisions will be made on the conclusion of monitoring should be incorporated into any plan which will be determined by whether objectives of the monitoring programme have been met.

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.

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. Locating some stations nearer turbines and along a gradient away from the turbines would help determine 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.

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 as discussed in Section 4.2. 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;
- 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 (median 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.

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). In addition, the development of best practice guidance for the selection of reference stations, temporal and spatial sampling extent and standardised reporting would be beneficial.

5. Project Stage Gate decision

It was determined during the interim workshop with the ORJIP Offshore Wind Steering Group and Project Expert Panel, that AMBI and biological trait analysis approaches would be taken forward post-Project Stage Gate.

The proposal for using ABC Curves was not taken forward post-Stage Gate because of time constraints and the limited availability of biomass data found within the collated OWF monitoring data. Considerations for multi-site analysis were also not taken forward due to some limitations identified in Section 4.2.1, logistic considerations and time requirements.

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Annex 2a Identified knowledge gaps regarding potential effects of OWFs on benthic communities

Effect	Indicative variables to be quantified	Description of some key knowledge gaps
RQ1: Are there suitable metrics to detect changes in benthic habitats that could be applied to offshore wind assessments?		
Traditional biological and physico-chemical metrics	Biota (abundance, species/taxon richness, habitat extent and composition, biomass, phyletic composition, characteristic species, INNS, SACFOR abundance scale) Sediment (PSA, Physico-chemical) Univariate and multivariate analysis	The majority of pre- and post-construction OWF monitoring reports compare benthic communities using traditional metrics such as abundance, diversity indices, species richness, and community composition. These approaches, however, provide limited information on the changes in ecological function of communities or information on the levels of disturbance of communities.
RQ2: Is there a measurable change (increase/decrease) in biodiversity and/or species composition?		
Temporal changes to benthic faunal composition before and after OWF construction	Species composition, diversity, and abundance of macrobenthic organisms before and after OWF installation (including univariate and multivariate analysis).	There does not appear to be a standard frequency of post-construction benthic surveys (e.g. annual, biannual, biennial) or standard duration of the post-construction monitoring. Not all pre-construction and/or post-construction survey reports and data sets are publicly available for specific OWFs. Reference stations would ideally be characterised by similar depth exposure and sediment type as the development site. No standardisation for number of reference stations, reference stations represented between 3% and 50% of

Effect	Indicative variables to be quantified	Description of some key knowledge gaps
		sampling locations across the 18 OWF projects reviewed for RQ1-5.
RQ3: Are there localised and regional ecological effects around the infrastructure?		
Changes to sediment composition and resultant impacts on benthic communities in the wake of monopiles	Sediment size classes; benthic epifauna and infauna; habitats/biotopes; and increasing distances away from infrastructure (particularly turbines) across pre- and post-installation periods and for the full duration of OWF operation. Suspended Particulate Matter (SPM) concentrations and composition, settling velocity, seabed sediment properties (type, sedimentation, and erosion rate), turbidity	The distances to which monopiles affect sediment composition in the wake of turbines, and the resultant impacts on benthic communities is not clear. Limited availability of long time series to detect changes and limited availability of vertical profile data and long-time series.
Effects of underwater noise and vibration on benthic fauna	Behavioural changes (e.g. predator avoidance, foraging efficiency etc.) and physiological changes (e.g. reproductive output, condition of larvae) in response to underwater noise and vibration representative of OWF	Impacts of underwater noise and vibration has been investigated for only a small number of species, mostly crustaceans, and is based mostly on laboratory experiments that have not investigated long-term (i.e. full OWF life cycle) impacts of these stressors on benthic fauna. For

Effect	Indicative variables to be quantified	Description of some key knowledge gaps
	environment and at increasing distances away from source Population- and community level impacts owing to impacts experienced by individual animals from noise Measurement of noise and vibration from pile driving and other noise-generating activities	underwater noise and vibration there are no threshold criteria to assess effects on benthic invertebrates as there are for fish and marine mammals (levels of vibration anticipated to be most relevant for benthic invertebrates). Responses of more taxa need to be tested and over longer timescales. Limited recent information for noise and vibration levels generated during OWF installation (hammering, vibrating, and drilling sounds).
Effects of Electromagnetic Fields (EMFs) on benthic fauna	Behavioural changes (e.g. influence movement, feeding, and migratory behaviour of species) in response to EMF emissions representative of OWF environment and at increasing distances away from the sources of these emissions Population- and community level impacts owing to impacts experienced by individual animals from EMFs	Little is known about the local and regional effects of Electromagnetic Fields (EMF) from subsea power cables on benthic species. Impacts of EMF has been investigated for only a small number of species, mostly crustaceans, and is based mostly on laboratory experiments that have not investigated long-term (i.e. full OWF life cycle) impacts on benthic fauna. Results vary across studies. Responses of more taxa need to be tested and over longer timescales.
Organic enrichment of sediments as a result of fouling organisms on infrastructure, and the	Total Organic Carbon, measured across the life cycle of an OWF and at full scale of OWFs	Hydrodynamic and sediment transport models predict that TOC concentrations around turbines can be expected to increase; models require validation and TOC measurements over time need to be considered alongside changes in

Effect	Indicative variables to be quantified	Description of some key knowledge gaps
potential impacts on sediment communities at a regional scale	Concentrations of physico-chemical parameters e.g. dissolved oxygen, pH, pCO2, alkalinity	benthic communities to establish potential biological and community-wide impacts at a local and regional scale. Anticipated increases in organic carbon levels in vicinity of turbine foundations following colonisation by biofouling organisms, in particular blue mussels. However, few studies have measured organic content levels from near the turbine foundation base and at increasing distances from the foundation to clarify the potential extent of the effect. Lack of long consistent time series for trend detection and interpretation.
The potential contribution of OWF infrastructure to the introduction and spread of non-native taxa and spread of native taxa	Distribution (spatial extent) of species in soft sediments pre- and post-OWF installation Species composition, abundance, and distribution of invasive species on artificial habitats. Connectivity between artificial habitats and nearby natural ecosystems (e.g., distance, current patterns).	The role of OWFs in promoting the connectivity between populations of benthic species is not clearly understood. Quantifying the role of OWF infrastructure in connectivity of species of conservation and/or commercial importance, as well as non-native species, is important in terms of better understanding regional ecological effects of OWF on benthic communities. Few of the post-construction monitoring programmes at OWFs included assessment of colonisation of the turbine foundations, and in most cases where these data were collected it was for one post-construction monitoring period only.

Effect	Indicative variables to be quantified	Description of some key knowledge gaps
Effects of hydrodynamic changes	Hydrodynamic modelling outputs, changes to sediment transport regime	Limited information relation to the role of turbulence in assessing changes to seabed substrates away from wind farm monopiles, and effects on sediment transport capability. Being investigated under ongoing ECOWind-ACCELERATE project.
RQ4: Are there changes in ecological function (e.g., functional groups) owing to biological impacts?		
Functional group changes	Changes in parameters such as feeding modes, life-history (e.g. reproductive traits, larval dispersal mode, life span), physiological (e.g. growth rates), behaviour (e.g. mobility)	The majority of pre- and post-construction monitoring compares benthic communities using traditional metrics such as abundance, diversity, species richness, and community composition. These approaches, however, provide limited information on the changes in functional roles of species or ecosystem level changes. Lack of studies that explicitly investigate changes in ecological functioning as a result of changes to soft sediments surrounding OWFs.
Habitat Alteration	Morphological changes in benthic habitats (e.g., substrate type, rugosity, spatial complexity). Changes in sediment composition, grain size distribution, and oxygen levels in sediments near artificial structures.	Limited understanding of how artificial structures influence benthic habitat morphology and create new settlement spaces for marine organisms.

Effect	Indicative variables to be quantified	Description of some key knowledge gaps
	Nutrient profiles and other aspects of sediment quality surrounding artificial structures. Composition, biomass, and diversity of fouling communities. Changes in structural complexity due to fouling organisms and recruitment rates of benthic species associated with fouling. Species composition, abundance, and behavioural patterns (e.g., sheltering, feeding) of higher trophic levels near artificial structures. Benthic community structure and diversity in adjacent natural habitats.	Insufficient quantification of the role of fouling organisms in enhancing habitat complexity and supporting additional benthic species. Unclear extent to which artificial structures aggregate higher trophic levels. Gaps in knowledge about the impact of organic matter transfer from artificial structures on nearby natural habitats, including changes to sediment composition and community structure. Need for further research on the development of hypoxic or anoxic conditions in sediments surrounding artificial structures.
Food Web and Trophic Interactions	Concentration and composition of suspended particulate organic matter (POM). Sedimentation rates and sediment composition near artificial structures. Growth, reproduction, and feeding efficiency of filter-feeding organisms. Biomass, diversity, and abundance of fouling organisms. Species composition and abundance of predators and scavengers near artificial structures.	Limited understanding of how altered food availability, driven by sedimentation and the presence of fouling organisms, affects filter feeders. Unclear extent to which fouling organisms influence turbidity, sedimentation rates, and primary producer dynamics. Gaps in knowledge about how artificial physical structures attract predators and scavengers, thereby modifying natural food webs.

Effect	Indicative variables to be quantified	Description of some key knowledge gaps
	Abundance and diversity of fouling communities and associated prey species.	Insufficient information on the foraging behaviour of higher trophic levels on fouling communities and surrounding fauna, and its impact on ecosystem dynamics.
RQ5: Can recovery and/or enhancement be demonstrated and in what timeframe?		
Recovery:		
Benthic macrofaunal communities may be able to return to pre-impacted states following OWF installation	Community composition, diversity, species richness, evenness, characteristic species	Difficult to assess recovery where adverse effects on benthos are not attributed to an OWF or other anthropogenic influence. All of the OWF post-construction monitoring reports reviewed indicated changes at the OWF site were due to natural variability. Long-term pre-impact datasets increase understanding of natural variability in the benthic environment and associated communities at a given location, although such data sets are rarely available (Coates et al., 2015).
Macrobenthic recovery after dredging activities	Species composition, diversity, and abundance of macrobenthic organisms before and after dredging. Sediment grain size, organic matter content, and oxygenation levels in the affected areas.	Limited information available for effects of dredging activity on soft sediment benthos although in frequently disturbed environments there can be relatively rapid recovery e.g. within two years (e.g. van Dalfsen et al., 2000, Coates et al., 2015).

Effect	Indicative variables to be quantified	Description of some key knowledge gaps
	Water quality parameters (e.g., turbidity, dissolved oxygen, salinity) and nutrient concentrations in the water and sediment. Rates of recolonisation, growth, and reproductive success of macrobenthic species after dredging. Extent and duration of sediment resuspension, turbidity, and habitat changes due to dredging activities.	Large-scale or long-term effects, particularly on higher trophic levels, remain uncertain.
Enhancement:		
Benthic / demersal fish and crustaceans may benefit from reserve effects i.e. exclusion of bottom trawling and increased prey availability around turbines Potential increased diversity of communities present due to introduction of OWF infrastructure	Pre- and post-OWF population sizes of benthic/demersal taxa Communities colonising turbine foundations	Uncertainties regarding the reserve effects, mixed results from studies, particularly since some studies were completed within the first couple of years following construction so the long-term influence of reserve effects have not been confirmed. To date, the majority of OWF infrastructure has not been explicitly designed or deployed for purposes of ecological enhancement. Limited studies addressing whether increases in diversity and biomass on OWF infrastructure could be considered to be representative of enhancement. Paucity of studies that have appropriate spatial and temporal replication concerning artificial reef communities, and so it is uncertain how these effects will translate at the true operational scale at which infrastructure is planned to be installed.

Annex 2b Biological traits, categories and descriptions (Clare *et al.*, 2022).

Trait	Category	Description
Maximum size (sr)	< 10	The maximum size (mm) that the taxon is known to reach during the adult stage.
	10–20	
	21–100	
	101–200	
	201–500	
	> 500	
Morphology (m)	Soft	External tissue is soft and not covered by any form of protective casing.
	Tunic	Body is covered by a protective outer tissue made up of, for example, cellulose, e.g., tunicates.
	Exoskeleton	Body is covered or encased in either a thin chitinous layer or calcium carbonate shell.
	Crustose	Body is hard and forms a thin layer over the substratum or another organism.
	Cushion	Body is soft and forms a cushion-like layer over the substratum or another organism.
	Stalked	Body is erect and typically attached.
Lifespan (l)	< 1	The maximum reported lifespan (years) of the adult stage of the taxon.
	1–3	
	3–10	
	> 10	
Egg development location (ed)	Asexual	Can reproduce asexually, either by fragmentation, budding, epitoky, etc.
	Sexual - pelagic	Eggs are released into the water column.
	Sexual - benthic	Eggs are released onto/into the seabed, either free or attached, e.g. by mucous.
	Sexual - brooded	Fertilised eggs are maintained by adult for protection, either within parental tube or body cavity.
Larva development location (ld)	Pelagic - planktotrophic	Larvae feed on plankton and spend a relatively long time in the water column.
	Pelagic - lecithotrophic	Larvae feed on yolk reserves and spend a relatively short time in the water column.
	Benthic (direct)	Larval stage missing (eggs develop directly into juveniles) or larvae are limited to the seabed.
Living habit (lh)	Tube-dwelling	Adults live in a tube, which may be lined with sand, mucus or calcium carbonate.
	Burrow-dwelling	Adults live in a permanent or temporary burrow.
	Free-living	Adults do not inhabit a restrictive structure. Able to move freely within and/or on sediments.
	Crevice/hole/under stones	Adults typically cryptic and inhabit spaces within coarse/rock substrate or algal holdfasts.

Trait	Category	Description
	Epi/endo-biotic	Adults live on or in another organism.
	Attached to substratum	Adults are attached to coarse substrate or rock.
Sediment position (sp)	Surface	Adults live on or just above the seabed.
	Shallow infauna	Adults live below sediment surface between 0 and 5 cm depth.
	Mid-depth infauna	Adults live below sediment surface between 5 and 10 cm depth.
	Deep infauna	Adults live below sediment surface at greater than 10 cm depth.
Feeding mode (f)	Suspension	Feeds on particulate food resources suspended in the water column.
	Surface deposit	Feeds on detritus (including algal material) on the sediment surface.
	Sub-surface deposit	Feeds on detritus located within the sediment matrix.
	Scavenger	Feeds on dead animals (carrion).
	Predator	Actively predates on animals (including small zooplankton).
	Parasite	Derives nutrition from its host organism.
Mobility (mob)	Sessile	Adults have little or no mobility. Typically attached or lives in (semi-) permanent burrow/tube.
	Swim	Adults actively swim in the water column (many return to the bed when not feeding).
	Crawl/creep/climb	Adults capable of some (typically limited) movement along the sediment or rock surface.
	Burrower	Adults capable of active movement within the sediment matrix.
Bioturbation mode (b)	Diffusive mixing	Vertical and horizontal redistribution of sediment and/or other particles.
	Surface deposition	Deposition of particles at sediment surface, e.g. from defecation or egestion (pseudofaeces).
	Upward conveyor	Translocation of particles from depth to sediment surface, e.g. during sub-surface deposit-feeding.
	Downward conveyor	The subduction of particles from sediment surface to depth, e.g. by feeding and/or defecation.
	None	Does not have any bioturbative capacity.

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