ANHOLT WIND FARM'S IMPACT ON BENTHIC BIODIVERSITY AT TURBINE AND FARM LEVEL

Technical Report from DCE – Danish Centre for Environment and Energy No. 330 2025

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Karsten Dahl
Ben J. O. Robinson
Helle Buur
Karoline Reducha Andersen
Nikolaj Reducha Andersen
Cordula Göke
Jørgen L. S. Hansen

Aarhus University, Department of Ecoscience

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Data sheet

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Abstract: This technical report describes benthic flora and fauna investigations in Anholt wind farm and reference areas in 2022. The study followed a BACI-design and assessed infauna inside and outside the wind farm before and after its establishment. Data on infauna inside the park from 2022 were compared to data from 1989-2010 before the park was built and showed that the fauna community inside the park had changed significantly as to total abundance, biodiversity, species richness and calculated environmental quality indices. However, similar changes had occurred outside the park, and these were not coupled with the wind farm but with general changes in the Kattegat area. A study on radiating effects on fauna and sediment was conducted at 30 m, 80 m and 130 m distance from the towers and revealed a weak distance effect in northward direction, but no general radiating effect could be seen on the seabed regarding benthos abundance, diversity, species richness and sediment carbon content. However, these findings may be biased since only one of the wind turbines had scour protection. Video transects of the fouling community on the monopiles exhibited atypical hard bottom fauna compared to natural boulder reefs in the Kattegat, with different epifauna and epiflora community compositions and distributions between the wind farm and the natural boulder reefs. Epifauna was relatively much more dominant on the wind turbine towers, and macroalgae had a shallower depth limit compared to natural boulder reefs.

Keywords:	Anholt wind farm, epifauna, infauna, macroalgae, BACI-design
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Preface

Background for the report and relation to other activities

This report contributes to the project "*Environmental mapping and screening of the offshore wind potential in Denmark*" initiated in 2022 by the Danish Energy Agency. The project aims to support the long-term planning of offshore wind farms by providing a comprehensive overview of the combined offshore wind potential in Denmark. It is funded under the Finance Act 2022 through the programme "Investeringer i et fortsat grønnere Danmark" (Investing in the continuing greening of Denmark). The project is carried out by NIRAS, Aarhus University (Department of Ecoscience) and DTU Wind. The overall project consists of four tasks defined by the Danish Energy Agency: https://ens.dk/energikilder/planlaegning-af-fremtidens-havvindmoelleparker

1. Sensitivity mapping of nature, environmental, wind and hydrodynamic conditions.

2. Technical fine-screening and assessment of the overall offshore wind potential based on the sensitivity mapping and relevant technical parameters

3. Assessment of potential cumulative effects from large-scale offshore wind development in Denmark and neighbouring countries.

4. Assessment of barriers and potentials in relation to coexistence.

This report addresses one component of Task 1: sensitivity mapping. Specifically, it provides an overview of areas within Danish offshore regions that are likely to be particularly vulnerable to offshore wind farm development regarding based on available data. Other subjects within Task 1 will be presented in separate reports in late 2024 and early 2025. A synthesis of all topics under Task 1 will be published in 2025.

The project has relied predominantly on historical data, with minimal new data collection. As a result, the sensitivity mapping is largely dependent on the availability and accessibility of pre-existing data across specific subject areas. From the outset, significant effort was made to incorporate all relevant data to comprehensively address the task requirements. However, certain existing datasets could not be accessed. Section specifies the data sources used in the sensitivity mapping for seabirds and outlines additional existing data. It is important to recognize that sensitivity mapping serves as a dynamic tool, which can be updated as new data becomes available.

The project management teams at both AU and NIRAS have contributed to the description of the background for the report and the relation to other activities in the preface. The report and the work contained within are solely the responsibility of the authors.

Sammenfatning

Denne tekniske rapport beskriver undersøgelserne af bundfauna og bund flora i Anholt Vindmølle Park samt i et nærliggende kontrolområde i Aalborg Bugt. Undersøgelsen omfatter den tidslige udvikling af infauna inden for og uden for parkområdet før og efter opførslen af parken (BACI-design). Inden for parken blev der udført transektundersøgelser med ROV, hvor begroningssamfundene på det hårde substrat på mølletårnene og den omkringliggende havbund blev dokumenteret. Sedimentets glødetab og sammensætningen af infaunasamfundet blev relateret til afstanden fra nærmeste mølletårn. Prøvetagningen af bundfauna inde i parken på den tidligere overvågningsstation 150 i 2022 viste signifikante ændringer i artssammensætningen sammenholdt med perioden 1989-2010 på samme station. Der var imidlertid også signifikante ændringer i artssammensætningen på en referencestation med samme bundtype uden for vindparkområdet, og med de inkluderede data kunne de generelle ændringer ikke knyttes til etableringen af vindparken. Artsdiversitet og artsrigdom viste samstemmende høje værdier, og anvendelse af miljøkvalitetsindeks viste ligeledes gode forhold. En tilsvarende sammenligning mellem biodiversiteten før og efter på station 150 viste en signifikant lavere artsdiversitet efter etableringen af parken, men denne udvikling kunne heller ikke umiddelbart tilskrives vindmøllerne, idet samme udvikling kunne ses på referencestationen uden for parken. Ændringerne skal ses i forhold til de generelt meget store mellemårlige variationer i både diversitet og tæthed i Kattegat, der er påvist for perioden 1989-2022 i andre undersøgelser, og som gør det meget svært at påvise lokale effekter i hele Kattegatområdet. Betydningen af afstanden fra prøvetagningspositionen og nærmeste vindmølle viste en signifikant svag effekt på infaunaens sammensætning, men kun i forhold til afstanden i nordlig retning. Der kunne således ikke påvises nogen generel radierende effekt fra mølletårnene på infaunaens sammensætning. Kun en af de tre undersøgte møller havde erosionsbeskyttelse i form af sten udlagt omkring monopilen. Sedimentets glødetab (mål for organisk materiale) viste lave værdier på gennemsnitligt 0,6 %, og tørstofindholdet var konstant på ca. 83 %. Glødetab og tørstofindholdet varierede meget lidt i forhold til sedimentdybden eller afstanden til nærmeste mølle. Video-transekter på mølletårnene dokumenterede et atypisk hårdbundssamfund, der var tydeligt forskelligt fra naturlige stenrev i Kattegat. Hårdbundfaunaen spiller en meget mere dominerende rolle på tårnene end floraen og var domineret af søanemoner, og vegetationen havde ikke nogen stor dybdeudbredelse.

Summary

This technical report describes the results of a study conducted in 2022 of the benthos community in Anholt wind farm and a reference area with a similar bottom habitat in nearby Aalborg Bugt. The study followed a BACI-design and assessed temporal infauna changes inside and outside the wind farm before and after its construction. Infauna was sampled from an inside monitoring station in 2022 and compared to historical data from 1989-2010 on the same station before construction. Over 10 years of production, the fauna community had changed significantly, with more pronounced changes at the station inside the park than at the reference station. Significant changes were observed in total abundance, biodiversity, species richness and calculated environmental quality indices, but these were coupled to general changes in the Kattegat area rather than to the establishment of the wind farm. Additionally, to study radiating effects from turbines on the fauna community, carbon sedimentation was analysed along transects radiating from the wind turbines at 30 m, 80 m and 130 m distances. The distance to the nearest wind turbine had a weak significant effect on community composition, but only in the northward direction. Overall, there was no general radiating effect on seabed benthos abundance, diversity and species richness. Only one of the three studied monopiles had scour protection at the base. Video transects on the monopiles documented an atypical hard bottom community that was distinctly different from natural boulder reefs in the Kattegat. The hard bottom fauna plays a much more dominant role than the flora on the monopiles and was dominated by sea anemones. The vegetation did not have a large depth distribution.

1 Introduction

The general aim of this study is to describe the responses of benthic communities to physical seabed changes caused by the construction of Anholt wind farm in eastern Kattegat. Another aim is to set up and test a generalised sampling design for detecting direct and indirect effects of small- and large-scale seascape changes on benthic communities.

The general hypothesis is that seascape changes have both direct and indirect effects on benthic habitats and communities. Direct effects are those that arise directly from the introduction of artificial substrates and seascape elements (e.g. wind turbine monopiles, transformer stations, scour protection around turbines, cable trances etc.) and therefore primarily concerns the epibenthic fouling communities establishing on the introduced hard substrates. Indirect effects are structural changes occurring in other parts of the food web, propagating to the benthic community and affecting community composition. For instance, bottom-up processes may have indirect effects by altering the sedimentation regime through local hydrodynamics around the monopiles or presence of filtrating organisms on the monopiles. Top-down processes describe changes in the presence and distribution of predators feeding on benthos. Another hypothesis is that effects on benthos community composition depend on the spatial scale of the assessment. In this study, we define local effects (small-scale) as changes related to individual wind turbines (scour protection and cables). These local responses of the fauna community can be described by community composition changes that depend on the distance to nearest wind turbine. When changes can no longer be linked to individual wind turbines, regional effects (park effects or medium-scale effects) may occur. These can be documented by comparing community changes within the park with those in a predefined reference area.

We use the "distance-decay-of-similarity-method" to identify local effects in the vicinity of the wind turbines where similarity in species ensample between two samples is related to the distance between sampling positions. To assess the local effect of a wind turbine, we include the distance to nearest wind turbine as an explanatory factor and define a local effect if the distance to the nearest wind turbine has a greater impact on the decay of similarity than the distance between samples in any other random direction, following the rationale of Gray et al. (1990). We apply this method to quantitative abundance data on the infauna. For the hard bottom epifauna, the samples are not quantitative, and the artificial substrates may change with distance (from painted steel on the monopile to scour protection), and possible radiating effects on epibiota will be described qualitatively.

We also aim to test for regional/park effects as a result of general and large-scale changes of the seascape (substrate, small-scale bottom topography etc.) and displacement and aggregation of existing seascape elements, such as individual boulders to minor reef structures from, for example, cable trances etc. These large-scale effects are tested using a classical BACI-design (Before After Control Impact). We utilize data from a former monitoring station located inside the wind farm before its construction (1989-2010). This station was revisited in 2022 and serves as control for local effects of the wind turbines. Another monitoring station, 409 in Aalborg Bugt, serves as a control for general park effects (i.e. comparison with data from station 150).

This report is a technical description of the experimental design and presents all data collections, the results of statistical analysis, meta-analysis and relevant data extracted from national and AU databases. We expect to publish an article in a peer-reviewed journal within a year based on the data presented in this report and other projects as well as the latest knowledge from the scientific literature.

2 Aim

The aim of this project is to describe the present state of benthos communities in Anholt wind farm and to analyse changes inside and outside the park area occurring over the 10-year production period. The project will

- describe the hard bottom communities on hard substrates introduced by monopiles and associated scour protection.

and

- test if there is an effect on the infaunal and epifaunal communities on the natural seabed in the vicinity of the individual monopiles and to test if such an effect can be related to the distance to the monopiles.
- investigate if there is an effect of the turbine towers on the sediment carbon content near the monopiles.
- study if the wind farm has influenced the infauna community at park level using a BACI-design (Before-After-Control-Impact) based on available monitoring data from 1994-2021 inside and outside the park.

3 Study site, field campaign and data collection

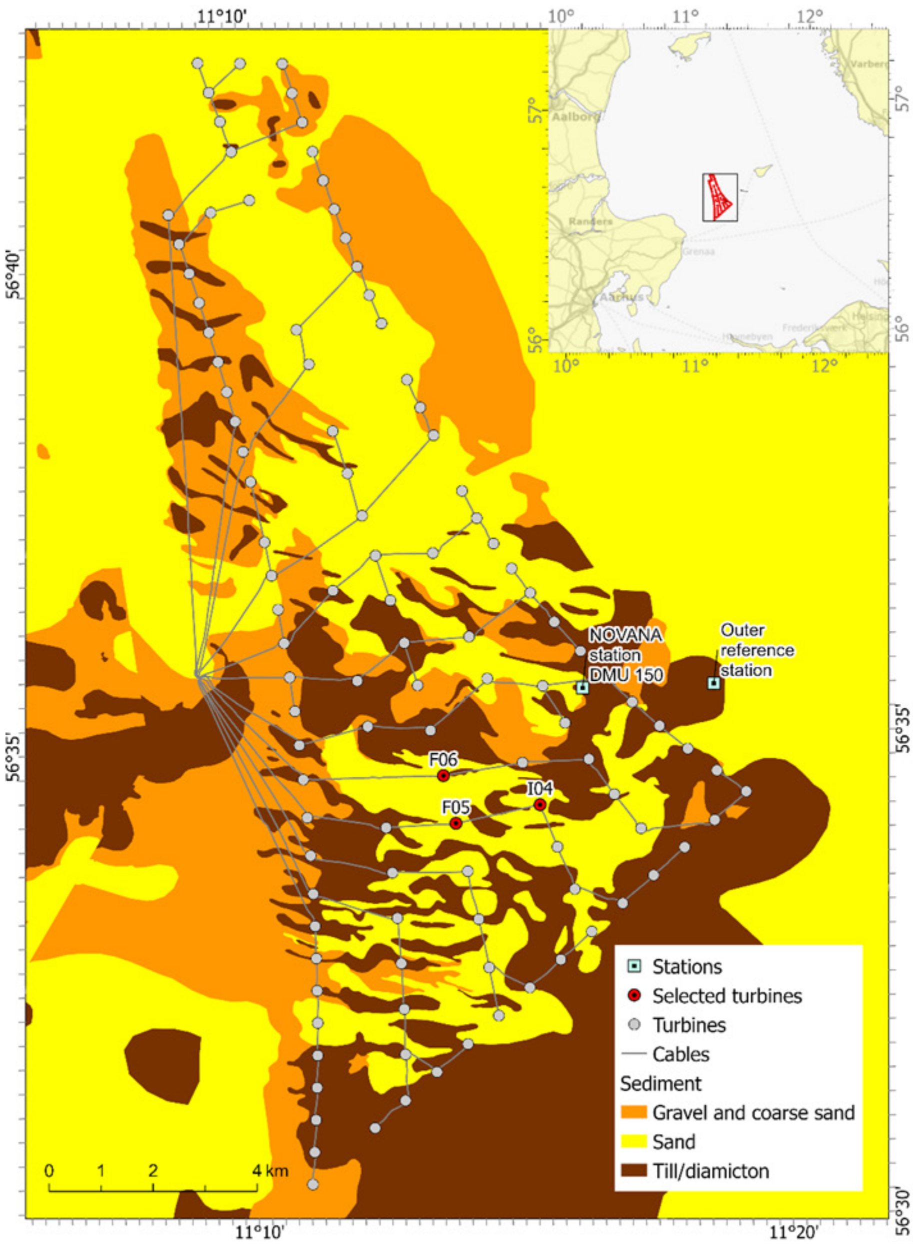
3.1 Selection of study site

Anholt wind farm, located between Grenå harbour and the island of Anholt, is a large wind farm with 111 turbines that are inter-connected with cables to three converter platforms (Figure 3.1). The wind farm was established between 31 December 2011 and June 2013.

Anholt wind farm has two benefits as a study site for local and regional effects on benthos. Firstly, it was established about 10 years before this project was proposed. This means that potential turbine tower and park effects on biota and sediment carbon turnover in response to an altered production regime have had ample time to reach steady state. Secondly, long-term benthic infauna data from the national monitoring program (NOVANA) were available from the area. Station 150 is located inside the park and was monitored during 1989- 2010. Sampling was ceased in 2010 due to restricted access to the farm area during the production period.

Anholt wind farm, located between Grenå harbour and the island of Anholt, is a large wind farm with 111 turbines that are inter-connected with cables to three converter platforms (Figure 3.1). The wind farm was established between 31 December 2011 and June 2013.

Figure 3.1. Anholt wind farm in Kattegat with mapped seabed sediments. The figure shows the location of the 111 turbines. The three turbines selected as sampling sites (I04, F05, F06), the old NOVANA infauna monitoring station (DMU 150) and an ROV reference station (outer reference station).

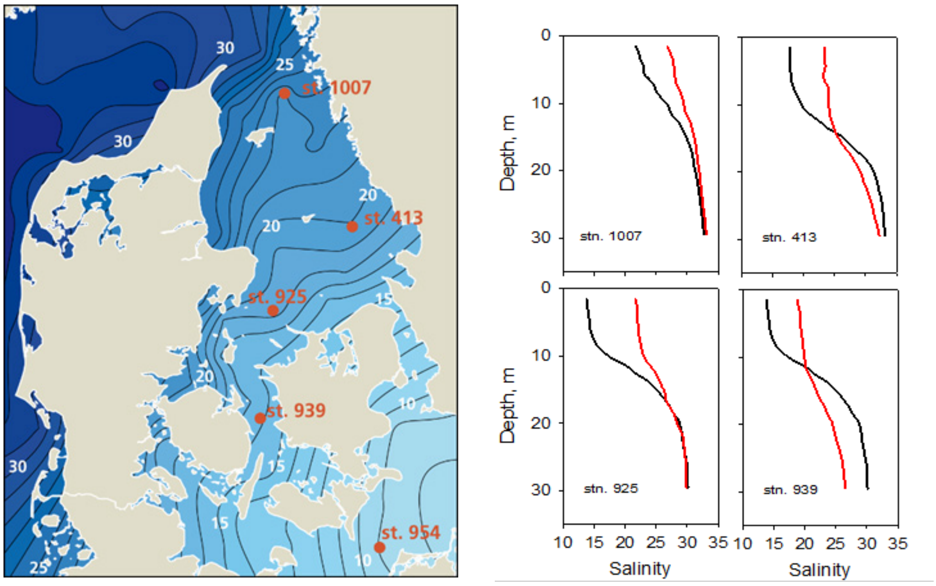


3.2 Physical conditions within Anholt wind farm

The water depth in the park area varies between 15 and 18 m (appendix 8.1). According to maps of the Anholt wind farm area, the seabed consists of three sediment types: "sand", "gravel/coarse sand" and "till/diamicton" (Figure 3.1). Seabed sediment maps show the sediment composition of the upper 0.5-1 m of the seabed. Till/diamicton are unsorted glacial deposits consisting of a heterogenous mixture of clay, sand, gravel and boulders of widely varying size and shape. The sediment present depends on materials brought by the ice and subsequent erosion processes. Sediment mapped as sand and coarse sand/gravel is sediment reworked by erosion and deposition.

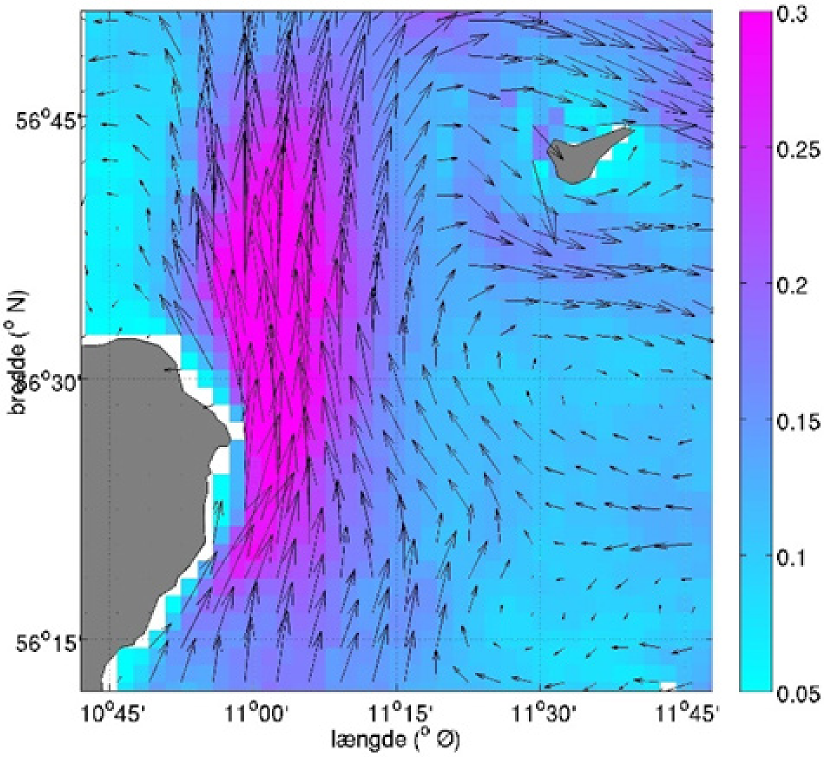
Nearby monitoring stations in the Kattegat and the Belt Sea, 925 and 413, represent the hydrography of the wind farm area. Yearly average salinity is approx. 20 in the upper 15 m of the water column. The Kattegat and the Belt Sea are located in the Baltic Sea-North Sea transition zone where the hydrography is characterised by a persistent halocline at about 15 m (Figure 3.2), which separates a surface layer of brackish outflowing Baltic water from a bottom layer of inflowing North Sea water. The sea surface temperature indicates a relatively enhanced mixing intensity southwest of the park area due to local upwelling (https://www.dmi.dk/friedata/observationer). Surface salinity fluctuates depending on current direction (i.e. in- or outflowing of the Baltic Sea). Since the water depth in the park area is close to pycnocline depth, it is uncertain how often the park area is covered by a layer of bottom water. The depth of the pycnocline in the park area also varies due to the east-west tilt of the pycnocline in the Kattegat area.

Figure 3.2. Left: Average surface (0-5 m) salinity from January to December. Right: Salinity profiles in winter (red curve) and summer (black curve) at the four monitoring stations marked on the left figure (from Dahl et al., 2003).



The modelled yearly average current flow is northward with a speed of 0.2-0.3 knots (She et al., 2007; Figure 3.3).

Figure 3.3. Modelled average current speed and direction (from She et al., 2007).



3.3 Field work

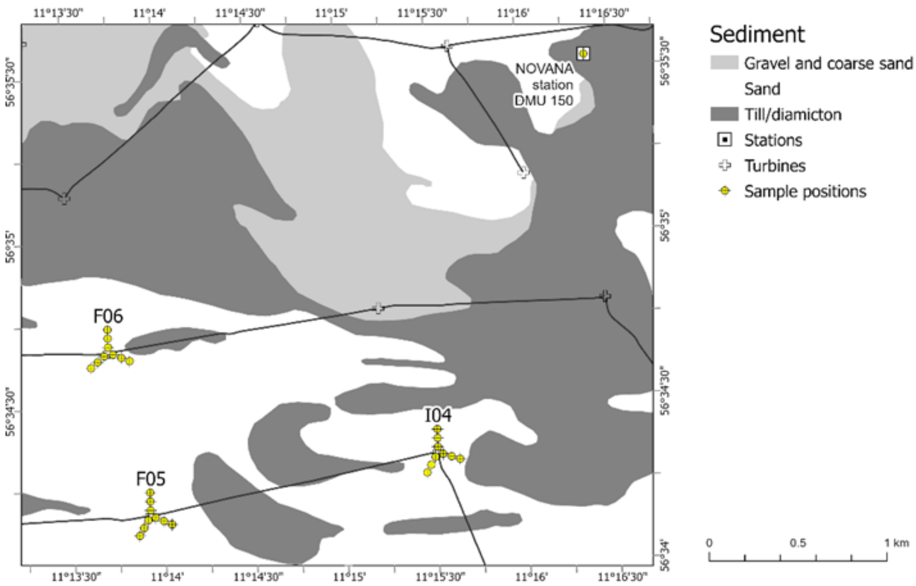
The investigation was carried out between 22 and 24 May 2023 using the AU research vessel Aurora, equipped with a dynamic position system allowing precise data sampling even close to the turbines.

Soft bottom fauna samples were taken during April-May as prescribed by NOVANA technical guideline M19 (Hansen & Josefson, 2020) where May differs from the period prescribed in NOVANA technical guideline M14 (Epifauna and macroalgae on boulder reefs; Dahl & Lundsteen, 2018) from 1st august to 5th September.

Turbines I-04, F-05 and F-06, located in the central part of the windfarm, were selected as sampling sites for the study of near-field effects. The old NOVANA monitoring station 150 served as reference station, and station 409 outside the farm area served as reference station for general effects within the wind farm area. The selection criteria for the sampling stations included comparable water depth and location inside the park, not at the edge.

At each turbine, three 130 m long transect lines were outlined in the directions north (N), south-east (SE) and south-west (SW) (Figure 3.4).

Three types of sampling gear were used: ROV, core sampler and pots.



Figur 3.4. Sampling transects around the tree selected turbines.

3.3.1 Data collection on epibenthic fauna and surface sediment composition

Video footage was collected at and around the three selected turbines I-04, F-05 and F-06. Additional footage was collected at NOVANA monitoring station DMU 150 and at a ROV reference site just east of the wind farm area (outer reference site, Figure 3.1). This data was gathered using an Oceanbotics SRV-8 ROV mounted with a HD camara. Footage was taken from the monopile, from the sea surface to the seabed and approx. 130 m from the turbines. Figure 3.5 illustrates the sampling. The seabed at DMU 150 and at the outer reference station was also surveyed over a 130-m transect.

Figure 3.5. ROV investigation of the monopile, the seabed close to the monopile and in the vicinity of the monopile.

The seabed transects were designed to cover an inner zone of the scour protection around the monopiles and the natural seabed outside the scour protection, but there was no scour protection on two of the three selected monopiles.

Epifauna and epiflora species composition and cover were estimated by visual interpretation of monopiles and seabed video footage. Cover was estimated from monopile subsections 0-0.5 m, 0.5–approx. 4 m, 7-10 m and 10-m to 0.5 m above the seabed and finally the last 0.5 m above the seabed. The depth interval between 4 and 7 m was complex with several protruding elements. This complexity was included in the description of the artificial substrate together with depth as it turned out that this influenced the biotic communities.

Description of the biological communities and sediment composition of the seabed around the monopiles was divided into two sub-transects, one in near vicinity of the monopile and one covering the rest of the transect.

Besides immobile/sessile species cover estimates, fish and crab abundances were recorded. Seabed sediment composition was described according to the NOVANA technical guideline for reef and bubble reef monitoring (Dahl & Lundsteen, 2018, in Danish). Biological composition description followed a modification of this, which meant that sampling for species identification/verification was not conducted. It was not possible, or only partly possible, to describe the cover of species living beneath the multilayered macroalgae communities using an ROV. A final modification was made to describe species cover on the seabed with no distinction between stable and unstable substrates. The modifications were necessary due to the constraints of using an ROV and not a diver-based solution.

3.3.2 Near-turbine infauna sampling

Infauna sampling was conducted along the three transects (N, SE and SW) surveyed by the ROV at 30, 80 and 130 m distance from the tower of the three selected turbines and along the three outlined transects. The sampling position was guided by a GPS mounted on Aurora's crane, which handled the core sampler (Figure 3.6). The sampling positions are listed in appendix 2.

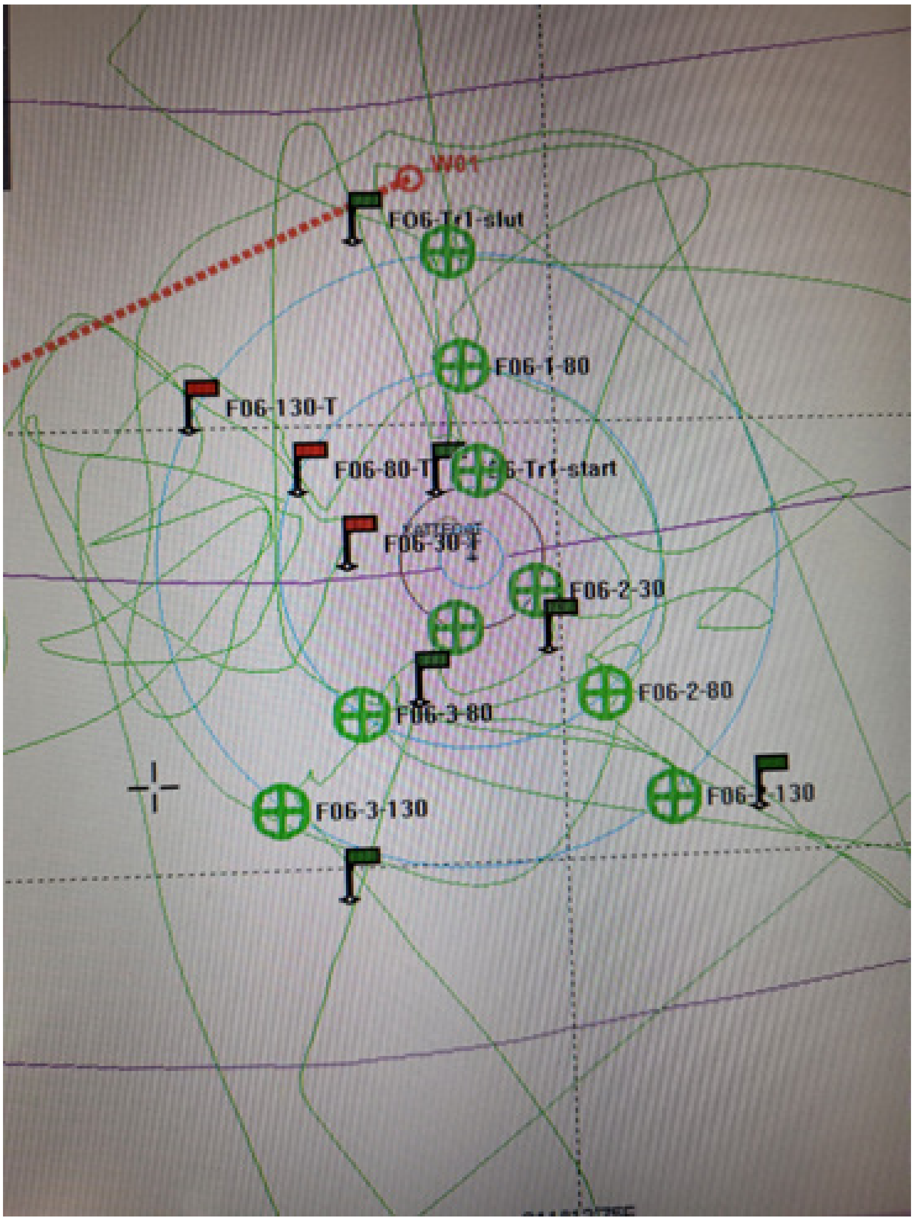


Figure 3.6. Example of benthic infauna sampling around wind turbine F06 located in the centre. The nine green marks represent the actual sampling position measured at the tip of the crane handling the benthic sampler. Screen dump from R/V Aurora's navigation system.

A Haps corer with a vibrator securing sampling even in coarse sediment was used (Figure 3.7). At each sampling site, five replicates were taken of which four were analysed for species-specific abundance and biomass, while the fifth was stored.

Sampling was carried out without anchoring using dynamic positioning (DP). R/V Aurora is a specialised vessel for marine research and its DP system ensures positioning accuracy during sampling. The Vibro-Haps corer was equipped with a 34 cm long cylinder with a diameter of Ø=13.5 cm, sampling 0.0143 m^2 of the seabed (Figure 3.6). When the Haps frame was set on the bottom, the vibro-aggregate was activated from the deck for about five seconds on sandy sediments. For a detailed description of the sampling and a chronological survey report see DCE (2022).

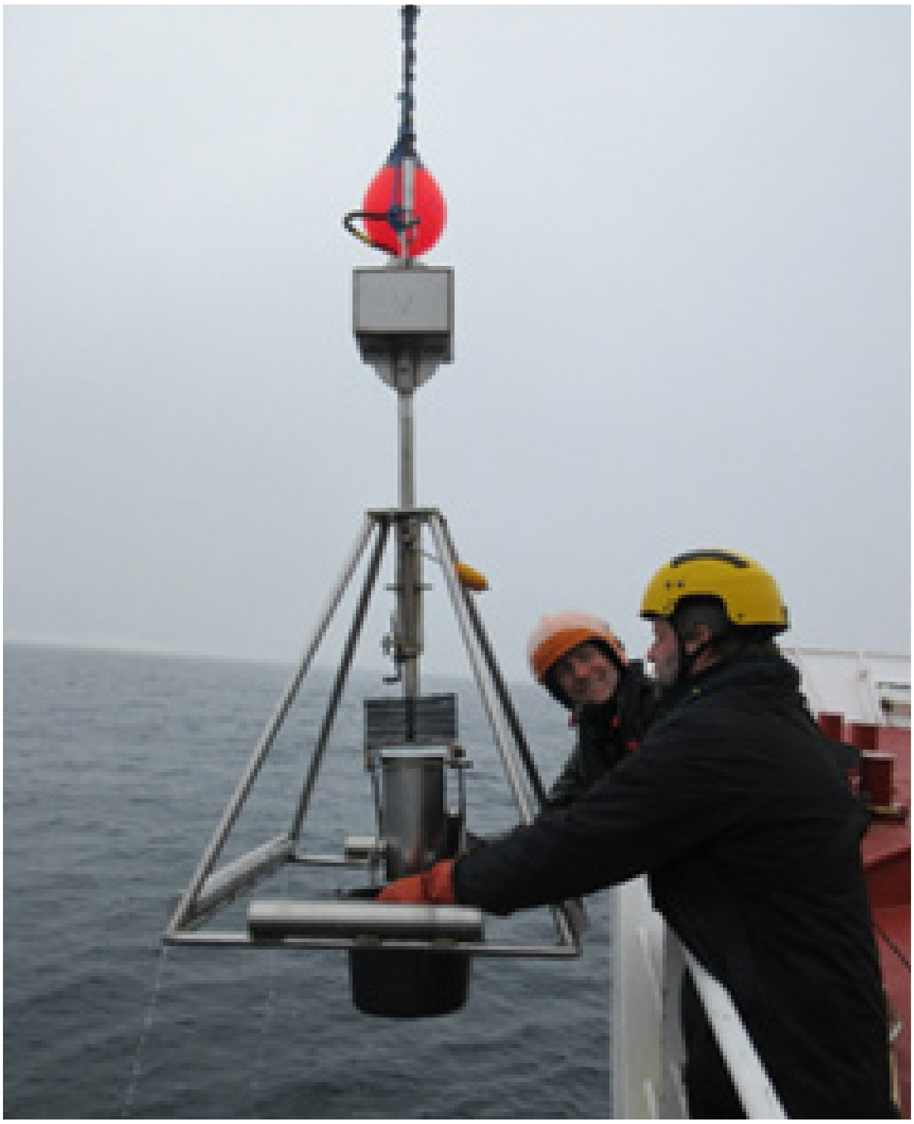


Figure 3.7. Haps corer equipped with a vibro-aggregate. Photo: Karsten Dahl

Upon successful retrieval of a Haps corer on deck, a 20 ml subsample of surface sediment was taken with an open-cut syringe for determination of dry matter content and ignition loss.

Samples were then sieved onboard the Aurora R/V using a 1 mm sieve (square holes). All material retained on the sieve was preserved in 70% ethanol (final volume), labelled (both inside and outside the container) and stored for later analysis in the laboratory.

3.4 Near-turbine sediment ignition loss

From every Haps sample, small surface sediment cores (length 8 cm long, Ø diameter 1.5 cm) were collected before sieving (see above) using an open-cut syringe, after which they were stored at 5°C and subsequently sliced into depth intervals of 0-1 cm, 1-2 cm, 2-3 cm, 3-5 cm and 5-8 cm. The samples were stored frozen and, after thawing, analysed for dry matter content and ignition loss following NOVANA guidelines (Kaas & Markager, 1998) according to which the samples were weighed, dried at 105°C for 24 hours, weighed again to obtain dry matter content and finally burned at 550°C for two hours to get ash free dry weight (AFDW).

3.5 Infauna sampling at station 150 and ROV reference station

Data from the former NOVANA infauna monitoring station "150", located within the present Anholt wind farm area, were retrieved from the database (see the sampling location in Figure 3.4 and Appendix 1 including bathymetry). Monitoring was undertaken from 1989 to 2010 and includes a total of 109 samples taken with a core sampler without vibro assistance.

NOVANA station 409 was selected as reference outside the Anholt wind farm area, having similar bottom type (sand/coarse sand), water depth, overlapping time series and sampling method (point station with replicates). A total of 194 samples were retrieved from the period 1989-2021.

3.6 Pot fishing

For all three turbines, 12-hour baited pot fishery was conducted along transect 1 at 30, 80 and 130 m distance, and the catches were specified, counted and then released.

3.7 Extraction of existing data

Infauna data from station 150 inside the wind farm and station 409 outside the wind farm were extracted from the NOVANA database for the period 1989-2010 for station 150 and from 1989-2023 for station 409.

In addition, epibenthic data were retrieved from the AU database hosting national reef monitoring data. The three closest reef monitoring locations, Kim's Top, Schultz's Grund and Store Middelgrund sampled in 2023, were used as epibiota reference sites for species composition.

4 Data analysis and statistical methods

4.1 ROV investigation

Visual identification of species was done by experienced taxonomists Karsten Dahl and Helle Buur to ensure a final data format of species-specific cover percentages.

4.2 Soft bottom laboratory work

The infauna samples were analysed in the laboratory according to NOVANA technical guideline M-19 for soft bottom fauna monitoring (Hansen & Josefson, 2014). In short, all retained materiel was sorted under an inverted microscope by trained personnel to recover all fauna, which were then divided into major taxonomic groups. A taxonomist identified the animals individually to the lowest possible taxon. The fauna were counted and weighed taxon by taxon, sample by sample. In accordance with the technical guidelines, the animals were stored for 3-6 months before weighing to allow the soft tissue weight to stabilise in alcohol. The final data format in the national database includes species-specific weight and abundance per sample. Finally, quality assurance was conducted, involving repeated sorting of the same sample by other specialists, crosscheck and validation of their taxonomic work at regularly held inter-calibration workshops and a final check of syntax against the WoRMS database.

4.3 Multi-variate statistics

The relationship between environmental parameters and univariate fauna community measures were determined using the statistical software package Sigma Plot®, and multivariate analysis of fauna community composition, including diversity and species richness indices, was made using the software package PRIMER (v.7) ®. Community similarity of samples was expressed by the Bray-Curtis similarity index following square root transformation of abundance data, and transformation was checked for suitability using shade plots.

5 Results

5.1 Seabed characteristics observed by ROV surveys

Turbine I04 had scour protection consisting of large cobbles/small boulders (20-30 cm) around the monopile. Turbines F05 and F06 had no scour protection but were surrounded by banks of dead blue mussel, *Mytilus edulis*, shells, which covered the seabed completely for approx. 4-5 m in the south-west and south-east direction and even further in the northern direction (Figures 5.1 and 5.2). The shells most likely originate from a mussel populations on the top of the turbine monopile.

The sediment outside the scour and shell beds around I04 and F05 consisted of fine sand with scattered shells or shell fragments (Figure 5.1, upper). The sediment around turbine F06 consisted of a mixture of sand and coarse sand with scattered minor pebbles (<20 mm). Larger shells of ocean quahog, *Arctica islandica,* and *Mya* species were found on top of the sediment around F06 (Figure 5.1, lower).

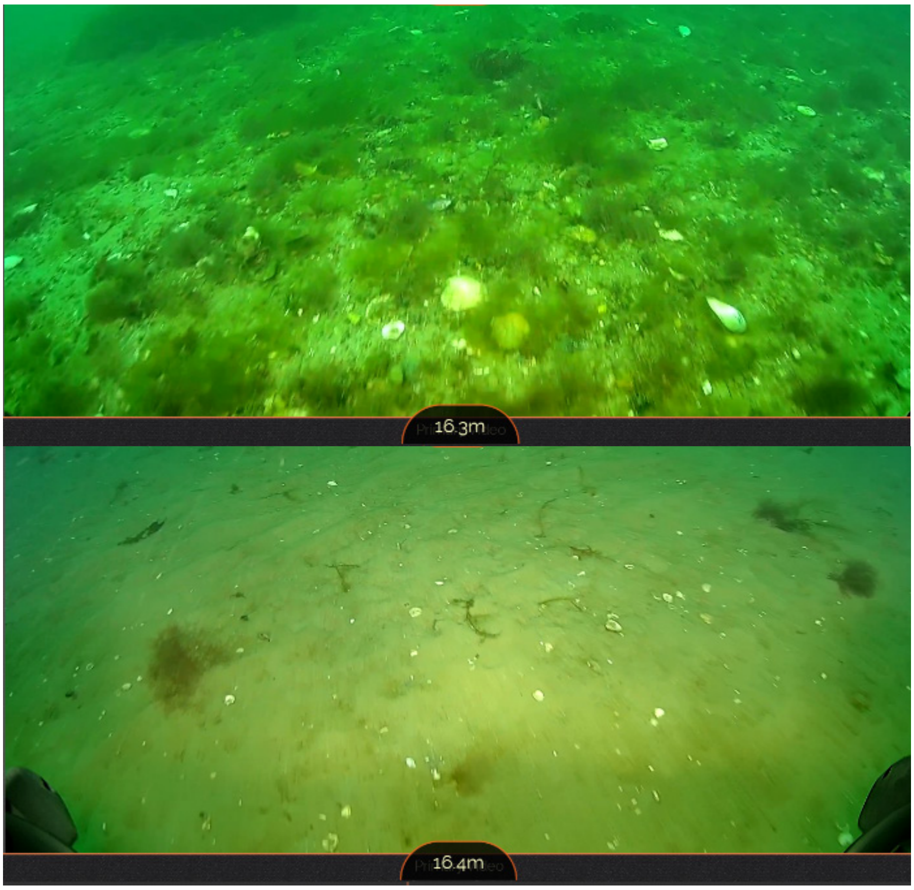


Figure 5.1. Upper photo: Coarse sandy sediment with minor cobbles and shells of ocean quahog, *Arctica islandica*, on the top sediment around turbine I04. Lower photo: Sandy sediment with shell fragments around turbine F06. Photos: Karsten Dahl

North of turbine F05, two depressions in the seabed with gravel and a single minor boulder on the edge were observed. Drifting macroalgae had aggregated in the depression, which was investigated.

The sediment around the old NOVANA station DMU 150 and the ROV reference station outside the farm area consisted of coarse sand with scattered pebbles and high densities of large ocean quahog shells and large *Mya* sp. shells. A few boulders were observed, consistent with the classification of the seabed as glacial deposits (Till/diamicton). The sediment around F06 was similar to that at the old NOVANA station DMU 150 and the outer reference station.

5.2 Sediment carbon content

Sediment dry matter content and ignition loss were measured in 365 samples from the three radiating transects around the wind turbines (350 samples) and from station DMU 150 (15 samples). In all samples, the dry matter content was very high, on average 81,5 ± 2.1% for the transect samples and 83 ± 1.4% for station 150 (Table 5.2). The variation was minimal, and no significant differences occurred between station 150 and the transects. No significant pattern was related to transect, distance to turbine tower or sediment depth. Sediment ignition loss measurements were all very low, generally below 1%, with a grand average of 0.63%. There were no significant differences between station 150 and the wind turbines or among turbine towers, transects or distances from the tower. The only significant pattern was related to sediment depth, where ignition loss declined linearly from 0.68% at the sediment surface (0-1 cm) to 0.52% at 8 cm depth (linear regression).

Table 5.1. Ignition loss in sediment core samples. Columns denote transect N = transect 1, SW = transect 2 and SE = transect 3, grouped by turbine number. Row names denote distance from the turbine, and subfixes denote sediment sample depths. All data are averages of Haps samples (2-4 replicates). ND = not determined.

Distance Depth		**F05**			**F06**			**I04**	
	TR 1	TR 2	TR 3	TR 1	TR 2	TR 3	TR 1	TR 2	TR 3
30m_0.5cm	ND	0.94	ND	0.63	0.73	0.69	0.58	0.61	ND
30m_1.5cm	ND	0.45	ND	1.16	0.66	0.64	0.56	0.57	ND
30m_2.5cm	ND	0.52	ND	0.65	0.79	0.78	0.55	0.55	ND
30m_4.0cm	ND	0.53	ND	0.87	0.66	0.68	0.58	0.52	ND
30m_6.5cm	ND	0.66	ND	0	0.63	0.97	0.56	0.39	ND
80m_0.5cm	1,09	0.53	0.52	0.57	0.8	0.77	0.52	0.58	0.54
80m_1.5cm	1,13	0.51	0.44	0.52	0.68	0.82	0.59	0.54	0.51
80m_2.5cm	1,05	0.67	0.41	0.52	0.8	0.67	0.45	0.54	0.54
80m_4.0cm	0,89	0.48	0.44	0.51	0.79	0.62	0.48	0.51	0.51
80m_6.5cm	0,68	0.5	0.36	0.45	0	0	0.44	0.54	0.58
130m_0.5cm	0,81	0.57	0.67	0.56	0.79	0.65	0.65	0.53	0.57
130m_1.5cm	0,94	0.43	0.69	0.62	0.74	0.71	0.57	0.62	0.53
130m_2.5cm	0,68	0.41	0.57	0.69	0.8	0.68	0.52	0.57	0.48
130m_4.0cm	1,02	0.47	0.6	0.67	0.8	0.65	0.49	0.53	0.47
130m_6.5cm	0,72	0.51	0.6	0.62	0.93	0.55	0.23	0.39	0.62

Table 5.2. Sediment dry weight content of fauna samples. Columns denote transect N = transect 1, SW = transect 2 and SE = transect 3, grouped by turbine number. Row names denote distance from the turbine, and subfixes denote sediment sample depths. All data represent averages of three Haps samples (2-4 replicates). ND not determined

Distance Depth	F05			F06			I04		
	TR 1	TR 2	TR 3	TR 1	TR 2	TR 3	TR 1	TR 2	TR 3
30m_0.5cm	ND	79	ND	84	82	82	81	80	ND
30m_1.5cm	ND	80	ND	84	85	83	81	81	ND
30m_2.5cm	ND	81	ND	83	84	82	82	81	ND
30m_4.0cm	ND	81	ND	82	83	83	81	81	ND
30m_6.5cm	ND	77	ND	ND	78	78	81	79	ND
80m_0.5cm	83	82	81	80	84	84	81	81	80
80m_1.5cm	83	83	82	80	85	83	81	81	81
80m_2.5cm	83	83	83	82	83	83	83	82	81
80m_4.0cm	83	82	82	82	81	81	82	82	81
80m_6.5cm	79	80	80	81	ND	ND	76	76	79
130m_0.5cm	83	81	81	81	84	82	81	81	81
130m_1.5cm	81	82	82	81	84	82	81	82	81
130m_2.5cm	81	83	82	81	84	83	82	82	82
130m_4.0cm	80	83	81	59	83	82	82	82	82
130m_6.5cm	81	81	80	78	81	81	81	ND	80

5.3 Epibenthic flora and fauna

5.3.1 Biology on the turbine towers

The epibiota on turbine towers, shell beds around turbines F05 and F06, scour protection around turbine I04 and the epibenthic biota on the natural seabed are presented in Table 5.3 for macrophytes, in Table 5.4 for invertebrate fauna and in Table 5.5 for fish.

All vertical transects on the three towers showed reduced biota cover just below the sea surface compared to the rest of the surface layer. Most dominant at this depth interval was the opportunistic brown algae species sea lace, *Corda filum*, which dominated on the north side (shadowed side) of all towers (Table 5.3).

Between 0.5 m and the junction zone on the towers about 4 m from the surface, the turbine was covered almost 100% by algal vegetation. Filamentous red algae, the brown algae maiden's hair, *Ectocarpus penicilatus*, and the larger perennial leaf-forming red algae sea beech, *Delesseria sanguinea*, were the most dominant species. Some video sequences revealed a dense cover of blue mussels underneath the vegetation on the turbine tower. The cover of Mytilus given in table 5.3 is likely a very conservative estimate.

The monopile junction comprises a 3 m depth interval from 4-7 m with several protrusions. The biology on the outer edge of the protrusions was similar to that in the depth interval above, with dominance of macroalgae species. In the area beneath protrusions at the junction, the community resembled that below the junction.

Below the junction, the algae were scattered and had low cover, and the community became dominated by plumose anemone, *Metridium senile* (Table 5.4).

Below 10 m depth, vegetation was almost absent and plumose anemones were almost completely dominant. Blue mussels were observed in the upper depth range. Breadcrumb sponge, *Halichondria panicea*, was observed with low cover. Scattered individuals of common starfish, *Asterias rubens,* spiny starfish, *Martasterias glaciale*, and dead men's fingers, *Alcyonium digitatum*, occurred in very low numbers near the bottom. One common sea urchin, *Echinus esculentus*, and a few black brittle stars, *Ophiocomina nigra*, were observed. Two crustacean species, barnacle, *Balanus Balanus*, and sea toad crab, *Hyas Araneus*, were also recorded.

The fish goldsinny wrasse, *Ctenolabrus rupestris*, was observed along all vertical transects; however, its numbers were 4-5 times higher at I04 with scour protection than at the two other turbines (Table 5.5). In addition, one short-spined sea scorpion, *Myoxocephalus scorpius,* was obsersved hanging on the upper vertical part of one tower.

The biological communities found on ROV video footage differ from those observed by divers at natural reef sites in the Kattegat, and the difference cannot be attributed to differences in sampling methods and sampling time alone (Table 5.6). The vegetation on the wind turbines showed a more distinct zonation and was restricted to the upper part of the water column, and it was dominated by annual filamentous algae species, while no large perennial brown algae like *Fucus* or *Laminaria* species occurred. Blue mussels were more abundant on the wind turbines than on reef sites at similar depths. Fauna communities dominated over macroalgal communities from 7 m depth downwards, with plumose anemones being completely dominant from 10 m. On natural reef sites, macroalgal vegetation usually dominates down to 18-23 m depth in Kattegat.

Figure 5.2. Biological zonation on turbine towers in Anholt wind farm. Photos: Karsten Dahl

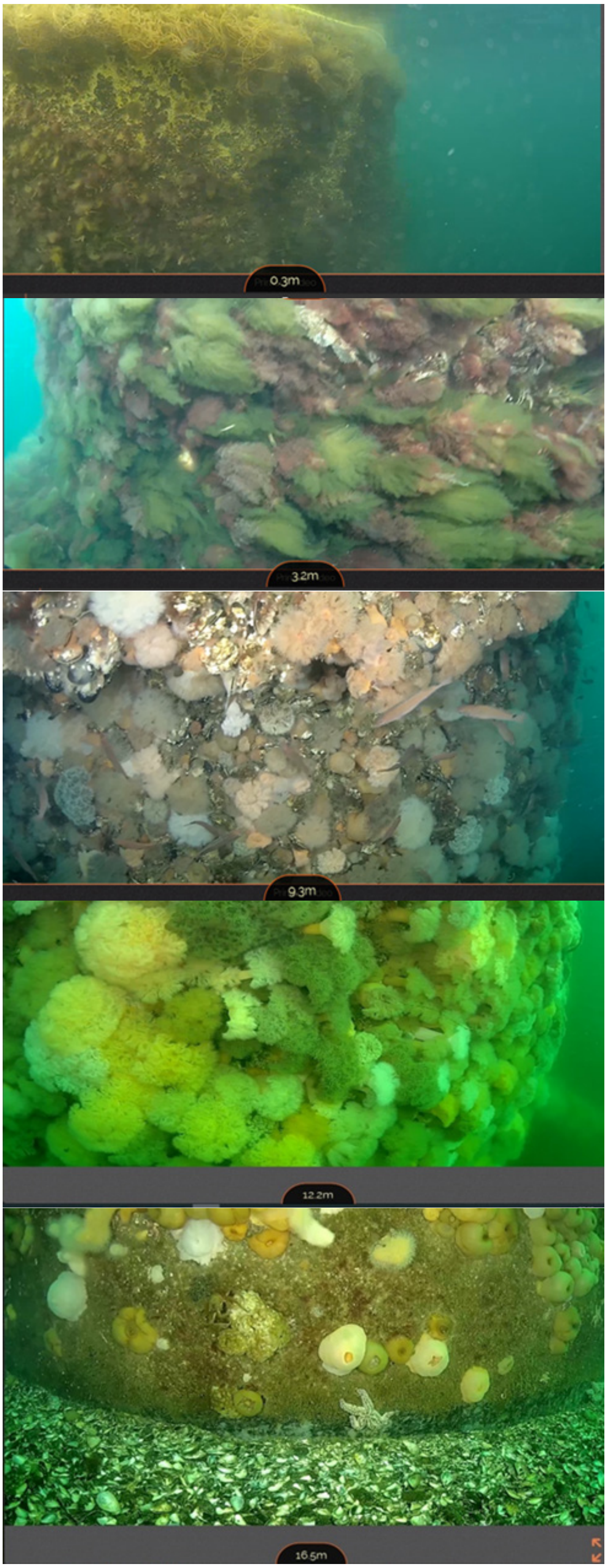


Table 5.3. Comparison of macroalgae depth zonation cover (%) on the wind turbines and natural stone reefs in the area (Kim Top, Schultzs Grund and Store Middelgrund).

Depth interval (m)	Type	Class	Anholt wind farm	Kims Top	Schultzs Grund	Store Middelgrund
0.5-6	Algae	Chlorophyceae	1.1	No data	0.1	No data
		Florideophyceae	67.7	No data	189.7	No data
		Fucophyceae	20.1	No data	67.0	No data
		Phaeophyceae	0.0	No data	0.1	No data
	Fauna	Anthozoa	5.6	No data	0.1	No data
		Asteroidea	0.1	No data	0.1	No data
		Bivalvia	18.8	No data	0.1	No data
		Crustacea	12.5	No data	0.2	No data
		Demospongiae	0.6	No data	15.0	No data
		Echinoidea	0.0	No data	0.0	No data
		Gymnolaemata	0.0	No data	60.3	No data
		Hydrozoa	0.0	No data	1.4	No data
		Pisces	0.1	No data	0.1	No data
		Polychaeta	0.0	No data	0.1	No data
		Pycnogonida	0.0	No data	0.1	No data
		N observations	***9***		***1***	
6.1-10	Algae	Chlorophyceae	0.0	No data	0.1	0.1
		Florideophyceae	14.3	No data	215.1	314.1
		Fucophyceae	0.0	No data	33.1	7.4
		Phaeophyceae	0.0	No data	3.0	0.1
	Fauna	Anthozoa	75.3	No data	0.0	0.1
		Ascidiacea	0.0	No data	0.1	0.1
		Asteroidea	0.3	No data	0.1	0.1
		Bivalvia	5.3	No data	0.1	0.1
		Calcarea	0.0	No data	0.1	0.0
		Crustacea	3.8	No data	0.2	0.2
		Demospongiae	3.1	No data	10.0	40.0
		Gymnolaemata	0.0	No data	32.6	30.6
		Hydrozoa	0.0	No data	0.1	0.2
		Phaeophyceae	0.0	No data	3.0	0.1
		Pisces	0.5	No data	0.1	0.2
		Polychaeta	0.0	No data	0.1	0.1
		Pycnogonida	0.0	No data	0.0	0.1
		Stenolaemata	0.0	No data	0.1	0.1
		N observations	***9***		***1.0***	***1.0***
10.1-18	Algae	Chlorophyceae	0.0	0.0	0.1	0.1
		Florideophyceae	1.0	145.4	78.0	164.5
		Fucophyceae	0.1	47.7	44.2	62.8
		Phaeophyceae	0.0	2.6	5.3	1.2
	Fauna	Anthozoa	83.9	5.1	0.2	0.1
		Ascidiacea	0.0	0.1	0.1	0.1
		Asteroidea	0.1	0.7	0.3	0.6
		Bivalvia	2.8	0.1	6.9	0.1
		Calcarea	0.0	0.1	0.0	0.0
		Crustacea	8.5	0.3	0.3	0.2

Continued….

Depth interval (m)	Type	Class	Anholt wind farm	Kims Top	Schultzs Grund	Store Middelgrund
		Demospongiae	1.6	0.1	5.0	1.5
		Echinoidea	0.0	0.1	0.1	0.0
		Gastropoda	0.0	0.1	0.2	0.1
		Gymnolaemata	0.0	32.1	29.5	6.9
		Hydrozoa	0.0	2.8	1.7	1.7
		Ophiuroidea	0.0	0.0	0.1	0.0
		Pisces	0.5	0.7	0.2	0.3
		Polychaeta	0.0	0.2	0.1	0.7
		Polyplacophora	0.0	0.0	0.1	0.1
		Stenolaemata	0.0	10.2	0.1	0.2
		N observations	**9**	**2**	**4**	**2**

5.3.2 Biology on shell beds and scour protection

Algae cover was well developed on the seafloor at 16 m depth where cobbles and small boulders made up the scour protection around turbine I04. Sea beech and sea oak, *Phycodrus rubens*, covered almost 1/3 of the cobbles/boulders. In addition, filamentous algae were noted but no large leaf-forming brown species like sugar kelp, *Saccharina latissimi* (Table 5.3). Scattered sea anemones and a single crab were observed (Table 5.4).

The biology on the shell beds at the two towers without scour protection differed substantially from the scour protection at the third tower. Perennial red algae species had very low cover, and the sparse vegetation was dominated by filamentous species. The shell bed on the northern side of turbine F06 was partly covered by detached and drifting sugar kelp, aggregated behind the tower according to the current direction. Overall crab abundance was 1-2 at four out of the six transects. The starfish *A. rubens* and *M. intestinalis* were the most abundant fauna organisms on the shell bed. More than four flounders (*Platichthys flesus)* were observed around F05 and F06 but none around scour-protected IO4.

5.3.3 Biology on the sandy seabed

Macrophyte cover was low on the sandy seabed around the six transects along towers I04 and F05 (Table 5.5). Filamentous algae and the brown algae desmarest's prickly weed, *Desmarestia aculeata,* often occurred attached to shells, and sugar kelp was seen drifting, with or without attached shells. The coarser sand with scattered smaller pebbles around F06 had a higher cover of both filamentous algae species and desmarest's prickly weed. Various starfish and crab species were observed, but their numbers declined with increasing distance from the towers.

5.3.4 Station DMU 150 and the ROV reference station

The brown algae desmarest's prickly weed was quite common at both DMU 150 and the outer ROV reference station east of the park (Table 5.3). Scattered perennial red algae species were also observed. Only a few fish species occurred along the approximately 100 m long transects, all in very low numbers (Table 5.3). Epibenthic invertebrate fauna was restricted to common starfish, shore crab (*Carcinus maenas*), great spider crab (*Hyas araneus)* and common hermit crab (*Pagurus bernhardus)* (Table 5.4). There were some similarities with the epibenthic communities on the coarse sandy seabed around F06. However, spiny starfish was not observed at 150 or the ROV station, in contrast to the three transects around F06.

Table 5.4. Macroalgae species and their estimated cover (%) at different depths around the investigated turbine towers (location and transects), the scour protection (I04), shell beds (F05 and F06) and the surrounding seabed. Estimated cover may exceed 100%.

Location	Direction Transects	Substrate	Depth (m)	Delesseria sanguinea	Phycodrys rubens	Phyllophora/coccotylus	Red filamentous algae	Chorda filum/ Halosiphon tomentosus	Desmarestia aculeata	Ectocarpus	Saccharina latissima	Cladophora rupestris
I04	N	Monopile	0-0.5					30				
			0.5-5	40			20			15		2
			7.3-10.0				10					
			10.0-15.7				1					
			15.7-16.3	Bad sequence/no data								
		Scour bed	16.5	25	2		5		0.1	35		
		Sandy seabed	16.7			0.1	5		3	1		
I04	SE	Monopile	0-0.5									
			0-4.3	20			50			20		5
			7-10	1			20					
			10-15.7									
			15.7-16.3									
		Scour bed	15.4	25	5		70				0.1	
		Sandy seabed	-16.2				2		2		0.1	
I04	SW	Monopile	0-0.5				50					
			0.5-4.5	0.1			70			10		1
			7.0-10.0				7					
			10.0-15.7							1		
			15.7-16	Bad sequence/no data								
		Scour bed	16.0	Bad sequence/no data								
		Sandy seabed	16.5				1		3		2	

Continued….

Location	Direction Transects	Substrate	Depth (m)	Delesseria sanguinea	Phycodrys rubens	Phyllophora/coccotylus	Red filamentous algae	Chorda filum/ Halosiphon tomentosus	Desmarestia aculeata	Ectocarpus	Saccharina latissima	Cladophora rupestris
F05	N	Monopile	0-0.5					50				
		442 MB	0.5-3.4	20			70	1		5		1
			6.7-10.0	0.1								
			10.0-16.0									
			16.0-16.5									
		Shell bed	16.0				1				5	
		Sandy seabed	16.5	5			10		5			
		Gravel bed with scattered stones			0.1		50				5	
F05	SE	Monopile	0-0.5				50	2				
			0.5-3.8	0.1			65			30		
			6.7-10.0	0.1								
			10.0-16.7									
			16.7-17.2									
		Shell bed	17.2				10		2		5	
		Sandy seabed	17.3		0.1		4		4		4	
F05	SW	Monopile	0-0.5					50		10		
			0.5-3.7	15			65	1		10		0.1
			6.6-10.0	Bad sequence/no data								
			10.0-16	Bad sequence/no data								
			16-16.5	Bad sequence/no data								
		Shell bed	16.0									
		Sandy seabed	16.4				5		5		5	
F06	N	Monopile	0-0.5					20				
			0.5-3.8	15			85	10		5		
			6.7-10.0	1			30					
			10.0-15.0	0.1								
			15.0-16.1									

Continued….

Location	Direction Transects	Substrate	Depth (m)	Delesseria sanguinea	Phycodrys rubens	Phyllophora/coccotylus	Red filamentous algae	Chorda filum/ Halosiphon tomentosus	Desmarestia aculeata	Ectocarpus	Saccharina latissima	Cladophora rupestris
		Shell bed	16.4		0.1				0.1		50	
		Coarse sand with pebbles and shells	16.5	0.1	2	1	7		7	5	7	
F06	SE	Monopile	0-0.5	No data due to tower construction								
			0.5-4	No data due to tower construction								
			7-10.0	45			5			2		
			10.0-15.7	5			0.1					
			16.0-16.5									
		Shell bed	16.4		0.1		20		0.1		2	
		Coarse sand with pebbles and shells	16.6		3	0.1	20		20		5	
F06	SW	Monopile	0-0.5									
			0.5-3.8	1			35	3		60		
			7-10.0	35			5					
			10.0-15.7	2	0.1							
			15.7-16.1									
		Shell bed	16.4		1		2		2		3	
		Coarse sand with pebbles and shells	16.6	0.1	1	0.1	20		3			
NOVANA st. 150		Coarse sand with pebbles and shells	16.8	0.1	0.1	0.1	5		20		5	
ROV outer REF station		Coarse sand with pebbles and shells	17.2	0.1	0.1	0.1	5		45		10	

Table 5.5 Identified invertebrate fauna species with percentage cover and species abundances given in brackets. Data are given in different depth intervals, scour protection (I04), shell beds (F05 and F06) and the surrounding seabed around turbine towers (locations and transects)

Location	Direction (transects)	Substrate	Depth (m)	*Mytilus edulis*	*Metridium senile*	*Haliclona urceolus*	*Halichondria panica*	*Alcyonium digitatum*	*Asterias rubens*	*Martasterias glaciale*	*Astropecten irregularis*	*Henricia sanguinolenta*	*Ophiocomina nigra*	*Echinus esculenta*	*Balanus balanus*	*Cancer pagurus*	*Carcinus maenas*	*Hyas araneus*	*Pagurus bernhardus*	*Electra pilosa*
I04	N	Monopile	0-0.5												50					
			0.5-5	30					0.1 (1)						20					
			7.3-10.0		80										10					
			10.0-15.7		90		2													
			15.7-16.3									Bad sequence/no data								
		Scour bed	16.5		0.1				0.1 (3)											
		Sandy seabed	16.7																	0.1
I04	SE	Monopile	0-0.5																	
			0-4.3	30					0.1 (2)						20					
			7-10	20	80		2		2						5					
			10-15.7	20	85										5					
			15.7-16.3		20					0.1 (1)										
		Scour bed	15.4		5				0.1								0.1 (1)			5
		Sandy seabed	-16.2						0.1(1)										0.1(1)	
I04	SW	Monopile	0-0.5	100																
			0.5-4.5	20											20					
			7.0-10.0		80	0.1														
			10.0-15.7		80										3					
			15.7-16			Bad sequence/no data														
		Scour bed	16.0			Bad sequence/few data			0.1 (2)	0.1 (1)										
		Sandy seabed	16.5						0.1 (3)	0.1 (1)	0.1 (1)									

Continued….

Location	Direction (transects)	Substrate	Depth (m)	*Mytilus edulis*	*Metridium senile*	*Haliclona urceolus*	*Halichondria panica*	*Alcyonium digitatum*	*Asterias rubens*	*Martasterias glaciale*	*Astropecten irregularis*	*Henricia sanguinolenta*	*Ophiocomina nigra*	*Echinus esculenta*	*Balanus balanus*	*Cancer pagurus*	*Carcinus maenas*	*Hyas araneus*	*Pagurus bernhardus*	*Electra pilosa*
F05	N	Monopile	0-0.5	50											10					
	442 MB		0.5-3.4	20					0.1 (7)						20					
			6.7-10.0	20	70				0.1 (4)						5					
			10.0-16.0	2	90				0.1 (1)						10					
			16.0-16.5		10			0.1(2)	0.1 (3)	0.1 (2)					0.1					
		Shell bed	16.0						0.1 (3)	0.1 (1)										
		Sandy seabed	16.5		0.1(1)				0.1 (1)	0.1 (2)						0.1(1)	0.1(1)		0.1(1)	
		Gravel bed with scattered stones														0.1(2)				
F05	SE	Monopile	0-0.5																	
			0.5-3.8	25					0.1 (2)											
			6.7-10.0	0.1	95															
			10.0-16.7		99															
			16.7-17.2		50				0.1 (1)	0.1 (1)										
		Shell bed	17.2						0.1 (1)	1 (6)						0.1 (2)		0.1 (1)		
		Sandy seabed	17.3						0.1 (1)	0.1 (1)	0.1 (3)					0.1 (1)			0.1(1)	0.1
F05	SW	Monopile	0-0.5																	
			0.5-3.7						0.1 (4)						30					
			6.6-10.0								Bad sequence/no data									
			10.0-16								Bad sequence/no data									
			16-16.5								Bad sequence/no data									
		Shell bed	16.0																	
		Sandy seabed	16.4						0.1 (1)								0.1(1)		0.1(3)	

Continued….

Location	Direction (transects)	Substrate	Depth (m)	*Mytilus edulis*	*Metridium senile*	*Haliclona urceolus*	*Halichondria panica*	*Alcyonium digitatum*	*Asterias rubens*	*Martasterias glaciale*	*Astropecten irregularis*	*Henricia sanguinolenta*	*Ophiocomina nigra*	*Echinus esculenta*	*Balanus balanus*	*Cancer pagurus*	*Carcinus maenas*	*Hyas araneus*	*Pagurus bernhardus*	*Electra pilosa*
F06	N	Monopile	0-0.5												30					
			0.5-3.8	20											20					
			6.7-10.0		50		20		0.1 (2)	0.1 (1)					10					
			10.0-15.0		40		10	0.1	0.1 (4)	0.1 (2)			0.1 (3)	0.1 (1)	50					
			15.0-16.1		25			30		1 (6)					10					
		Shell bed	16.4						0,1 (9)	0,1 (9)		0.1 (2)						0.1 (1)		
		Coarse sand with pebbles and shells	16.5						0.1 (1)	0.1 (2)	0.1 (1)						0.1 (1)		0.1 (2)	
F06	SE	Monopile	0-0.5	No data due to tower construction																
			0.5-4	No data due to tower construction																
			7-10.0	0.1	45		5													
			10.0-15.7		92															
			16.0-16.5		50			3	0.1 (3)	1 (4)										
		Shell bed	16.4						0.1 (1)								0.1 (1)			
		Coarse sand with pebbles and shells	16.6						0.1 (1)	0.1 (1)							0.1 (2)	0.1 (1)		
F06	SW	Monopile	0-0.5																	
			0.5-3.8	5					0.1 (1)						0.1					
			7-10.0	2	55		3								0.1					
			10.0-15.7		95		1		0.1 (1)						0.1					
			15.7-16.1		45			2	1 (3)	1 (2)								0.1 (1)		
		Shell bed	16.4		0.1					0.1 (3)							0.1 (1)			
		Coarse sand with pebbles and shells	16.6						0.1 (1)	0.1 (1)								0.1 (1)	0.1 (1)	
NOVANA st. 150		Coarse sand with pebbles and shells	16.8						0.1(1)									0.1 (1)	0.1(1)	
ROV REF station		Coarse sand with pebbles and shells	17.2						0.1 (1)								0.1 (2)	0.1 (2)		

Table 5.6. Identified fish species, species with percentage cover and species abundances given in brackets. Data are given in different depth intervals, scour protection (I04), shell beds (F05 and F06) and the surrounding seabed around turbine towers (locations and transects)

Location	Transect	Direction	Substrate	Depth (m)	Ctenolabrus ru-pestris	Trachinus draco	Platichthys flesus	Pisces	Myoxocephalus scorpius	Eutrigla gurnardus	Pholis gunnellus	Gobiidae
I04	1	N	Monopile	0-0.5								
				0.5-5	0,1 (5)							
				7.3-10.0	0,1 (6)							
				10.0-15.7	1 (16)							
				15.7-16.3				Bad sequence/no data				
			Scour bed	16.5								
			Sandy seabed	16.7		0,1 (1)	0,1 (2)					
I04	2	SE	Monopile	0-0.5								
				0-4.3	0,1 (2)							
				7-10	2 (41)							
				10-15.7	1.0 (12)							
				15.7-16.3								
			Scour bed	15.4	0.1 (2)							
			Sandy seabed	16.2		0,1 (2)	0,1 (1)					
I04	3	SW	Monopile	0-0.5								
				0.5-4.5	0,1 (9)							
				7.0-10.0	1 (11)			0,1				
				10.0-15.7	1 (17)							
				15.7-16				Bad sequence/few data				
			Scour bed	16.0				Bad sequence/few data				
			Sandy seabed	16.5		0,1 (3)	0,1 (2)					
F05	1	N	Monopile	0-0.5								
		442 MB		0.5-3.4								
				6.7-10.0	0,1 (2)							
				10.0-16.0	0,1 (1)							
				16.0-16.5								
			Shell bed	16.0	0,1(1)		0,1 (5)					
			Sandy seabed	16.5		0,1(1)	0,1 (5)					
			Gravel bed with scattered stones				0,1 (1)					
F05	2	SE	Monopile	0-0.5								
				0.5-3.8	0.1 (1)				0.1 (1)			
				6.7-10.0								
				10.0-16.7	0,1 (1)							
				16.7-17.2								

Continued….

Location	Transect	Direction	Substrate	Depth (m)	Ctenolabrus rupestris	Trachinus draco	Platichthys flesus	Pisces	Myoxocephalus scorpius	Eutrigla gurnardus	Pholis gunnellus	Gobiidae
			Shell bed	17.2			2 (4)					
			Sandy seabed	17.3			0,1 (1)			0,1 (1)		
F05	3	SW	Monopile	0-0.5								
				0.5-3.7	0,1 (5)							
				6.6-10.0	0,1 (3)							
				10.0-16				Bad sequence/no data				
				16-16.5				Bad sequence/no data				
			Shell bed	16.0								
			Sandy seabed	16.4		0,1 (3)	0,1(2)			0,1(1)		
F06	1	N	Monopile	0-0.5								
				0.5-3.8	0.1 (1)	0,1 (1)						
				6.7-10.0	0,1 (2)	0,1 (1)						
				10.0-15.0	0,1 (2)							
				15.0-16.1								
			Shell bed	16.4	0,1 (1)		2 (5)					
			Coarse sand with pebbles and shells	16.5			0,1 (2)					
F06	9	SE	Monopile	0-0.5				No data due to tower construction				
				0.5-4	0.1(1)							
				7-10.0	0.1(2)			0,1(1)				
				10.0-15.7	0,1 (1)							
				16.0-16.5								
			Shell bed	16.4			1 (1)					
			Coarse sand with pebbles and shells	16.6							0,1 (1)	
F06	8	SW	Monopile	0-0.5								
				0.5-3.8								
				7-10.0								
				10.0-15.7	0,1(1)			0,1(1)				
				15.7-16.1								
			Shell bed	16.4			3 (6)					
			Coarse sand with pebbles and shells	16.6			0.1 (1)	0,1 (1)				
NOVANA st. 150			Coarse sand with pebbles and shells	16.8	0,1(1)	0.1 (1)	0,1 (3)					0,1(1)
ROV outer REF station			Coarse sand with pebbles and shells	17.2			0,1 (1)					

5.4 Infauna

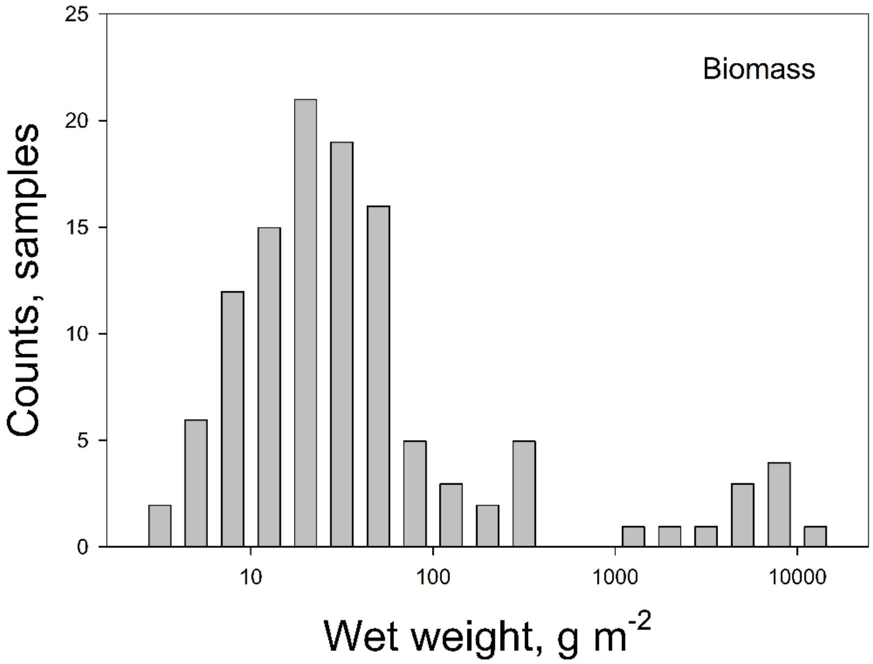
5.4.1 Infauna abundance, biomass and species richness

All planned samples were successfully retrieved from the transects around the three wind turbines and from the former monitoring station (station 150). A total of 117 Haps samples, covering 0.0143 m^2 inside the park area, were analysed for abundance, biomass, biodiversity and species composition. The total number of registered individuals was 3110, distributed among 113 species or taxa groups, with 55 annelids, 23 arthropods, 21 mollusks and 4 echinoderms. In addition, 10 taxa belonging to other phyla were registered. Of the 113 taxa, 81 could be identified to species level.

Table 5.7. Estimates of infauna average abundance, species richness (number of species in one sample), biomass, biodiversity and environmental quality indices from the Anholt wind farm. "Replicate" refers to the number of Haps samples taken at each location. Biomasses and abundances are tabulated in units of gram wet weight and number of individuals per square metre. Species richness is the number of species recovered in one Haps sample. Shannon diversity, AMBI and DKI are calculated for each individual Haps sample and averaged station by station with standard deviation for DKI values.

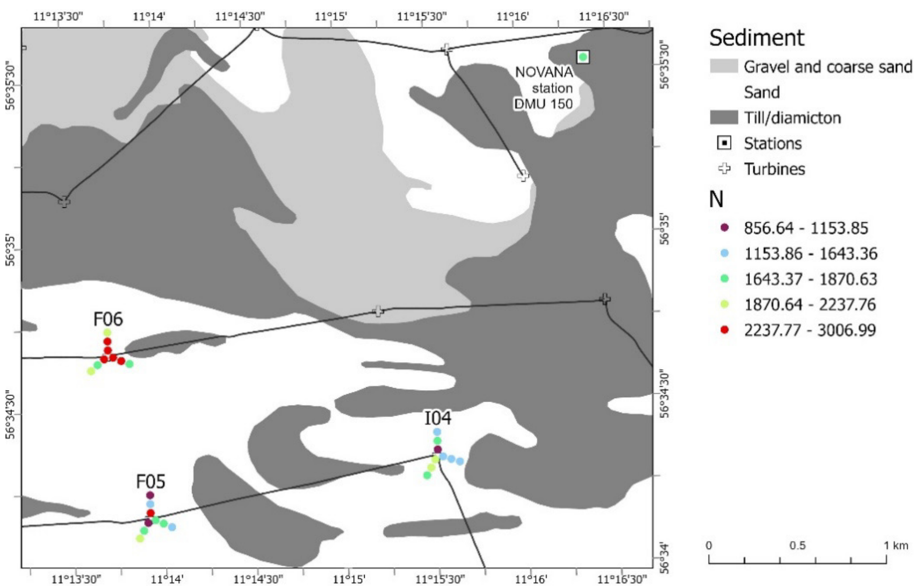
ID station	Replicate, samples	Abundance, N m^{-2}	Species, S	Biomass, g WW m^{-2}	AMBI	H´	DKI v.3
F05_1_130	4	2727	14	109	1.3	3.3	0.65±0.43
F05_1_30	4	1731	13	38	0.9	3.4	0.9±0.02
F05_1_80	4	857	9	51	1.4	2.9	0.76±0.04
F05_2_130	4	909	8	7	0.9	2.9	0.8±0.07
F05_2_30	4	1626	11	15	0.9	3	0.84±0.08
F05_2_80	4	1643	10	64	0.9	3	0.84±0.05
F05_3_130	4	1871	12	30	0.8	3.1	0.88±0.04
F05_3_30	4	1154	7	83	0.9	2.2	0.74±0.02
F05_3_80	4	1538	10	62	0.6	2.8	0.85±0.02
F06_1_130	4	1399	11	17	0.7	3.1	0.86±0.05
F06_1_30	4	2448	16	57	1.3	3.6	0.9±0.03
F06_1_80	4	2483	14	19	1	3.3	0.9±0.04
F06_2_130	4	1836	14	15	1.7	3.3	0.83±0.08
F06_2_30	4	2710	20	25	1.3	4	0.94±0.01
F06_2_80	4	3007	18	115	1.6	3.7	0.9±0.02
F06_3_130	4	1469	13	13	1.6	3.5	0.86±0.02
F06_3_30	4	2238	17	110	1.5	3.7	0.91±0.04
F06_3_80	4	2010	13	36	1.5	3.2	0.84±0.1
I04_1_130	4	1556	8	54	0.5	2.6	0.81±0.08
I04_1_30	4	1818	7	18	0.9	2,1	0.73±0.07
I04_1_80	4	1626	9	27	0.6	2.8	0.84±0.03
I04_2_130	4	2185	9	23	0.6	2.4	0.8±0.09
I04_2_30	4	1836	10	19	1	2.7	0.81±0.03
I04_2_80	4	2564	10	365	0.8	2.6	0.81±0.07
I04_3_130	4	2133	11	39	1	2.9	0.84±0.04
I04_3_30	4	1993	11	51	0.8	3.1	0.87±0.02
I04_3_80	4	1364	11	83	0.9	3.2	0.86±0.02
Ref150	10	1713	11	68	0.9	2.8	0.83±0.05
Average	-	1869	11,6	54	1.00	3.1	0,84±0.05

Figure 5.3. Distribution of total infauna biomass of all sampling stations and transects. The samples forming the log-normal distribution to the right all contain sea quahog (*Arctica islandia*).



Biomass data showed an average wet weight of 581 g m^{-2}, with a median value of only 26 (Table 5.7). The large discrepancy between mean and median values was due to 11 specimens of ocean quahog, *Arctica islandia*, which accounted for about 9% of the total biomass. The rest of the fauna community contributed with, on average, 54 g wet weight m^{-2} for all samples. The biomass distribution of ocean quahog and the rest of the fauna community showed two distinct log-normal distributions (Figure 5.3), separated by two orders of magnitude in median value, with no overlap in the two distributions.

Figure 5.4. Total infauna abundances (all species) along transects and at DMU station 150. Values represent station averages (individuals m^{-2}). I04, F05 and F06 are the three wind turbines.



The average abundance of animals (Table 5.7, Figure 5.4) was 1869 m^{-2}, ranging from 559 to 3846 m^{-2} (median = 1748). Total abundance was significantly higher ($P<0.001$, t-test) around turbine F06, with average values of 2177 individuals m^{-2} compared to the average of all the other samples (from F05, I04 and station 150) of 1717 individuals. No significant differences were found between any of the other turbines (Holm-Sidak test).

Species richness measured as the number of species per Haps sample (S) ranged between 4 and 20 (Figure 5.7). Species richness was significantly higher (P<0.001, t-test) around turbine F06, with an average value of 15.1 species/samples compared to the average of all the other samples (from F05, I04 and station 150) of 9.48 (10.6 for station 150 alone). No significant differences were found between any other turbines (Holm-Sidak test).

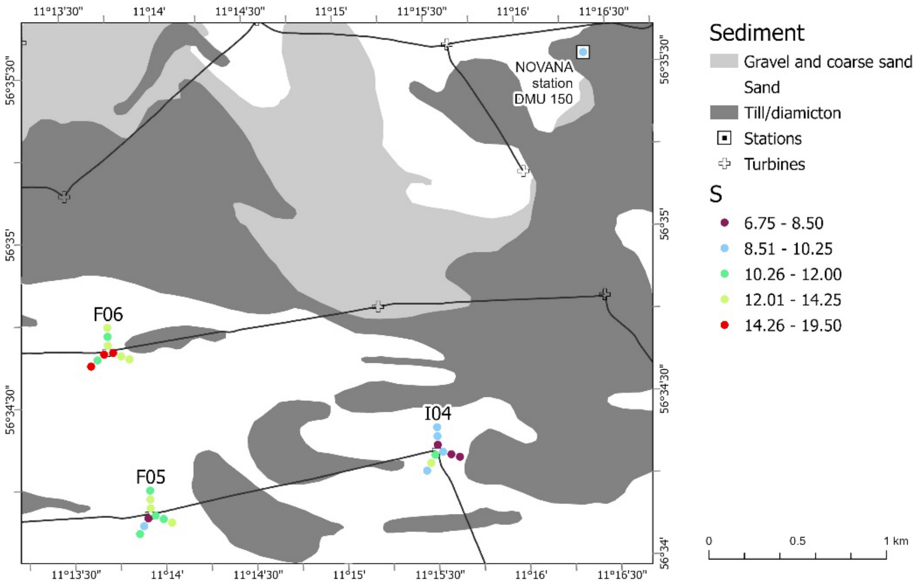


Figure 5.5. Total abundances (all species) along transects and at DMU station 150. Values represent station averages (m^{-2}).

For all samples, average Shannon diversity (H`) was 3.03, ranging from 2.06 to 3.96 for individual samples (Figure 5.6). Shannon diversity was significantly higher (P<0.001, rank sum test) around turbine F06, with an average value of 3.49 compared to the average value of 2.87 for all other samples (F05, I04 and station 150). No significant differences were found between any other turbines (Dunn´s test).

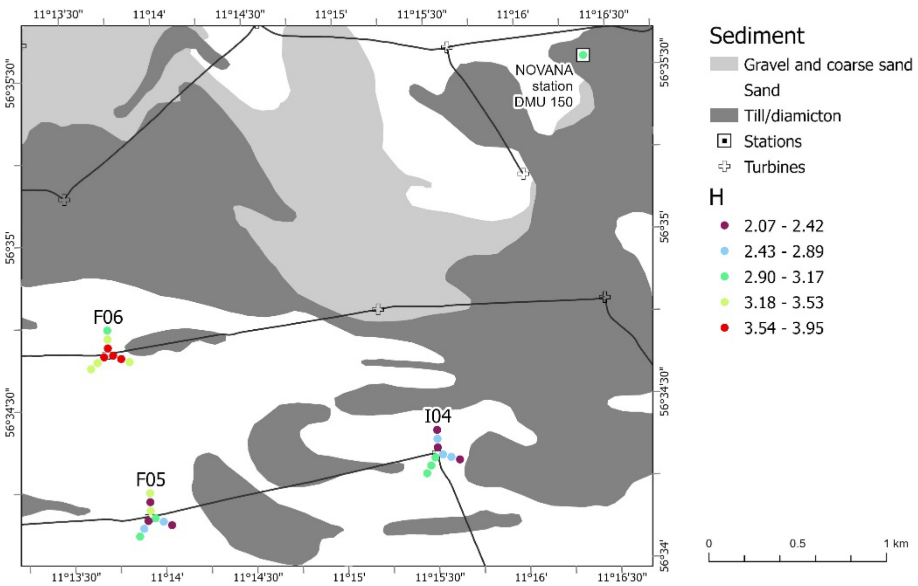
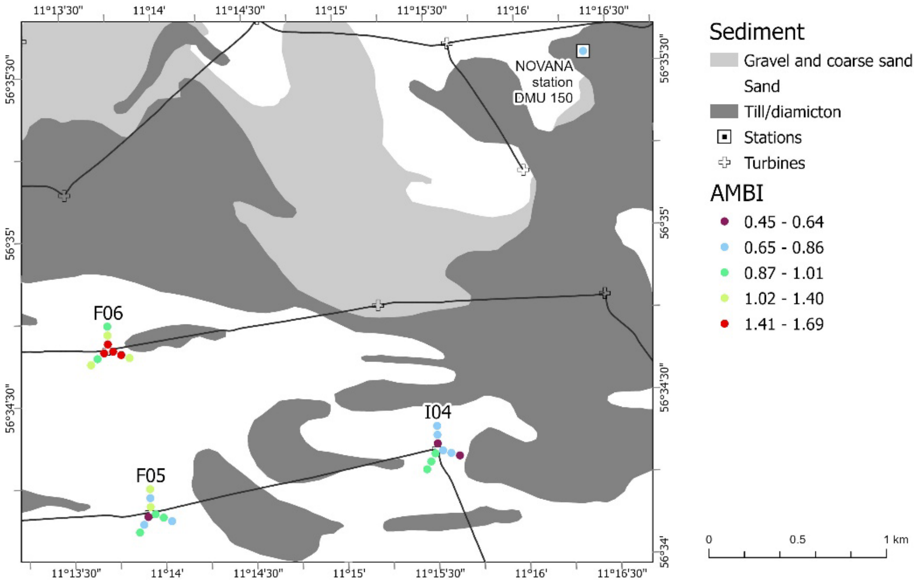


Figure 5.6. Average values of infauna Shannon diversity (H) at the sampling stations.

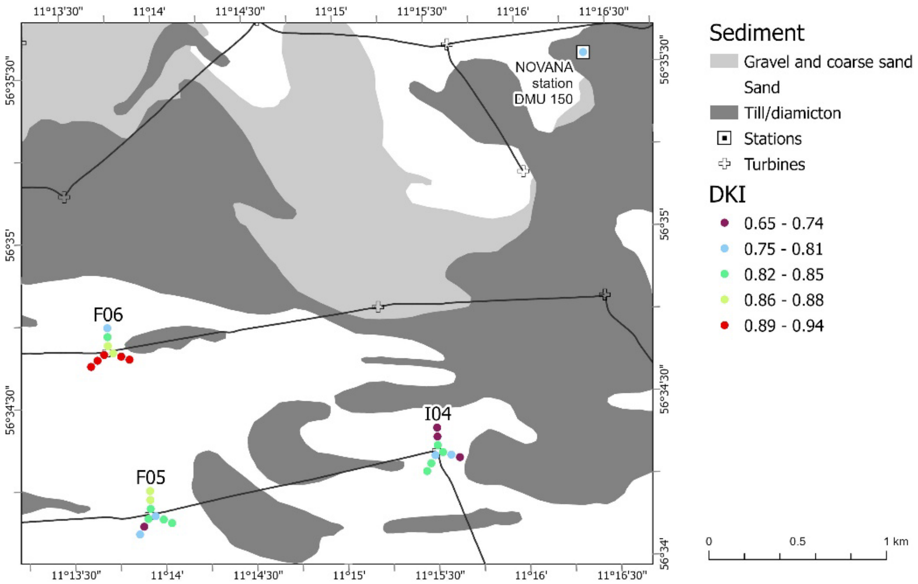
Calculations of AMBI (Azti Marine Biotic index) (Borja et al., 2000; Borja et al., 2007), ranging between 0 and 7, with the lowest values indicating the best environmental conditions, showed an average value of 1.0 and ranged between 1.68 (worst) and 0.45 (best). AMBI values were significantly higher (P<0.01, rank sum test) around turbine F06 (slightly worse) than the average value for all the other samples. No significant differences were found between any other turbines (Dunn´s test). Although turbine F06 showed slightly worse conditions (a larger proportion of tolerant species in the species assemblage) than the rest of the samples inside the park, the general AMBI level indicated good conditions.

Figure 5.7. Average AMBI values at the sampling stations.



DKI (Borja et al., 2007; Josefson et al., 2009; Hansen, 2018) is a unitless index ranging between 0 and 1, with higher values indicating better environmental conditions. It was calculated from AMBI and the Shannon diversity index and showed consistently high values between 0.65 and 0.95 across all samples, with an average of 0.83. The DKI values were significantly higher ($P<0.01$, rank sum test) around turbine F06 (DKI = 0.88) than the average of all other samples (0.81). No significant differences were found between any other turbines (Dunn´s test). Although stations around turbine F06 showed better environmental conditions than the rest, all samples indicated that the general environmental conditions in the area were good.

Figure 5.8. Average DKI values at the sampling stations.



ES10 describes the expected number of species found in a sample of 10 randomised individuals, and its values ranged between 3.4 and 10 (max value), with a global average of 6.5 (Figure 5.9). As the other biodiversity indices, ES10 had significantly higher values in the area around turbine F06 than the rest of the samples (7.4 compared with 6.2) (P<0.01, rank sum test).

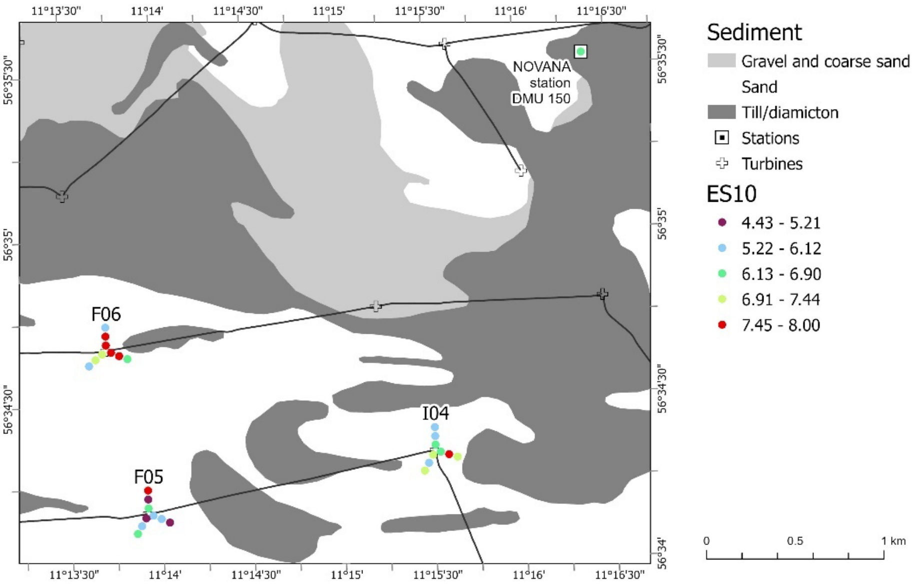


Figure 5.9. Average values of rarefaction permuted values of species richness S (ES10 is the expected number of species per 10 randomised individuals).

5.4.1 Before and after change in biodiversity

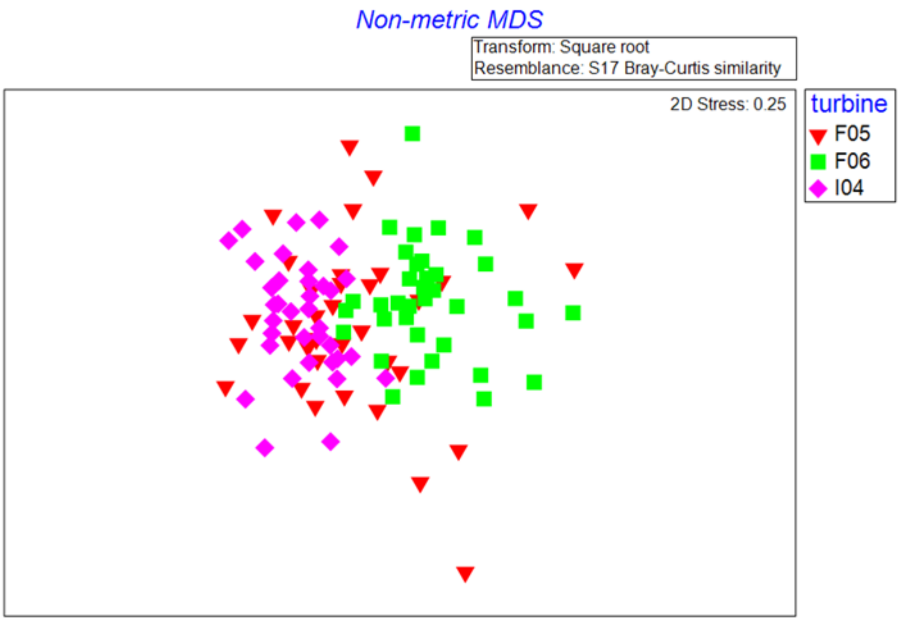
Average Shannon diversity (H´) at station 150 was 2.80 (N = 10) in 2022 and 3.3 in 1989-2010 (N=152), which was a significant difference (t-test, P=0.002). A similar significant difference was observed at nearby station 409 in Ålborg Bugt, with an average Shannon diversity of 3.05 in 1989-2010 (N=152) and 2.07 in 2022 (P=0,001, Mann-Whitney rank sum test).

5.5 Community analysis

5.5.1 Distribution of communities

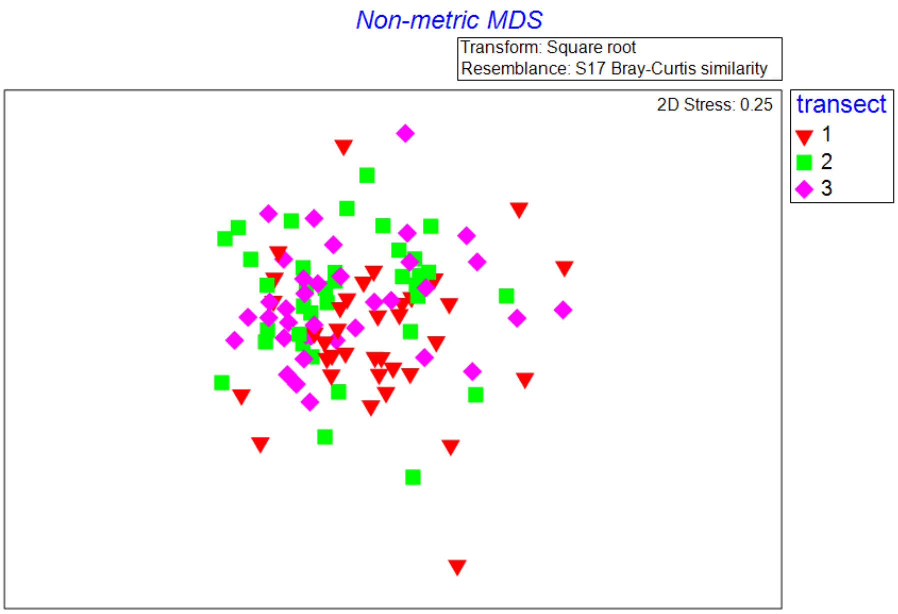
The similarity in community composition between individual samples was assessed using Bray-Curtis similarity on square root-transformed abundance data. The results of the ANOSIM (analysis of similarity) are displayed using non-metric ordination. Samples associated with the wind turbines were ordinated by individual turbines (F05, F06 and I04; Figure 5.10), transect direction (1-3, Figure 5.11) and distance from the tower (30 m 80 m 130 m, Figure 5.12).

Figure 5.10. nMDS of infauna community structure. Each point represents an individual sample from the three turbines F05, F06 and I04. Symbols represent turbines.



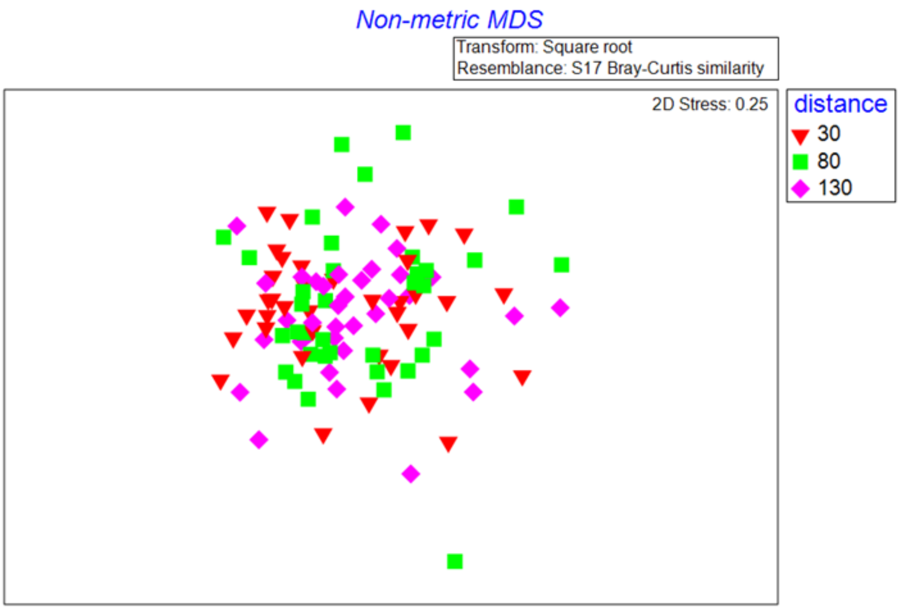
Among these factors, only the individual wind turbines showed a difference in community composition, where wind turbine number F06 differed from F05 and I04. This aligns with the analysis of univariate variables (N, S, H, DKI, AMBI and ES10) and thus confirms that the infauna community on F06 differs markedly from the other two. However, the ordinations have a high stress value (>0.20), so interpretations should be broad and cautious, as the two-dimensional ordination requires additional axes to fully describe the community similarity.

Figure 5.11. nMDS of infauna community structure. Each point represents an individual sample from the three turbines F05, F06 and I04. Symbols represent transect 1 (north), transect 2 (south-east) and transect 3 (south-west).



Permutational analysis, PERMANOVA, was applied to test for single and combined effects of the three factors – turbine, transect and distance – on community composition. It confirmed that turbine F06 differed markedly from the other turbines. However, significant differences were also detected between turbine F05 and I04 (P<0.0001). As to transect number, transect 1 (N) differed significantly from transect 2 and 3 (P<0.0013 and p<0.0042, respectively).

Figure 5.12. nMDS of infauna community structure. Each point represents an individual sample from the three turbines F05, F06 and I04. Symbols represent the distance from turbines: 30, 80 and 130 m, to which the sample was assigned.



The distance of the stations from the tower showed no significant pattern across transects and turbine number, and no general radiating effect could be confirmed.

Global PERMANOVA results revealed that the distance from turbines was not a significant factor in describing the structure of the infaunal community around the turbines (table 5.8). However, considered together with the factors turbine and transect as an interactive effect, it became significant (Table 5.8). Further, pairwise analysis (Table 5.9) showed that transect 1 (north) was the only level reporting a significant or near-significant difference (~0.06) in distance from the turbine. The exception was transect 3, where a significant difference was found between 30 and 80 m distance for turbine F05.

Table 5.8. Results of PERMANOVA analysis comparing soft sediment community structures of three turbines (F05, F06 and I04).

Global Pairwise tests	DF	Pseudo - F	P-value	Unique permutations
Turbine	2	8.6076	<0.00001	90804
Transect	2	1.8416	0.0033	90322
Distance	2	0.97667	0.5138	90226
Interactive effects				
Turbine x Transect	4	2.8765	<0.00001	87182
Turbine x Distance	4	1.5271	0.0059	87137
Transect x Distance	4	1.563	0.0038	87007
Turbine x Transect x Distance	8	1.7659	<0.00001	83192

Table 5.9. P-values from 3-way PERMANOVA analysis of the combined effects of turbine transect distance based on infauna abundance data.

	FO5			FO6			I04		
	30-80	30-130	80-130	30-80	30-130	80-130	30-80	30-130	80-130
Transect 1 (N)	0.028	0.031	0.022	0.06	0.025	0.028	0.024	0.032	0.064
Transect 2 (SW)	0.821	0.39	0.82	0.111	0.165	0.276	0.504	0.058	0.672
Transect 3 (SE)	0.047	0.087	0.361	0.411	0.059	0.425	0.114	0.461	0.778

5.5.2 Comparison between reference areas and the wind farm

The community structure around the wind turbines was compared with the community structure at the two monitoring stations – station 150 inside the park, serving as a reference for near-turbine radiating effects, and station 409 outside the wind farm, serving as a reference for general effects inside the park. ANOSIM analysis showed that all stations, including the outermost (130 m distance), were significantly different from reference stations 150 and 409. Therefore, the reference stations cannot be used as controls for radiating reef-effects. This is consistent with the observation that only one transect direction showed an effect on community composition. This is also clear from a non-metric MDS-plot, despite the high stress value (Figure 5.13).

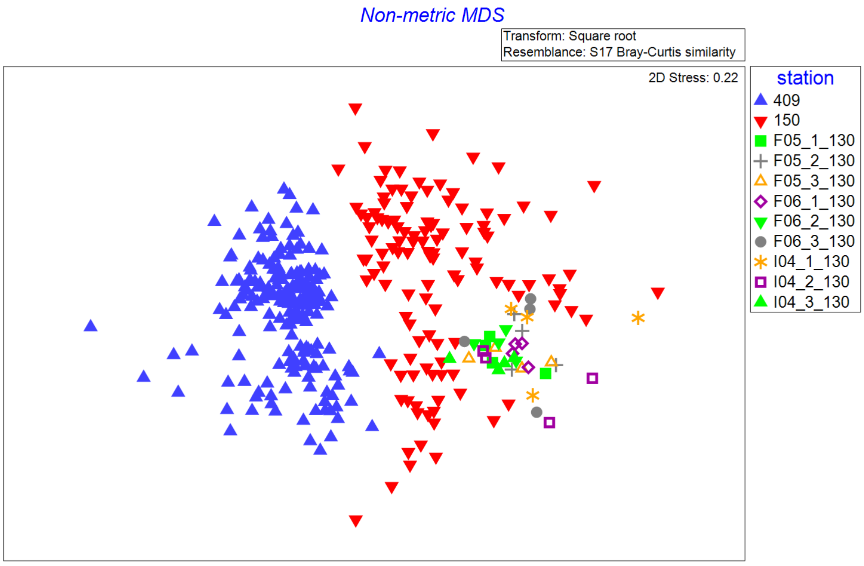


Figure 5.13. nMDS of infauna community structure. Each point represents an individual sample from the three turbines and reference stations.

Across the entire dataset, infauna communities in- and outside the park varied and were not similar during the period 1989-2023 (Figure 5.13). The greatest similarity between the two reference sites and the turbines was between the latest reference station observations in 2023 and the turbine data from 2023 (Figure 5.14). This means that the differences observed at station 150 before and after the establishment of the park cannot be attributed to the park but to general changes in the area (the park and station 409).

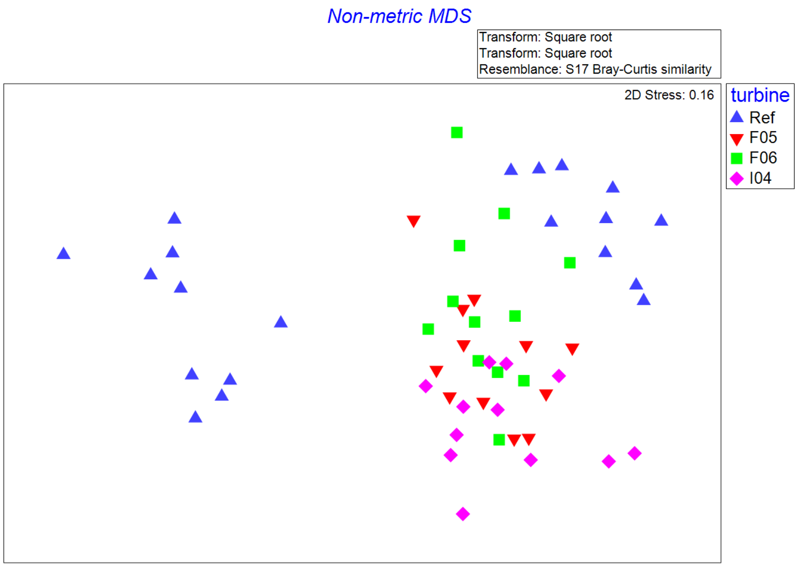


Figure 5.14. nMDS of infauna community structure. Each point represents an individual sample from the three turbines and both reference stations (409 and 150 joint and termed Ref) for 2023.

6 Summary of key results

6.1 Sediment classification

There was good agreement between the sediment (sand) observed around the ROV transects and existing maps with seabed classifications for turbines F05 and I04. Around turbine F06, the sediment consisted of coarser sand and gravel despite being mapped as sand. Reference station 150 and the outer ROV reference station were both mapped as till (glacial deposits), but the composition of the sediment along the ROV transects resembled that of F06, with coarse sand, scattered gravel and a few small-sized boulders. The abundance of dead ocean quahog, *Arctica islandica*, and *Mya* shells was greater in areas classified as glacial deposits.

Sediment profiles showed generally low ignition loss and high dry matter content across all samples. Variation between the reference site (150) and the wind turbine sites was insignificant. Only the depth profile showed a significant decline with depth, whereas no clear horizontal pattern was detected between the turbines, transects or distances from the individual turbines.

6.2 Differences in epibenthic communities in the wind farm and on natural reefs

Although the ROV technique used in this study is not directly comparable with diver observations conducted on boulder reefs, the epibiotic communities on artificial substrates and natural substrates differ markedly. The ROV has limitations in obtaining quantitative biodiversity data compared with diver surveys as it cannot describe the cover of species below the macroalgae canopy, and many species cannot be identified to species level. Despite these limitations, it is possible to make general comparisons between communities described with an ROV in wind farm areas and data sets obtained from thorough diving surveys on natural reefs.

In the open part of the Kattegat, natural reefs are dominated by macroalgae down to 18-23 m depth. Below this, light attenuation is so pronounced that the epifauna becomes dominant, dead men's hand, *Alcyonium digitatum*, often being the most important species. On the turbine towers, the depth distribution of full (100%) macroalgae cover was constrained to the upper 4-5 m, where the macroalgae vegetation was dominated by filamentous algae. No light measurements were undertaken, but the observed community structure was likely due to shading from the vertical structure and tower, reducing direct and diffuse light. Significant amounts of large blue mussels were found beneath the algal canopy. In contrast, dense mats of blue mussels are extremely rare on natural boulder reefs in the Kattegat where they are eaten by starfish. However, the algae vegetation on the scour protection around turbine I04 at approx. 17 m depth was relatively well-developed and comparable to that of natural rock reefs.

Below the overhangs of the tower construction at 5-7 m depth, the community shifted to a fauna-dominated one, and below 10 m depth, plumose anemone, *Metridium senile*, was completely dominant. In the Kattegat, *Metridium* is also found on vertical sides under overhangs on ”bubble reefs”. Plumose anemone is found on boulder reefs in the Kattegat but with a scattered, low cover.

Generally, zones with blue mussels and plumose anemone are common on offshore installations. The observed community on Krigers Flak is very different and dominated by blue mussels (Dahl et al., in prep.).

The communities at the three investigated turbines were very similar. However, 4-5 times more gold shinny wrasse were found around the scour-protected turbine I04. Gold shinny wrasse is the most common fish species on Danish reefs today, and its high abundance around I04 may be linked to the artificial reef at the foot of the tower. No observations of cod and other gadoids were made. Flounders were observed on the shell banks beneath the two towers without scour protection as well as on the surrounding seabed.

6.3 Infauna in- and outside the Anholt wind farm

The biodiversity of infauna communities was relatively high and characterised by relatively sensitive species. All the applied univariate indices indicated good environmental quality for both reference stations and the stations around the turbine. Comparison of biodiversity before and after the wind farm was built (station 150) showed significant changes inside the wind farm after its establishment. However, similar changes have occurred outside the wind farm, and these cannot be coupled to the wind farm. Biodiversity measurements showed significantly higher values at the station around wind turbine F06, with coarser sand than at stations F05 and I04.

Infauna community analyses showed significant differences between all three wind turbines and the two reference stations. Therefore, station 150 is not suitable as a reference station for local effects around the turbines, and station 409 cannot be used as a reference for changes before and after the establishment of the park. The community shift between turbines and reference areas could be due to other environmental factors such as spatial heterogeneity of the sediment compositions.

All turbines showed significant differences between infauna communities when compared to each other (Table 5.4). However, a pattern emerged when isolating the effect of distance on transect 1 (north) (Table 5.8). This pattern was not observed on transect 2 (south-east) and transect 3 (south-west). The observed patterns could be attributed to local shadow or hydrodynamic effects rather than a general radiating reef effect, suggesting a large influence by dominant current conditions. Without a clear boundary or reference stations (control), the extent of the reef effect cannot be determined. Changes in community compositions were detected up to 130 m distance, with no comparable samples taken beyond this distance.

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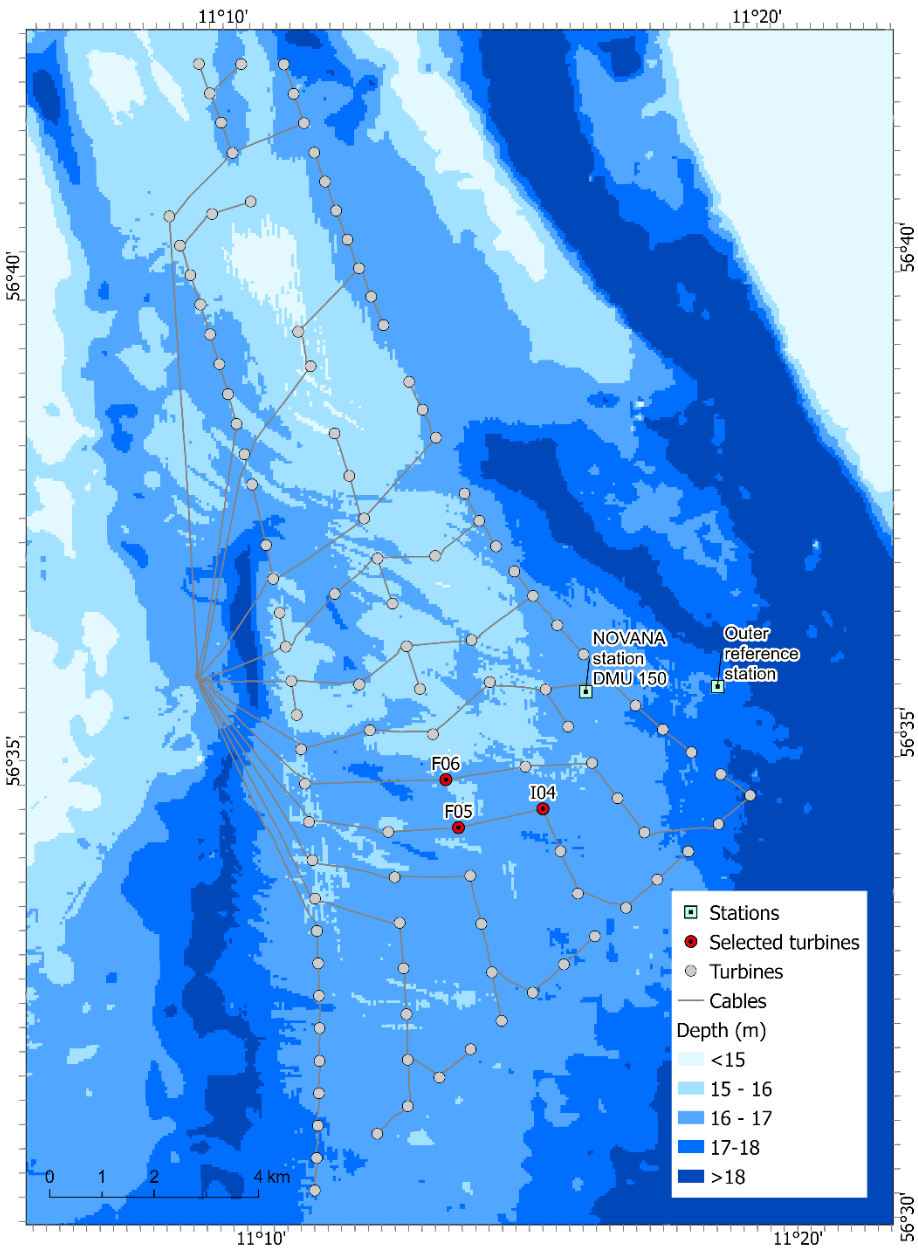
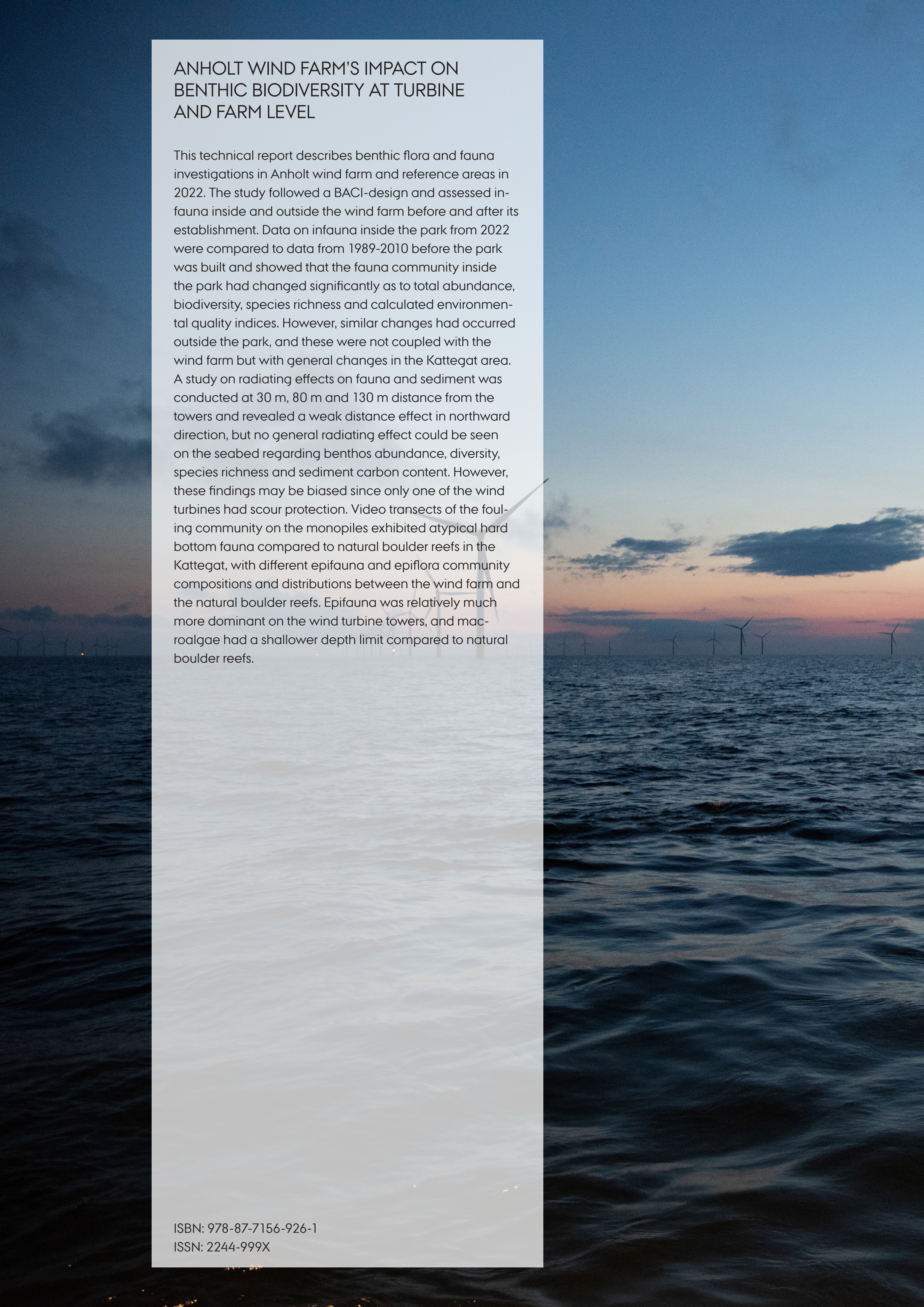
8 Appendix

Appendix 1. Bathymetry in Anholt wind farm.



Appendix 2 Sampling positions of Haps core sampler and pot fishery.

Gear	Sampling station	Transect	Distance	Longitude	Latitude
Haps	F05	1	30	56°34'1871	11°13'9185
	F05	1	80	56°34'2146	11°13'9213
	F05	1	130	56°34'2409	11°13'9231
	F05	2	30	56°34'1591	11°13'9394
	F05	2	80	56°34'1366	11°13'9678
	F05	2	130	56°34'1166	11°13'9989
	F05	3	30	56°34'1578	11°13'9039
	F05	3	80	56°34'1422	11°13'8644
	F05	3	130	56°34'1237	11°13'8325
	F06	1	30	56°34'6888	11°13'7191
	F06	1	80	56°34'7129	11°13'7130
	F06	1	130	56°34'7393	11°13'7089
	F06	2	30	56°34'6610	11°13'7409
	F06	2	80	56°34'6375	11°13'7676
	F06	2	130	56°34'6163	11°13'7950
	F06	3	30	56°34'6531	11°13'7077
	F06	3	80	56°34'6341	11°13'6684
	F06	3	130	56°34'6133	11°13'6355
	I04	1	30	56°34'3533	11°15'5099
	I04	1	80	56°34'3778	11°15'5072
	I04	1	130	56°34'4051	11°15'5043
	I04	2	30	56°34'3298	11°15'5373
	I04	2	80	56°34'3150	11°15'5766
	I04	2	130	56°34'3032	11°15'6167
	I04	3	30	56°34'3205	11°15'4989
	I04	3	80	56°34'3042	11°15'4567
	I04	3	130	56°34'2864	11°15'4186
HAPS	DMU150			56°35'5300	11°16'3800
HAPS	Reference			56°35'5354	11°18'8455
POTS	F05		30	56°34'1808	11°13'8812
	F05		80	56°34'1917	11°13'8553
	F05		130	56°34'2104	11°13'8164
	F06		30	56°34'6728	11°13'669
	F06		80	56°34'6900	11°13'6497
	F06		130	56°34'7046	11°13'6066
	I04		30	56°34'3540	11°15'533
	I04		80	56°34'3711	11°15'5534
	I04		130	56°34'3916	11°15'5778



ANHOLT WIND FARM'S IMPACT ON BENTHIC BIODIVERSITY AT TURBINE AND FARM LEVEL

This technical report describes benthic flora and fauna investigations in Anholt wind farm and reference areas in 2022. The study followed a BACI-design and assessed infauna inside and outside the wind farm before and after its establishment. Data on infauna inside the park from 2022 were compared to data from 1989-2010 before the park was built and showed that the fauna community inside the park had changed significantly as to total abundance, biodiversity, species richness and calculated environmental quality indices. However, similar changes had occurred outside the park, and these were not coupled with the wind farm but with general changes in the Kattegat area. A study on radiating effects on fauna and sediment was conducted at 30 m, 80 m and 130 m distance from the towers and revealed a weak distance effect in northward direction, but no general radiating effect could be seen on the seabed regarding benthos abundance, diversity, species richness and sediment carbon content. However, these findings may be biased since only one of the wind turbines had scour protection. Video transects of the fouling community on the monopiles exhibited atypical hard bottom fauna compared to natural boulder reefs in the Kattegat, with different epifauna and epiflora community compositions and distributions between the wind farm and the natural boulder reefs. Epifauna was relatively much more dominant on the wind turbine towers, and macroalgae had a shallower depth limit compared to natural boulder reefs.

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