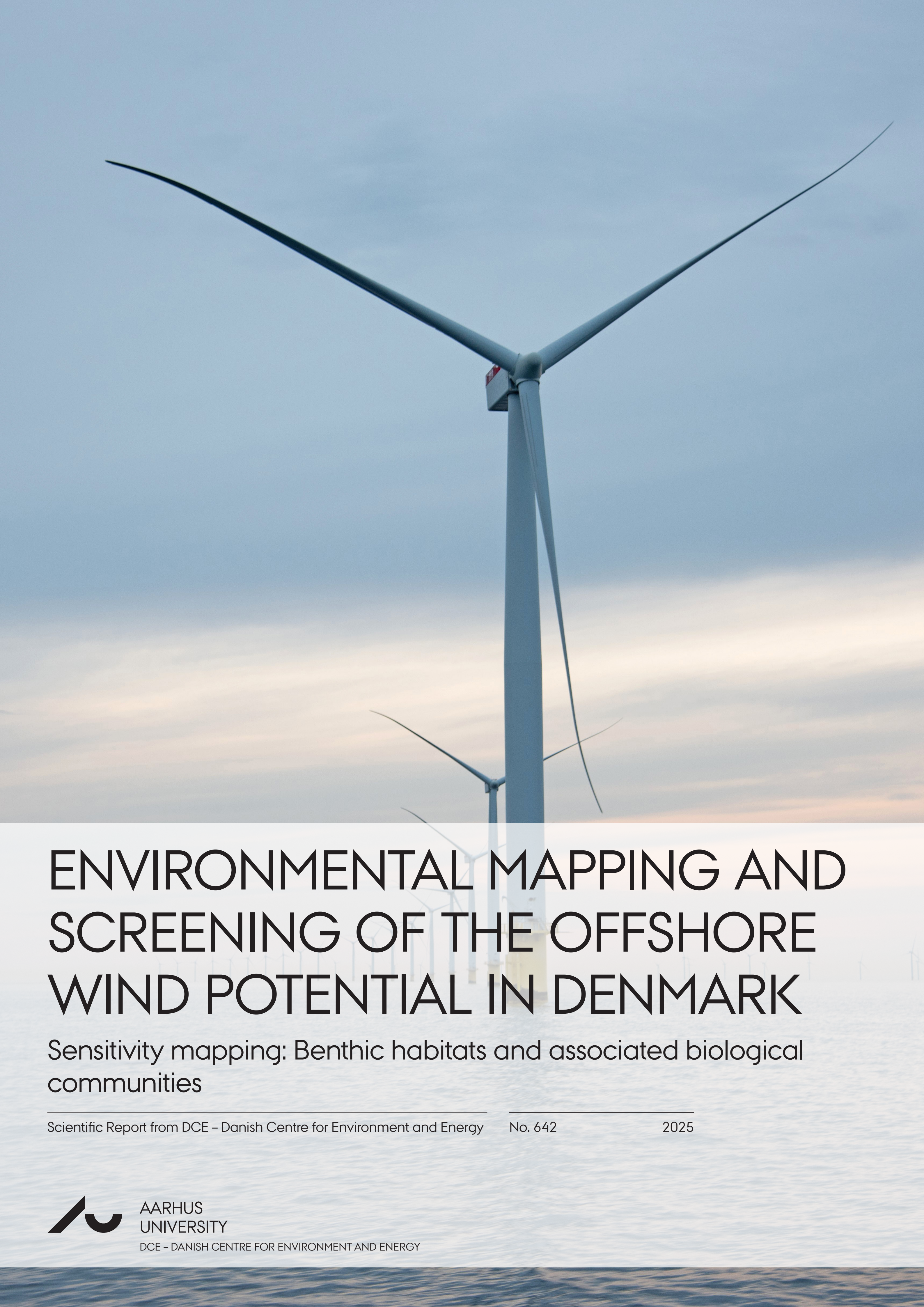

ENVIRONMENTAL MAPPING AND SCREENING OF THE OFFSHORE WIND POTENTIAL IN DENMARK

Sensitivity mapping: Benthic habitats and associated biological communities

Scientific Report from DCE – Danish Centre for Environment and Energy No. 642 2025

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Abstract: This report assesses the sensitivity of benthic habitats and biological communities to establishment of offshore wind farms in Danish waters. Sensitivity was estimated as the percentage of each broad habitat within the North Sea/Skagerrak, Kattegat, and Baltic Sea basins. The study's purpose is to inform overall sensitivity mapping of natural, environmental, wind, and hydrodynamic conditions for future wind farm planning.

Keywords: Sensitivity mapping, benthic habitats, benthic communities, offshore wind farms

Front page photo: Anholt vindpark by Karsten Dahl

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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/ansvarsomraader/vindmoeller-paa-hav/planlaegning-af-fremtidens-havvindmoelleparker):

- Sensitivity mapping of nature, environmental, wind and hydrodynamic conditions.
- Technical fine-screening and assessment of the overall offshore wind potential based on the sensitivity mapping and relevant technical parameters
- Assessment of potential cumulative effects from large-scale offshore wind development in Denmark and neighbouring countries.
- 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 benthic habitats and associated biological communities based on available data. Other subjects within Task 1—such as fish, marine mammals, bats, wind and hydrodynamics and ecosystem modelling—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 3 specifies the data sources used in the sensitivity mapping for seabirds and outlines additional existing data. It is important to recognise 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 rapport giver en vurdering af de bentiske habitaters følsomhed over for etablering af havvindmølleparker i de danske farvande og beskriver de biologiske samfund, der er tilknyttet. Der er anvendt en tilgang baseret på EU's havstrategidirektiv. Formålet med havstrategi direktivet er at opnå god miljøtilstand, som sammen med andre elementer også er defineret ved at opretholde "havbundens integritet". Som målsætning for, at havbundens integritet er opretholdt, har EU besluttet, at der maksimalt må være et tab på 2 % på de overordnede habitattyper, som er defineret med henblik på forvaltningen af direktivet. Ligeledes må der maksimalt være 25 % ugunstige påvirkninger på disse habitater. Flere målsætninger for yderligere indikatorer, der beskriver havbundens integritet, forventes at blive vedtaget af EU i fremtiden.

Det eksisterende overordnede habitatkort er i projektet blevet opdateret med nye havbundssedimentoplysninger. Blødbundsfauna fra basisundersøgelser for havstrategi kortlægningsområder og planlagte havvindmølleparker er blevet kombineret med data fra det danske overvågningsprogram og knyttet til det nye habitatkort.

Havbundens følsomhed blev estimeret som procentdelen af hver overordnet habitattype inden for de tre bassiner i danske farvande, Nordsøen/Skagerrak, Kattegat og Østersøen. En lav procentdel indikerer højere følsomhed og en høj procentdel lavere følsomhed. Formålet med at angive en habitatfølsomhed i denne undersøgelse er, at vurderingen kan bruges i den overordnede følsomhedskortlægning af natur, miljø, vind og hydrodynamiske forhold i relation til den fremtidige planlægning af havvindmølle parker.

Derudover estimerede vi, hvor meget de eksisterende og planlagte havvindmølleparker kunne påvirke hver enkelt overordnet habitattype, baseret på den 2030-plan der er leveret af Energistyrelsen. Vindmølleparkernes bidrag til tabet af bentiske levesteder er relativt begrænset og knyttet til opførelsen af møllefundamenter og erosionsbeskyttelsen omkring mølletårnet. Det samlede estimerede tab er i alle tre bassiner langt fra at nå tærskelniveauet for habitattab på 2 %. Den forventede effekt på bentiske samfund i nærheden af erosionsbeskyttelsen (reveffekten) er også lille og langt fra tærskelværdien på maksimalt 25 % negativ effekt. Imidlertid kan det potentielle kumulative tab ved alle former for pres genereret ved etablering af vindmølleparker være af et omfang, der er relevant for direktivets tærskelværdi, hvis ny viden dokumenterer en overordnet negativ parkeffekt. I Østersøen fylder de eksisterende og planlagte vindmølleparker mellem 25 og 100 % af tre af de mere følsomme overordnede habitater. Det er imidlertid vigtigt at huske på, at andre belastninger som for et eksempel fiskeri og indvinding af råmaterialer også genererer tab og pres på havbunden, men en vurdering af den kumulative effekt af alle belastninger lå uden for denne rapports rammer.

Analysen dokumenterer forskelle i blødbundssamfund mellem Nordsøen/Skagerrak, Kattegat og Østersøen. Dette stemmer overens med den anvendte tilgang til følsomhedsanalyse med henblik på at behandle hvert enkelt overordnede habitat som forskellig i de tre bassiner. Desuden dokumenterer multivariat analysen de vigtigste karakteriserende arter for hver naturtype og dannede grundlag for beskrivelse af samfundsstruktur.

Mens nogle af virkningerne af offshore vindmølleparker er blevet undersøgt, er andre effekter og deres størrelse i øjeblikket ukendt og kræver yderligere undersøgelser. Vurderingen af følsomhed og potentielle påvirkninger i denne analyse bygger på den bedst tilgængelige viden, men med adskillige forenklinger og antagelser, da viden om økologiske effekter af vindmøller og vindparker stadig er utilstrækkelig. På trods af disse faglige mangler anskueliggør rapporten, i hvilke områder og for hvilke bentiske overordnede naturtyper de største arealmæssige udfordringer kan komme med den fremtidig udbygning af havvindmølleparker.

Summary

This report provides an assessment of the sensitivity of the benthic habitats and associated biological communities to offshore wind farms in Danish waters. A Marine Strategy Framework Directive (MSFD) based approach was adopted, with the aim of the MSFD is to achieve good environmental status, which, among other elements, is defined by maintaining "sea-floor integrity". Sea-floor integrity in this framework is considered as maximum of 2% loss on broad habitat types defined for the purpose of the MSFD and a maximum of 25% adverse effects on these habitats. More targets for additional indicators are expected to be decided upon by EU in the future.

The existing broad-scale habitat map was updated with new seabed sediment information. Soft bottom fauna baseline data for MSFD habitat mapping projects and planned offshore wind farms have been combined with data from the Danish monitoring program and linked to the new habitat map.

The sensitivity was estimated as the percentage of each broad habitat within the three subregions in Danish waters, the North Sea/Skagerrak, Kattegat and the Baltic Sea. A low percentage indicates higher sensitivity and a high percentage lower sensitivity. The purpose of the habitat sensitivity provided in this study is to be used in the overall sensitivity mapping of nature, environmental, wind and hydrodynamic conditions in relation to the planning of future wind farms.

Additionally, we estimated how much the existing and planned offshore wind farms could impact each broad habitat type, based on the 2030 plan provided by the Energy Agency. The contribution of wind farms to the loss of benthic habitats is minor and linked to the construction of turbine foundations and scour protection surrounding it. It is in all cases far from reaching the threshold level of habitat loss of 2%. The expected effects on benthic communities in the vicinity of the scour protection (the reef effect) are also minor and far from the 25% target of adverse effect. However, the potential cumulative loss by all types of pressures generated by establishing windfarms can be relevant for the MSFD thresholds if new knowledge documents that there are overall negative park effects. In the Baltic Sea, three of the highly sensitive broad habitats are covered between 25 and 100 % by the existing and planned wind farm areas. It is important to keep in mind that other pressures like fishery and extraction of raw material also generate loss and pressure on the seafloor, but an assessment of the cumulative effect of all pressures was beyond the scope of this report.

Community analysis revealed distinct soft-bottom communities between the North Sea, Kattegat and Baltic Sea sub-regions. This agrees with the sensitivity analysis approach to treat each broad habitat as distinct between subregions. Furthermore, multivariate analysis revealed the key characterising species for each habitat type and provided the basis for description of community structure.

While some of the impacts of Offshore Wind Farms (OWFs) have been investigated, other effects and their magnitude are currently unknown and require further studies. The assessment of sensitivity and potential impacts based on the best available knowledge, but with several simplifications and assumptions, as the state of knowledge of ecological effects of wind turbines and wind parks are still insufficient. Despite these knowledge gaps, the report illustrates in which areas and for which benthic habitat types the greatest areal challenges may arise with the future expansion of offshore wind farms.

1 Introduction

International obligations to protect the Danish marine environment

Several EU directives are in play when it comes to managing the nature and environmental quality of the Danish marine areas, and the recently adopted Nature Restoration Act from the European Union (EU) may also become relevant in the near future. At present and in this context, we found the Marine Strategy Framework Directive (MSFD) most relevant to include in the work, as it specifically sets targets for loss and effects of benthic habitats in European waters.

The objective of the Marine Strategy Framework Directive is to achieve good environmental status. Good environmental conditions are defined based on 11 adopted descriptors that collectively describe the state of the sea, such as protecting the sea's biodiversity and food web. They also describe "anthropogenic pressures on the marine environment such as commercial fisheries, or pollutants such as marine litter, contaminants, or the input of energy." The 11 descriptors are listed in Table 1.

Table 1. Descriptors used in the Marine Strategy Framework Directive to assess the environmental status.

Descriptor 1	Biodiversity is maintained
Descriptor 2	Non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystems
Descriptor 3	Populations of all commercially-exploited fish and shellfish are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock
Descriptor 4	Food webs ensure long-term abundance and reproduction of species
Descriptor 5	Human-induced eutrophication is minimised, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms and oxygen deficiency in bottom waters
Descriptor 6	Sea-floor integrity[1] is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected
Descriptor 7	Permanent alteration of hydrographical conditions does not adversely affect marine ecosystems
Descriptor 8	Concentrations of contaminants are at levels not giving rise to pollution effects
Descriptor 9	Contaminants in fish and other seafood for human consumption do not exceed levels established by Union legislation or other relevant standards
Descriptor 10	Properties and quantities of marine litter do not cause harm to the coastal and marine environment
Descriptor 11	Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment

[1] Sea-floor integrity and seabed integrity are used synonymously by the EU

Development of offshore wind can have an influence on several of the mentioned indicators, either directly or in interaction with the management of other pressure factors. Offshore wind farms can, for example, act as steppingstones for non-indigenous species and have an impact on biodiversity, food webs and the integrity of the seabed.

In order to assess whether good environmental status has been achieved, the commission has initiated work to define criteria and methodological standards (indicators) for each descriptor and agreed on some threshold values. This work is ongoing.

In summer 2023, the European commission decided on two threshold values for descriptor 6: Sea-floor integrity[2]. For seabed habitats to be in good environmental status, the thresholds for extent of loss and adverse effects on seabed habitats are:

- no more than 25% should be adversely affected by human pressures
- no more than 2% should be irreversibly lost

More targets for additional indicators are expected to be decided upon by the EU in the future. The chosen thresholds are based on a strategy paper by The Technical Group on Seabed Habitats and Sea-floor Integrity[3], which details for the 25% target: that the *"spatial extent of each habitat type which is adversely affected, through change in its biotic and abiotic structure and its functions (e.g. through changes in species composition and their relative abundance, absence of particularly sensitive or fragile species or species providing a key function, size structure of species), by physical disturbance"*. It also defines that the thresholds apply to each broad habitat type. For this purpose, in an EU wide project, the broad habitats have been updated for application of the MSFD (Vasquez et al., 2023). In addition, there have been no national or EU-level decisions regarding the baseline year for the natural extent of the habitats against which the loss is to be assessed nor was a decision taken on the specific geographic units (subregions) to be used for the assessment at the onset of the report.

While it is acknowledged in the description of descriptor 1, marine biodiversity[1], that biodiversity is relevant for the benthic habitats, descriptor 1 does not encompass the benthic habitats, and they are purely managed by the thresholds of descriptor 6.

Preventing loss of broad habitats, or at least minimizing the area reduction within each region, should help maintain gamma (landscape) diversity. Gamma diversity is defined as the overall species diversity across a geographic area or region (Kier et al., 2005; Brummitt et al., 2021), an important index when considering optimizing land use, spatial planning and wildlife conservation. As species require particular niche(s) to proliferate, providing a diversity of broad habitats or niches will provide the greatest opportunity for the continuation of current marine biodiversity and related ecosystem services (Carlucci et al., 2020; Richards & Lavorel 2023).

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[2] Descriptors under the Marine Strategy Framework Directive. European commission link: https://environment.ec.europa.eu/topics/marine-environment/descriptors-under-marine-strategy-framework-directive_en#:~:text=In%20the%20marine%20strategies%20EU%20Member

[3] Common Implementation Strategy - Recommendations from TG Seabed. https://circabc.europa.eu/ui/group/326ae5ac-0419-4167-83ca-e3c210534a69/library/5fc8729b-7cc4-4f53-869c-9c56f6907416/details

Disturbances

Offshore windfarms introduce a variety of different and distinct disturbances onto the marine seafloor, such as habitat change through the introduction of wind turbines into the environment. The wind turbines, cables and the scour protection (rock dump) can introduce hard substrate into previous soft sediment environments. Initial disturbance caused by deploying these structures includes penetration, abrasion and damage to surface and sub-surface features. The trenching, jetting and ploughing required for the installation of an offshore windfarm will also cause similar disturbances, however, also with an increase in suspended material in the water during construction. The increased input of suspended material into the water column will increase turbidity and, potentially, suffocate the marine benthic fauna within the surrounding area.

The deployment of offshore windfarms will introduce several disturbances including hydrological changes, with water movement (tide, wind and ocean currents) modified by structures, which can cause a shift from a high to low energy environment or *vice versa*. The changes in the energy of water movement would likely be reflected in substrate, sediment transport/supply, topography and biota. Increased mixing between nutrient rich bottom water and nutrient poor surface water may also stimulate primary production downstream the farm area. Further disturbances could include electromagnetic fields (Gill, 2005), an increase in underwater noise (Faulkner et al., 2018) and a greater chance of contamination by pollutants (Tyler-Walters et al., 2022) altering the behaviour, development or survival of disturbance-sensitive species.

However, beyond the initial deployment, the hard substrate itself is a new artificial substrate that can substantially change the character of the local area, e.g. from mud or sand to rock and biogenic reef. The influence of hard substrate can also extend to the surrounding area, termed reef effect (Degraer et al., 2020), through the deposition of shell and attraction of more or other fish species and other predators. Previous work has estimated this effect to extend to < 100 m range beyond the scour (Wilhelmsson & Malm 2008); however, studies on Anholt suggests this could be up to 120 m and water current dependent (Dahl et al., 2025b)

The installation of offshore windfarm turbines and scour protection introduces hard substrates and provides substrate for benthic invertebrates to settle and grow on and shelter for fish and crab (Wilhelsmsson et al., 2006; Wihlhelmsson & Malm 2008). However, the wind turbines themselves can create water drag and associated turbulent mixing on regional scales (Christiansen et al., 2023). Within local region, the turbines have decreased seasonal stratification and enhanced vertical mixing in the surrounding areas (Cazenave et al., 2016). Epifaunal species, such as blue mussels (*Mytilus edulis*), benefit from enhanced advective food supply, with increased inputs to the seafloor of excreted ammonium and fecal pellets resulting in increased biomass in the infauna community (in specific areas) (Maar et al., 2009). The 'reef effect' from offshore windfarms is generally attributed to some degree of 'bottom-up' controls, with increased productivity on the turbine itself translating to the surrounding community.

The 'reef effect' is further complicated, however, by the attraction of predatory species to hard erect structures on the seafloor. The predators will prey upon the surrounding fauna, creating a 'top-down control'. Large boulders as scour protection provide ideal habitat for shore crabs (*Carcinus maenus*) for prey and shelter. Field studies found highly abundant crab populations around wind turbines that could not be sustained by the food sources in the nearby surroundings, even with enhanced production (Maar et al., 2009). This would suggest that crabs are migrating away from the turbines, exporting their predation pressure (top-down control) to more remote environments and returning to the scours for shelter. This hypothesis would concur with the exceptionally low biomass detected in the infauna surrounding the turbines (Maar et al., 2009), with an increase in productivity at the prevalent downstream area due to 'bottom-up' increased productivity. Further evidence is presented by artificial reef studies that found the increase in predatory species exceeds the increased productivity (Smith et al., 2016).

The introduction of offshore windfarm turbines and scour protection will likely change the ecosystem dynamics with a combination of 'bottom-up' and 'top down' controls. Both 'bottom-up' and 'top down' controls will likely interact and export their influence well beyond the range of the foundations. However, research is ongoing, and the predicted influence of the 'reef effect' is still unclear. An assumption had to be made on the prevalent water currents, nature of the foundation (size of turbine, and size/extend of boulders), and fishing pressures would be key factors in the dynamics of the 'reef effects' and, eventually, degree and area of influence. Going forward, this report will consider these changes and place them within historical and ecological context within the wider marine environment.

Fishing is one of the dominant disturbance activities affecting European waters. Particularly concerning are the adverse effects of bottom contacting gear on the seafloor, with some of the highest intensities detected within the Skagerrak-Kattegat (Eigaard et al., 2017). Mobile bottom-contacting fishing gear reduces the biodiversity and biomass, has a negative impact on benthic habitat complexity and alters functional and productivity of the benthos (Collie et al., 2000, Kaiser et al., 2006, Buhl-Mortensen et al., 2016, Hansen & Andersen 2024).

Inner Danish waters have been trawled for at least 80 years, with the majority, of trawling causing several direct and indirect changes to the benthic environment (Riemann & Hoffmann 1991, Hansen & Andersen 2024). The impact of fisheries has been highlighted to reinforce that when investigating disturbance on the seabed, the current state of the seafloor is far from a pristine state, and discussing effects of introduction of offshore windfarms must be considered with this perspective. Often, the deployment of offshore windfarms restricts the access to the area of bottom contacting gear, and removing this disturbance effect may cause a dramatic shift in the benthic community.

Recovery and sensitivity

As discussed previously, offshore windfarms introduce a variety of different disturbance factors to the marine environment, however, the response of the benthic communities and species is not universal. Benthic fauna and flora may have a high tolerance to the disturbance factor (i.e. smothering), this is termed *resistance* and can lead to reduced or completely negated impact. Other benthic fauna and flora may not be able to tolerate the disturbance itself, but rapidly recover or re-invade the unoccupied niches, termed *resilience*, returning to the previous state within a short duration (Hughes et al., 2007).

Benthic communities may also be dependent on the surrounding communities' and habitats' composition and disturbance state, as these are the source of new larval recruitment or new individuals to replace those lost. The dependency of a disturbed community on surrounding areas for recovery can be considered as *recovery regimes*, with a spectrum from *isolated regimes,* which rely on recovery from internal sources, to *rescue regimes,* which rely on external (surrounding) sources for recovery (Zelnik et al., 2019).

Due to the complexity of interaction between types of disturbance, habitat types, species, resilience, resistance and recovery regimes, the community responses can be challenging to forecast. As such, this report includes a conservative approach considering the entire offshore site as *adversely affected*, with the caveat that benthic community change will vary in response and recovery. This report will analyse the benthic fauna within benthic broad habitats and discuss likely impacts and changes within these habitats given offshore windfarm installation.

Aim

The aim of this report is to provide sensitivity information on benthic habitats (and associated fauna and flora) across the Danish waters divided into the North Sea/Skagerrak, Kattegat and the Baltic Sea in relation to the installation, maintenance and decommissioning of new offshore windfarms.

This report addresses the available data within Danish waters, analysing knowledge gaps and highlighting areas of insufficient data coverage and where further data on the benthic environment would be required. The analysis includes all recent sampling efforts within the past 10 years across Danish waters and contextualizes the confidence we can place in the report's conclusions.

The sensitivity analysis will be ranking the area coverage of each broad habitat, assuming that less common habitat types are more sensitive and the more common habitat types less sensitive. Further benthic community analysis will also be provided, describing the difference in structure, abundance and species composition between habitat types and subregions and providing details of the communities impacted by future OWF construction.

The report will also assess the potential effect of the expected OWF development until 2030 in relation to set targets for the MFSD descriptor benthic integrity.

2 Methods

We divided the study area into the three subregions North Sea/Skagerrak (NS), Kattegat (KT) and the Baltic Sea (BS), broadly following MSFD delineations. The chosen boundary between North Sea/Skagerrak and Kattegat is the HELCOM border at Skagen. Kattegat includes parts of The Sound and is delineated from the Baltic Sea at the Sound bridge and at a line between Ebeltoft and Sjællands Odde.

To focus on the broad habitats suitable for OWFs construction, we excluded a zone one kilometre from the shoreline and all fjords. The approach included removing the closed fjords, Wadden Sea, and simplifying the exclusion to also span areas enclosed by islands.

All available data sources were checked for data necessary for the analysis, including updating the broad habitats data with new sediment information and combining soft bottom fauna baseline data for MSFD habitat mapping projects and planned OWF with data from the Danish monitoring program. Soft bottom sample density was analysed across all subregions using a 16 km buffer around the stations to describe sample distribution. Soft bottom samples and hard bottom sampling station were overlayed onto broad habitats and subregions to identify which areas were either completely or partially lacking biological monitoring. This information was considered carefully when drawing conclusions and considering the confidence in the results.

2.1 Sensitivity analysis

The sensitivity analysis is based on the sizes of the broad habitats for each of the three subregions, with rare broad habitats (lower spatial extent) relatively more sensitive to an impact than common broad habitats (greater spatial extent). This relates to the risk of exceeding threshold values set for the MSFD descriptor seabed integrity (maximum 2% irreversible loss and no more than 25% adversely affected by human pressures). The strength of this approach is therefore that by preventing habitat loss or fragmentation of already rare broad habitats, it should keep gamma (landscape) diversity as high as possible.

To be able to classify the sensitivity of a given broad habitat in a given subregion into three classes: *Higher Sensitivity*, *Medium Sensitivity* and *Lower Sensitivity* based on area coverage, two threshold values were set:

- The threshold value between higher and medium sensitivity was set to 5% cover of the subregion area.
- The threshold value between moderate and lower sensitivity was set to 15% cover of the subregion area.

The threshold values were decided upon after an iterative process, which on one hand identified areas of highest sensitivity, but on the other hand also left space for future wind farms, which will be limited by other factors as well. The purpose of the sensitivity data generated in this step is to be used in the further process of mapping the overall sensitivity of nature, environmental, wind and hydrodynamic conditions in relation to windfarms.

2.2 Coverage of existing OWFs and future OWF development until 2030

A scenario for development of OWF describing existing OWFs and the expected OWF development until 2030 (Danish Energy Agency 2024) was provided for all work packages under the project Environmental Mapping and Screening Of The Offshore Wind Potential In Denmark. (Danish Energy Agency, 2024).

The impact assessment is based on the percentages of the broad habitat types covered by a development scenario in relation to the targets set by the MSFD. The MSFD targets set in 2023 for descriptor 6, seabed integrity, require that no more than 25% of the seabed habitat is adversely affected by human pressures, and they set a limit of 2% for irreversible loss. When considering what is reversible change and what is adversely affected by human pressure, the report builds on previous work in this field that considers > 25 years community shift as irreversible or habitat loss and < 25 years as adversely affected (Tyler-Watt et al., 2022). An example of irreversible impact or loss would include the introduction of hard substrate and subsequent change of habitat, whereas the increase in marine noise due to increased marine traffic would be considered reversible.

2.2.1 Potential Impact levels of OWFs

Turbine towers in Danish waters have been constructed in areas dominated by soft(er) sediment (sand to gravel). There is no doubt that the physical construction of wind towers and the surrounding scour protection changes the habitat condition from an infauna dominated community to an epibenthic community. This change is considered a loss of habitat and due to the expected long lifetime of the turbines and the unknown future use of designated park areas, it is assessed as a permanent change.

It was found highly likely in a study at Nysted Wind Farm that there is a reef effect (increased top-down control) caused by increased predation pressure on the surrounding seabed (Maar et al., 2009). In the Anholt study (Dahl et al., 2025b), part of this overall screening project, we found a minor effect on benthos up to 130 m at the outer boundary of the investigated area, measured as the distance from the nearest turbine or scour protection. Due to lack of scour protection at two of three studied turbine towers and changing seabed habitats, we cannot determine with certainty whether the observed reef effect is caused by a top-down effect or whether there is a minor bottom-up effect. The size and magnitude of hydrographic changes generated by windfarms have so far not been well documented. However, new knowledge is expected to emerge from model work and *in situ* measurements initiated by the Danish Energy Agency and conducted by DCE as part of the overall strategic project.

Due to this lack of consensus within the field, the assessment is conducted with three types of potential impact. The impacts are organized in three levels with an increasing number of interacting factors and greater spatial extents involved, but with different levels of knowledge and confidence.

The calculations of spatial impact of direct construction impact (type 1) and reef effect (type 2) on different broad habitats are not based on the exact positioning of wind turbines, but only on the number of mills within a park. The spatial impact is calculated based on the extent of the wind park itself and the broad habitats it overlaps.

Type 1: Direct construction impact

The areas were calculated based on the numbers of mills in each OWF. As a simplified approach, a circular area with a radius of 24 m (Glarou et al., 2020) was assumed for a turbine and the scour protection resulting in assumed loss of habitats of 1,810 m^2 per wind turbine. The impact of other installations (e.g. the power converter stations) and cables was not considered spatially, causing an underestimation of the impacts. In this report, we consider the impact as an irreversible loss of broad habitat, as the impact will exceed 25 years and completely alter the habitat fundamentally.

Type 2: Reef effect

Previous work has placed the extent of the "reef effect", the range of influence on the benthic community, at < 100 m, however, the work at Anholt suggests it may be > 120 m, depending on the water current. Given the current state of knowledge, 100 m from the center point of the turbine should cover the majority of the influence, and as the potential of "reef effect" diminished with the distance, the exact end-range could be difficult to detect. Furthermore, there are suggestions that the type of scour protection and other factors will alter the influence of the "reef effect" in both magnitude and extent (Dahl et al., 2025b, Maar et al., 2009). Alterations to the radius will change the area of marine habitat lost, but, in most cases, not which marine habitat type is removed. Thus, in this study, we have decided to use an annulus with a radius of 100 m from the center of the wind turbine position, but exclude the area of the construction impact. This results in an area of 29,606 m^2 per wind turbine (approximately three hectares). The impact acts on the biological component of the habitat and, in this context, we consider the reef effect as an adverse effect and not an irreversible habitat loss, as, although it could last >25 years, this represents an alteration to the community and not a fundamental change in habitat.

Type 3: All other potential impacts

The on-going anthropogenic disturbances during the operational phase tend to be relatively minor, but continuous. This includes changes to the hydrography of the area (with its own related impacts – i.e. reef effect discussed in level 2), increased boat traffic, marine noise in the area and changes in the electromagnetic field. Further effects, such as larval production and dispersal, could lead to non-local impacts, or the new hard substrates can act as stepping stones for non-indigenous species. The one exception to this is the *presumed* removal of bottom contacting fishing activity from the offshore windfarm site. Removal of fishing pressure will likely lead to rapid changes (recovery) in the community, exceeding that caused by the offshore windfarm.

The negative effects on the benthic habitats are not limited to the area of the OWF. In lack of more detailed knowledge on the order of magnitude of impacts on the benthic habitats, the complete OWF areas, as provided in the scenario 2030, were assumed to be impacted. This may constitute a worst case of the effects of OWFs on benthic habitats. The impact is considered as an adverse effect and not an irreversible habitat loss, as, although it could last >25 years, this represents an alteration to the community and not a fundamental change in habitat.

2.3 Description of the communities of the broad habitats

2.3.1 Soft bottom fauna

Initial analysis of the soft sediment benthic fauna included a biodiversity assessment (Shannon Index, $H' = \log n - \frac{1}{n}\sum_{i=1}^{k} \log p_i$, Shannon & Weaver, 1963) of each broad habitat within each subregion (North Sea/Skagerrak, Kattegat and Baltic Sea). Of primary interest were species richness and Shannon diversity index, with the latter adding a measure of evenness into the metric. After concluding that both metrics provided similar results, data on the Shannon diversity index were reported in the results, since the Shannon diversity includes a weighting of rare species, while also accounting for species abundance (Figure 2.10).

Soft sediment benthic data was reviewed and processed for multivariate analysis and imported into PRIMER V7 software. This was used to compare the similarity and dissimilarity soft-sediment benthic community within multivariate space, with each species/taxa considered a variate. The benthic data contained a large amount of low and zero values, and to prevent a singular highly abundant taxa from dominating the statistical analysis, a fourth root transformation was performed across all the data. Shade plots were used to confirm that this transformation appropriately scaled the data, allowing a greater influence of rare and low abundance taxa. The transformed data was then used to construct a Bray-Curtis similarity index comparing the resemblance (similarity) of all stations.

Bray-Curtis similarity index was tested with a 2-way crossed ANOSIM (Analysis of Similarity). This is a non-parametric test of significance difference between groups (Table 4.10). The test for difference between subregion groups across all broad habitats and the test for difference between broad habitats were analysed across all subregions.

Multivariate analysis results were displayed using a nMDS (non-metric Multidimensional Scaling). Due to the high number of zero values (absent species), with many stations having a few species, all nMDS graphs had a 0.1 metric proportion correction applied to prevent data collapse. nMDS data collapse occurs when there is a high number of variables with the same value (in this case many species with 0 abundance) across all stations, which causes the non-metric scaling to move these points too close together in multidimensional space.

The representative species for the significant differences between and across stations, subregion and broad habitats, were explored using one and two-way SIMPER analysis (Similarity Percentages) on the transformed data. This identified the species/taxa that contributed most to the significant differences between stations and which species were highly abundant or shared among these groups. A short overall description of the most common species for each broad habitats in the three subregions was also given.

2.3.2 Eelgrass and hard bottom flora and fauna

The spatial extent of eelgrass beds today is not known, only the coverage along transects selected due to the presence of the species. Known transects with eelgrass populations are presented on a map but are not used further in the assessment.

Hard bottom flora and fauna are associated with either bedrock or boulders and cobbles. Boulders and cobbles on the seabed can be found within the mixed substrate class. In this report, classification of communities on hard bottom of flora and fauna is not conducted due to limited financial resources. However, a short expert description is provided for each of the three subregions.

3 Data

3.1 Benthic broad habitats

The benthic broad habitats are based on the EUSeaMap, which was released in 2023. The release includes the sixth version of the broad habitats with the new EUNIS classification system adopted in 2021. EUNIS codes and the MSFD broad habitats, a compatible and linked system, were provided to be used in the context of the Marine Framework Directive (Vasquez et al., 2023); the latter is the system used for the current analysis. The MSFD broad habitats include sediment information and biological zones similar to the EUNIS broad habitat types, but the sediment information can utilize different aggregation levels.

The broad habitats are a combination of the seabed substrate and environmental parameters that describe the biological zones (Vasquez et al., 2023). The Danish waters cover the infralittoral, circalittoral, offshore circalittoral and upper bathyal zones.

Infralittoral and circalittoral are delineated by seabed PAR (photosynthetically available radiation). The parameters used for the delineation of circalittoral/offshore circalittoral are wavelength and depth for the North Sea/ Skagerrak and depths for Kattegat. In the Baltic Sea, it is either depth or the probability that the seafloor is below the halocline, depending on the salinity of the area. The border between offshore circalittoral and upper bathyal is defined by the depth. (Vasquez et al., 2023)

The broad habitat types use a modified version of the Folk classification system having seven sedimentary substrates, hard substrates and, additionally, biogenic substrate (Vasquez et al., 2021, 2023) delineating the following types or a combination thereof:

- Rock
- Coarse Substrate
- Mixed Sediment
- Sand
- Muddy Sand
- Sandy mud
- Mud

The broad habitats for Danish waters are based on the Danish sediment map (Leth et al., 2021) and the independently modelled biological zones by EUSeamap (Vasquez et al., 2023). This makes it possible to update the sediment information and combine it with the biological zones to replace sediment information for areas, where new data is available, but not included in the broad habitats map.

Two types of data were available for an update: Sediment data from the geological surveys from the preliminary site investigations for planned OWFs and substrate data from a survey for the MSFD in the North Sea (Table 3.1, Figure 3.1). The Broad habitats map is updated as part of conducting this analysis.

Table 3.1. Data summary for the update of the broad habitats. If not stated otherwise, the data includes sediment information. *The geographical area is shown in figure 2.2

Data description	Project	Time period	Geographical area*	Data provider	Data status
Sediment information	Thor	Not examined	1	GEUS	Included
Sediment information	Nordsø I	Not examined	2	Energinet	Included
Sediment information	Kattegat	Not examined	3	Energinet	Included
Sediment information	Hesselø South	Not examined	4	Energinet	Included
Sediment information	Hesselø cancelled	Not examined	5	Energinet	Included
Sediment information	Kriegers Flak II	Not examined	6	Energinet	Included
Sediment information	Bornholm south	Not examined	7	Energinet	Included
Sediment information	Bornholm north	Not examined	8	Energinet	Included
Sediment information	Vesterhav Syd & Vesterhav Nord	Not examined		GEUS	Excluded due to its very small area
Substrate information	NS habitat mapping	2019-2020	9	GEUS	Included

In Danish usage, the term substrate refers to the uppermost seabed (approximately upper 10 cm) of the seabed and the term sediment describes the deeper layers of the seabed (approximately 50 cm). Substrate and sediment are using different classification systems (Table 3.2.)

Data for the planned OWFs were provided as sediment information and were therefore included following the same methodology with which the Danish sediment map was converted. Even though the data were provided as sediment, there can be differences in equipment and methodology used to collect the data. This can lead to differences when the data is officially integrated into the sediment map compared to the approach in this project.

The substrate mapping in the North Sea was conducted by GEUS. After consultation of Jørgen Leth, GEUS, we decided to include the data as well, since it improves the survey density in the North Sea considerably.

The sediment and substrate classes were converted to the MSFD habitat types as shown in table 3.2. The table covers only conversion for those biological zones where data for update was available.

Table 3.2. Conversion of sediment and substrate to classes used in the MSFD broad habitat types for the areas, where data was available

Sediment	MSFD class	Substrate
Mud and sandy mud	Mud	
Muddy sand		1a: Silty sand
Sand	Sand	1b: Sand (incl. sandbanks)
Gravel and coarse sand	Coarse sediment	2a: Sand, gravel and pebbles - few larger stones
		2b: Sand, gravel, pebbles – seabed cover of larger stones 1-10%
Quaternary clay and silt	Mixed Sediment	1c: Patterned sandy bottom/solid clay with sand
Till/diamicton		3: Gravel, sand and large stones 10- 25%
		4: Gravel, sand and large stones > 25%
Sedimentary rock	Rock and biogenic reef	

Despite efforts to harmonize methodology, different sediment aggregations can be used by different countries based on the mapping history in the respective country. For the extracted data, the class "Circalittoral mud or Circalittoral sand" is used by Sweden and stretches slightly into the Danish EEZ around Bornholm.

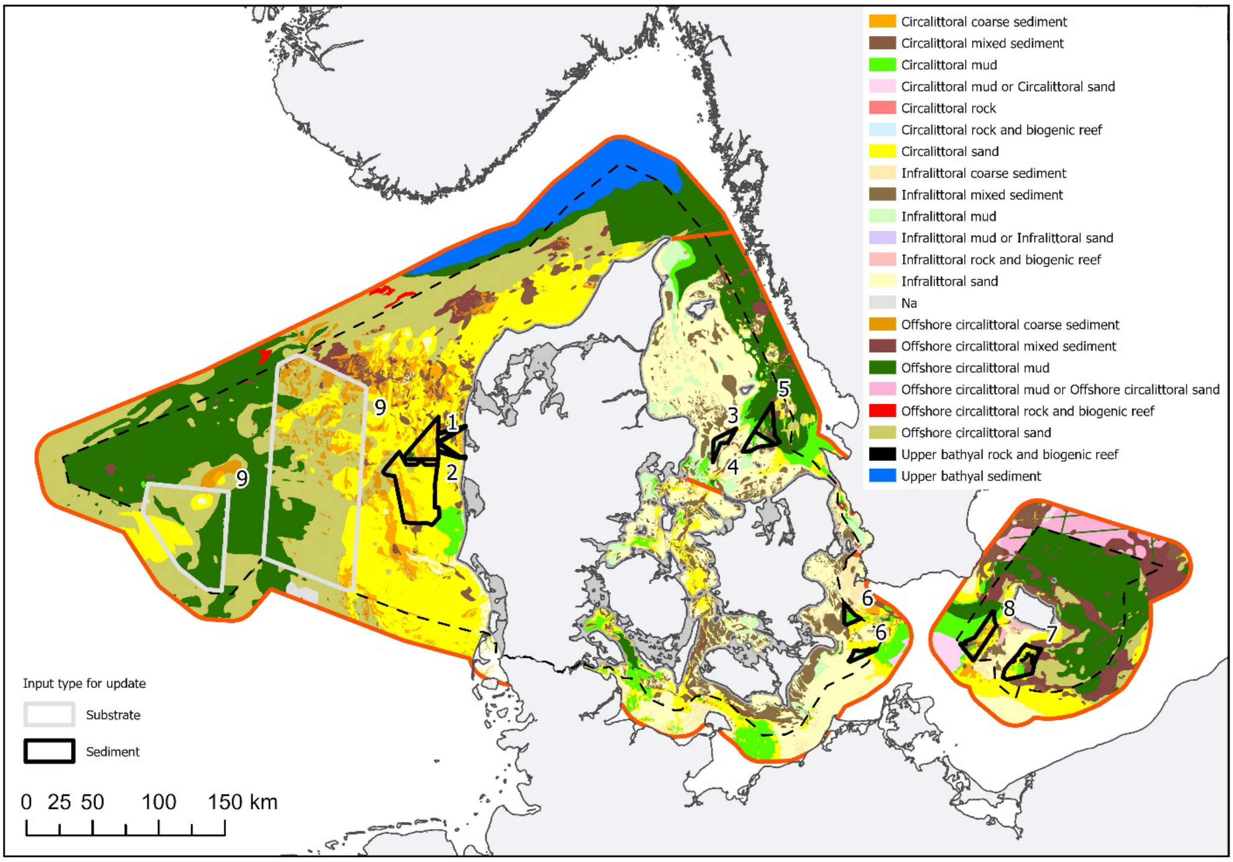


Figure 3.1 Broad habitat types and the nine areas (table 3.1) where the sediment information was updated (larger version available in appendix)

3.2 Monitoring data

3.2.1 Soft Bottom Fauna

The benthic soft bottom fauna is monitored as part of the national program (Det Nationale Overvågningsprogram for Vandmiljø og Natur - NOVANA). The program follows specific technical guidelines (Hansen & Josefson, 2020), and data is stored in the Vanda database. NOVANA samples are taken with two different strategies: as point stations, where up to ten samples are taken at the same location, or sample areas, where the 42 samples are spread over a larger area (Hansen & Høgslund, 2024).

Additionally, we identified soft bottom fauna baseline data for MSFD habitat mapping projects and planned OWF (Energiø Nordsøen and Hesselø) that follow or almost follow the technical guidelines in the period between 2014 and 2023. (Table 3.3, Figure 3.2)

Data from baseline studies for the OWF and MSFD habitat investigations might deviate from the guidance by only containing single samples per station. This deviation is acceptable for the scope of this report. The MSFD habitat mapping data is included in the Vanda-database as well.

Tabel 3.3. Data summary for soft bottom fauna analyses conducted between 2014 and 2023 The geographical area of the available data is shown in figure 3.2. For the unavailable data, we did not collect information about extent or data provider

Data description	Project	Time period/Publication date	Geographical area	Data provider	Data status
Monitoring data	NOVANA data	continuous	Danish EEZ	MST	**Included**
Monitoring data	Sæby Offshore Wind Farm, Sediments, water quality and hydrography. Energynet.dk.	2014	Not examined	Not examined	Unavailable
Monitoring data	Bundfaunaundersøgelser fra Sæby Havmøllepark (Rambøll, Sæby Offshore Wind Farm. Benthic flora and fauna	2014	Not examined	Not examined	Unavailable
Monitoring data	Oil and gas industry monitoring data	continuous	Not examined	Not examined	Unauthorized
Monitoring data	Habitatkortlægning, Lillebælt syd	Publication date 2022	Not examined	Not examined	Unavailable
Monitoring data	Vesterhav Nord Offshore Wind Farm and Grid Connection: Baseline and EIA report on benthic flora, fauna and habitats.	Publication date 2015	Not examined	Not examined	Unavailable
Monitoring data	Marinbiologiske baselineundersøgelse, Omø syd	Publication date 2014	Not examined	Not examined	Unavailable
Monitoring data	Horns Rev 3 Offshore Wind Farm. Benthic Habitats and Communities. Technical report no. 4,	Publication date 2014	Not examined	Not examined	Unavailable
Monitoring data	Kortlægning, Omø Syd	Publication date 2016	Not examined	Not examined	Unavailable
Monitoring data	Bunddyr og -planter, Kriegers Flak	Publication date 2019	Not examined	Not examined	Unavailable
Monitoring data	Bundflora og -fauna, Energiø Nordsøen	2022	NS energiø, 2022	Aarhus University	**Included**
Monitoring data	Bundflora og -fauna, Energiø Bornholm	Publication date 2022	Not examined	Danish Energy Agency	Unavailable
Monitoring data	Bundflora og -fauna, Hesselø	2021	Hesselø, 2021	Aarhus University	**Included**
Monitoring data	Bundflora og -fauna, Nordsø Lot 1	Not published	Not examined	Not examined	Unavailable

From the available data, we selected the latest sample of the station within the period 2014 -2023 for the analysis (Figure 3.2). We worked with the positions of the samples for the calculation of the coverage and overlay with the polygon data from the previous steps.

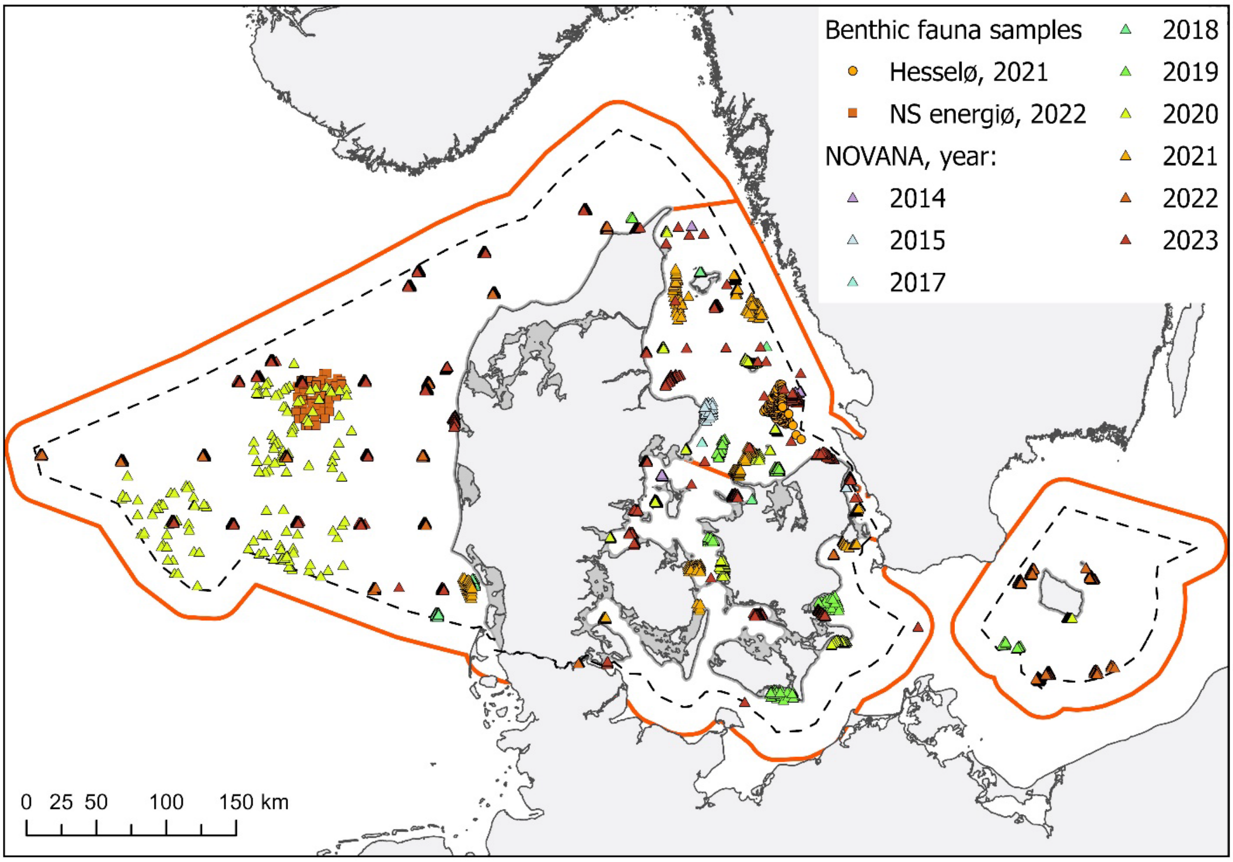


Figure 3.2. Sample positions for soft bottom fauna and time of the last monitoring

3.2.2 Eelgrass

Eelgrass monitoring is a major component in the NOVANA monitoring program (Bruhn et al., 2022). Eelgrass can be found on a range of sediments from coarse sand to muddy sand. Eelgrass meadows rarely exceed 6 meters depth along the coastline of inner Danish waters and even less in the fjords (Hansen & Høgslund, 2023). Figure 3.3 top shows the distribution of the full eelgrass monitoring program. Most sampling locations are in fjord systems or so coastal that they fall out of the delineation set for this analysis (Figure 3.3 bottom). The remaining stations are too coastal, so that their potential conflicts with offshore wind development are related to land connections of the cables, which is not within the scope of this study. For this reason, eelgrass is not considered relevant for the sensitivity analysis.

3.2.3 Hard bottom flora and fauna

Hard bottom communities are also a major component in the NOVANA monitoring program (Bruhn et al., 2022) and are communities that form on, or form themselves, hard substrate, including bedrock, boulders and biogenic structures.

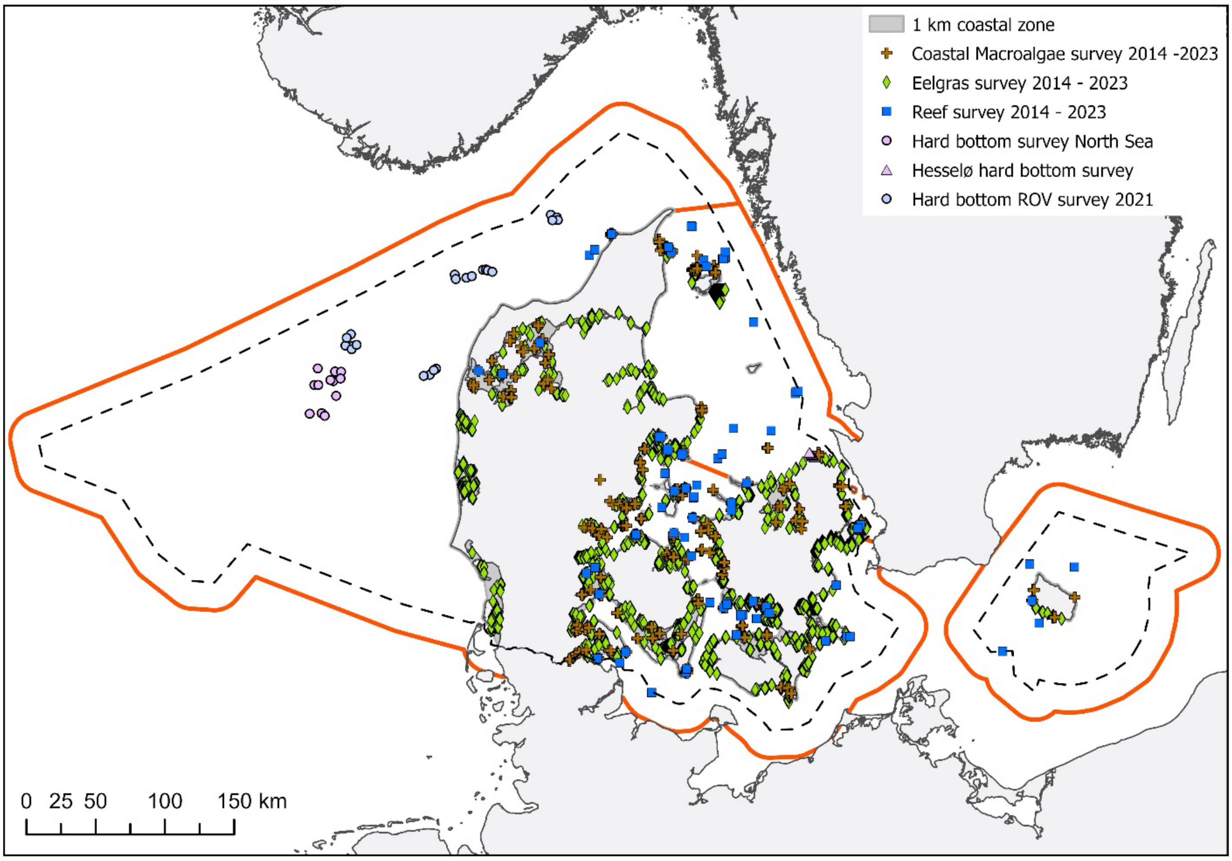
Coastal macroalgae investigations on boulders located on the mixed seabed sediment type are carried out along the coasts and, most often, at water depths shallower than 10 m (Høgslund et al., 2014). Some investigated sites also include hard bottom fauna investigations (Lundsteen & Dahl, 2017). The investigations are carried out by divers along a depth transect, where hard substrate is present. Most investigated sites are located within 1 km from the shore and, hence, excluded from this study (Figure 3.3 top and bottom).

Most investigations on reef structures in open waters are conducted by divers (Dahl & Lundsteen, 2018). On water depth deeper than 25 m in Skagerrak and the northern North Sea, monitoring is conducted by an ROV. Diver investigations are conducted at a number (2-6) of locations reflecting the depth distribution of the reef (station). ROV investigations are conducted along 100 m transects at each location. Some reef locations are investigated yearly and some once every 5 years. The locations are shown in figure 3.3 (bottom).

Some data on hard bottom flora and fauna have also been collected in the northern North Sea on patches with reef structures as part of the baseline investigation of the Energy Island. Similarly, patches of reef structures were investigated east of Gilleleje as part of a baseline investigation for the power connection to land from the planned Hesselø windfarm. The baseline investigation in the North Sea was conducted by ROV, and the investigation at Gilleleje used both ROV and diving. The OFW baseline investigations used the same guideline as used for NOVANA monitoring. Known hardbottom flora and fauna investigations are listed in table 3.4.

Tabel 3.4. Data summary for hard bottom flora and fauna, which was conducted between 2014 and 2023. *The geographic extent is shown in figure 3.3

Data description	Project	Time period/Publication date	Geographical area*	Data provider	Data status
Monitoring data, diver, ROV	NOVANA data	continuous	Danish waters	MST & Aarhus University	Included
Monitoring data ROV	Bundflora og -fauna, Energiø Nordsøen	2022	Hesselø hard bottom survey	Aarhus University	Included
Monitoring data, diver, ROV	Bundflora og -fauna, Hesselø	2021	Hard bottom survey North Sea	Aarhus University	Included



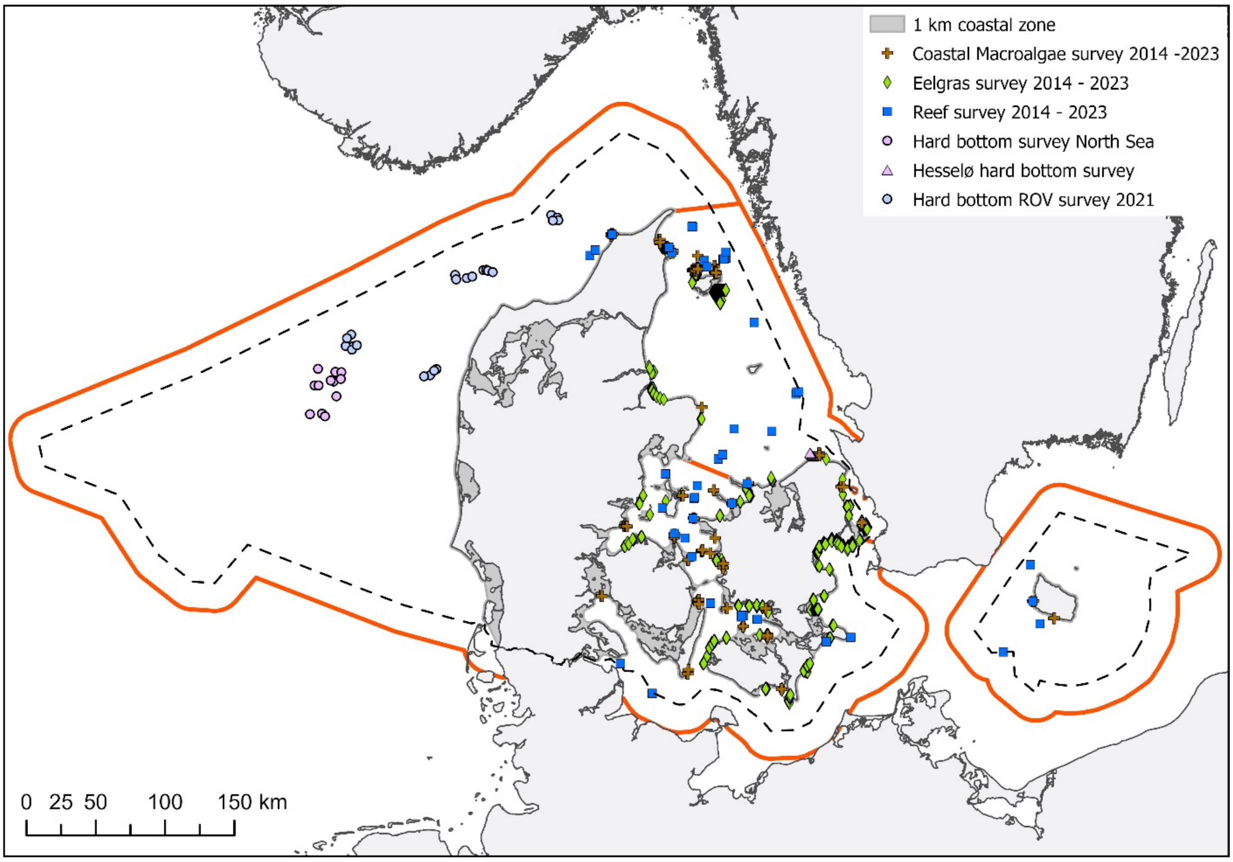
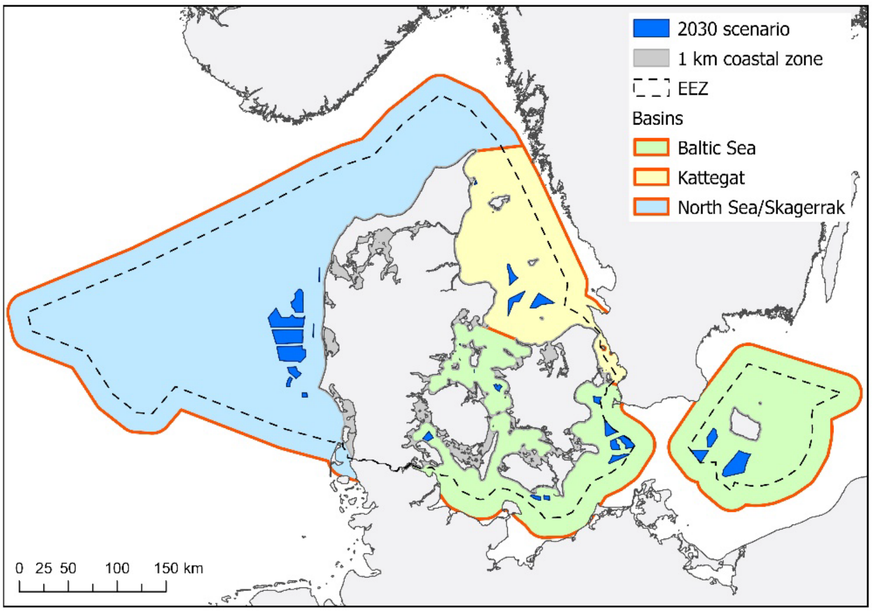


Figure 3.3. Top: Survey program for benthic flora and hard bottom flora and fauna. Bottom: survey locations for benthic flora and hard bottom flora and fauna outside the coastal 1 km buffer.

3.3 Delineations and scenario data

The EEZ border is used as the outer boundary for the analysis. We use the term EEZ to include all Danish marine waters from the coastline, including territorial and internal waters. Since two of the Danish soft bottom fauna stations (see chapter 3.2.1) are situated outside the Danish EEZ, we used a buffer of 20 km to retrieve the broad habitat types from the neighbouring countries for these stations. For the analysis of areas and densities, data outside the EEZ is excluded. (Figure 3.4).

Figure 3.4. Delineations used for the analysis of the benthic habitats. The hashed line indicates the Danish EEZ and the outer red boundary the buffer-zone.



We used information of the existing and planned OWFs until 2030 (Scenario 2030), which was provided for this project by the Danish Energy Agency (Danish Energy Agency 2024). The scenario provides data for the wind park areas and the placement and number of wind turbines per OWF (Figure 3.5). The OWF areas and the number of wind turbines were derived from the supplied GIS data for the scenario. (Table 3.5)

All delineations, including the broad habitat types and the OWF areas for the scenario 2030, were combined into one polygon layer and provided with an ID and an area. The areas were calculated in ETRS89 LAEA.

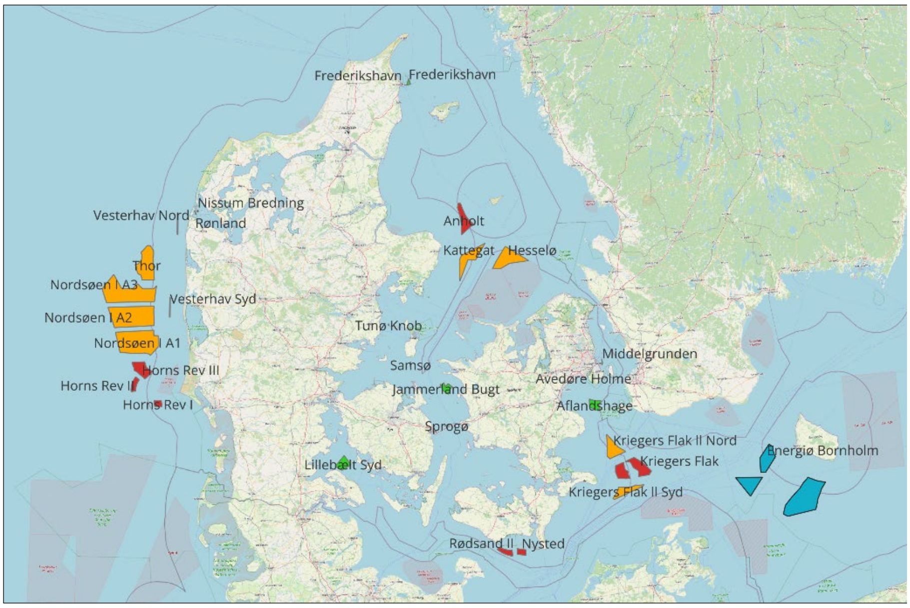


Figure 3.5. Scenario over OWF areas included in the 2030 expansion plan. Red areas represent established parks as of 2023, orange areas indicate upcoming tender zones, green areas are projects from the open-door scheme, and blue areas denote the Energy Island Bornholm. (Source: Danish Energy Agency 2024)

Tabel 3.5. Area and number of wind turbines of the OWFs contained in scenario 2030 (Danish Energy Agency 2024)

OWF name	Area km^2	Number of wind turbines
Aflandshage	43.31	26
Anholt	90.48	111
Energiø Bornholm 1	241.27	93
Energiø Bornholm 2	410.32	161
Frederikshavn	5.73	5
Hesselø	165.57	84
Horns Rev I	19.62	80
Horns Rev II	31.38	91
Horns Rev III	90.31	49
Jammerland Bugt	31.14	20
Kattegat	122.04	67
Kriegers Flak	173.15	72
Kriegers Flak ll Nord	99.24	118
Kriegers Flak ll Syd	75.26	112
Lillebælt Syd	54.21	11
Middelgrunden	0.81	15
Nordsøen I A1	401.65	67
Nordsøen I A2	400.49	67
Nordsøen I A3	400.40	67
Nysted	23.05	72
Rødsand II	31.73	90
Samsø	0.88	9
Sprogø	0.34	6
Thor	209.55	72
Tunø Knob	0.32	10
Vesterhav Nord	7.31	21
Vesterhav Syd	6.71	20

4 Results

In this study, we focused on the spatial analysis of Danish waters divided into three subregions, while specifically excluding the coastal areas. The coastal zone covered approximately 8,403 km^2. By removing the coastal zones from our analysis, the total area was approximately 96,200 km^2. Within the EEZ excluding the coastal area, North Sea/Skagerrak was the largest of the three subregions with app. 57,800 km^2, The Baltic Sea covered app. 23,600 km^2 and Kattegat was the smallest with app. 14,700 km^2.

4.1 Distribution of the broad habitat types

The Danish broad habitats were dominated by sand in the infra- and circalittoral zone and mud and sand in the offshore circalittoral zone. The different broad habitat types were not evenly distributed between the subregions. (Figure 4.1, Table 4.1)

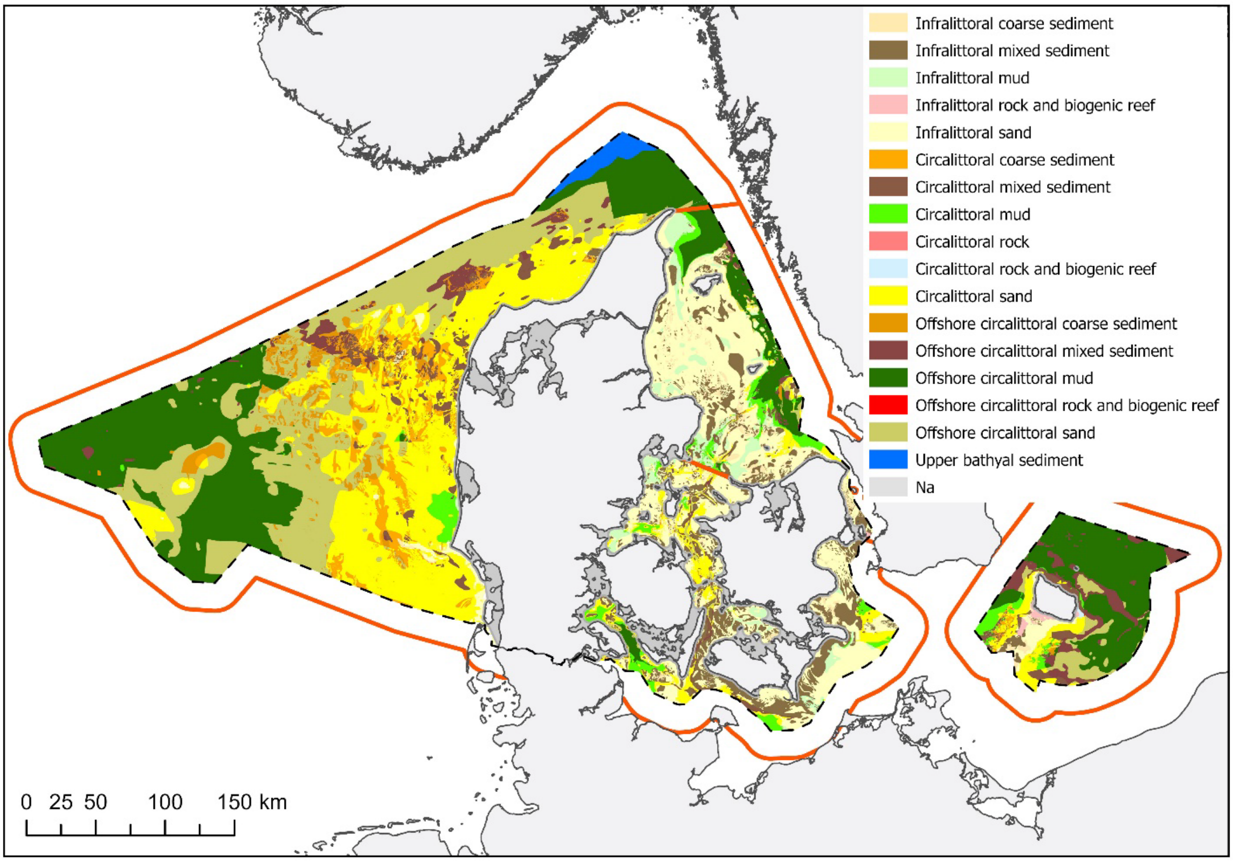


Figure 4.1. MSFD broad habitat types in the Danish EEZ. (larger version available in appendix)

In the North Sea and Skagerrak, *Circalittoral sand*, *Offshore circalittoral mud* and *Offshore circalittoral sand* dominate, each accounting for 25 – 30 % of the subregion area. Ten broad habitat types had a coverage of less than 10%, and four types present in one of the other two subregions were not present (Table 4.1, Figure 4.3).

Kattegat was dominated by *Infralittoral sand* with a coverage above 45% of the subregion area. *Infralittoral mixed sediment* and *Offshore circalittoral mud* covers 10 – 20 % of the area each, and further ten broad habitats had a coverage below 10%. Four types were not present. (Table 4.1, Figure 4.3)

Infralittoral sand and *Offshore circalittoral mud* were, with 24 %, each the most widespread broad habitat types in the Baltic Sea followed *by Circalittoral sand* and *Infralittoral mixed sediment,* with 10 – 20 %, respectively. Eleven further types were below 10%, and 9 types are not present. (Table 4.1, Figure 4.3)

Rock and *Rock and biogenic reef* were the least present habitat types and were mostly mapped in the Baltic Sea and, to a lesser extent, in Kattegat. The upper bathyal zone only occurred in the northernmost part of the North Sea and Skagerrak.

Tabel 4.1. Area and percentage of the MSFD broad habitat types in the three subregions. 34 km^2 without assigned MSFD broad habitats are not included in the analysis.

	NS		KT		BS	
	Km^2	%	Km^2	%	Km^2	%
Infralittoral coarse sediment	72	0.1%	778	5.3%	439	1.9%
Infralittoral mixed sediment	85	0.1%	1,807	12.3%	3,457	14.6%
Infralittoral mud	22	<0.1%	1,374	9.3%	646	2.7%
Infralittoral rock and biogenic reef			17	0.1%	166	0.7%
Infralittoral sand	747	1.3%	6,702	45.5%	5,653	23.9%
Circalittoral coarse sediment	3,333	5.8%	11	0.1%	149	0.6%
Circalittoral mixed sediment	1,718	3.0%	103	0.7%	1,059	4.5%
Circalittoral mud	541	0.9%	845	5.7%	1,114	4.7%
Circalittoral rock					2	<0.1%
Circalittoral rock and biogenic reef					22	0.1%
Circalittoral sand	16,732	29.0%	448	3.0%	2,766	11.7%
Offshore circalittoral coarse sediment	2,207	3.8%	28	0.2%	20	0.1%
Offshore circalittoral mixed sediment	1,479	2.6%	169	1.1%	1,361	5.8%
Offshore circalittoral mud	15,241	26.4%	2,258	15.3%	5,571	23.6%
Offshore circalittoral rock and biogenic reef					1	<0.1%
Offshore circalittoral sand	14,739	25.5%	201	1.4%	1,207	5.1%
Upper bathyal sediment	870	1.5%				
Complete subregion	57,785	100%	14,741	100%	23,632	100%

4.2 Distribution of the biological data

4.2.1 Soft bottom fauna monitoring data

A total of 4,147 samples were available for the complete study area, collected at 398 stations.

In the North Sea, the NOVANA stations were organized in an approximate grid with 45 – 60 km distance. The project-based baseline data from the habitat and the OWF investigations increased the data density. The lowest data density was found in Skagerrak and along the border to Norway. Of the three subregions, North Sea and Skagerrak had the lowest, and Kattegat the highest sample density. The Baltic Sea, east of Ertholmene, was not monitored, and the density was very low in the western Baltic's open waters south of the Belts. Coastal stations are not included in the analysis. Since the Baltic Sea subregion has a long coastline, removing the coastal stations could have had an uneven influence on the density. (Figure 4.2)

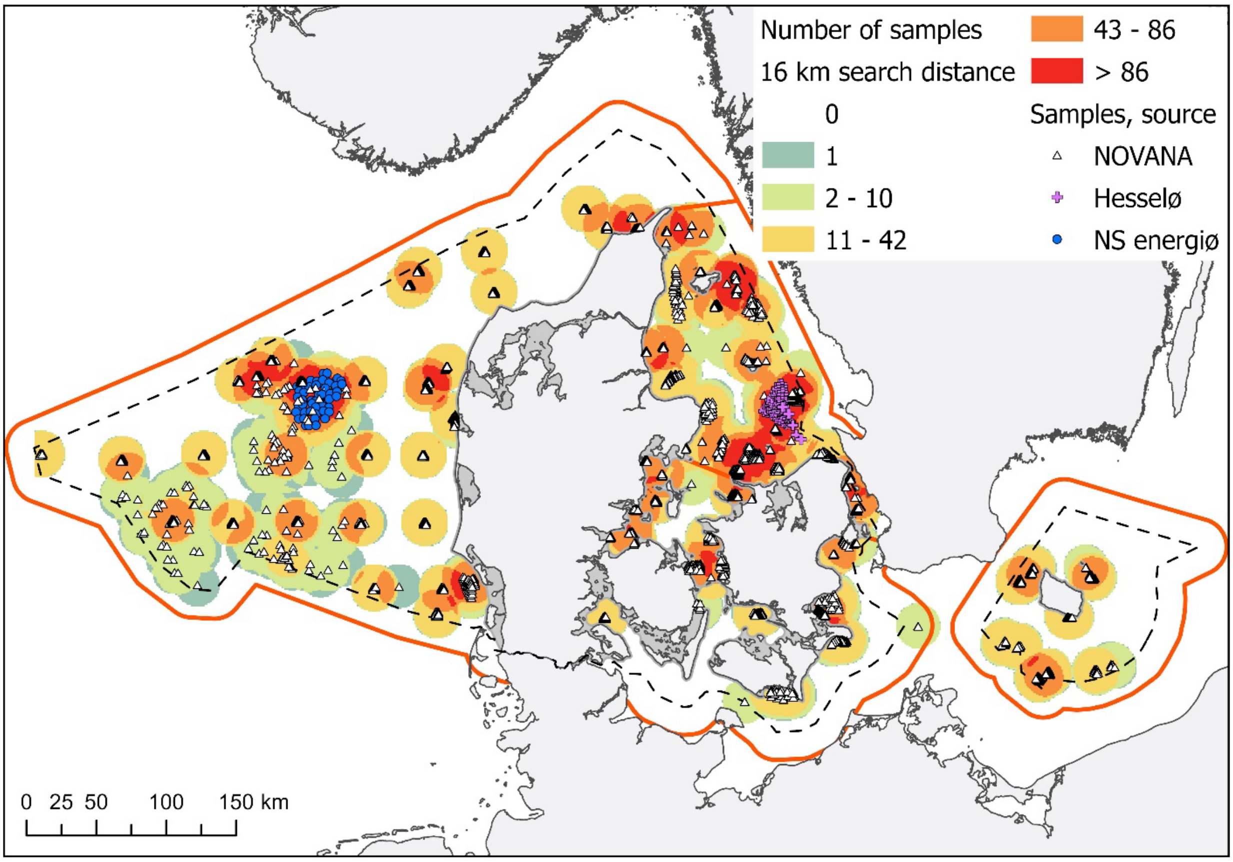


Figure 4.2. Soft bottom fauna sample positions and number of samples as point density with 16 km search distance

It is not possible to take samples in all sediment, but the classification used for the broad habitats is not in all cases detailed enough to simply exclude habitats that cannot be sampled. The softbottom sampling effort to some extent mirrors the broad habitats, with sampling on seabed with hard substrate avoided. For this reason, broad habitats, such as *mixed sediment,* are likely avoided due to low success rate.

The total study area was on average represented by 1 sample per 23 km^2, however, the sampling effort was far from uniform, with upper bathyal sediment and most of the *rock and biogenic reef* habitats not having any samples. *Offshore circalittoral mud* and *circalittoral mud* had the lowest coverage. The infralittoral zone was best covered and the softer sediments were in general covered better than coarse and mixed sediments. (Table 4.2)

Table 4.2. Number of soft bottom samples per broad habitat across all three subregions. The sampling with core or grab sampler is only possible on soft sediments. * is covered solely by hardbottom flora and fauna and ** is also covered by hard-bottom flora and fauna investigation

MSFD broad habitats	Number of samples	Density (sample/km^2)	Area/station (km^2/sample)
Infralittoral coarse sediment	96	0.074	13
Infralittoral mixed sediment**	158	0.030	34
Infralittoral mud	303	0.148	7
Infralittoral rock and biogenic reef	1	0.005	184
Infralittoral sand	1,078	0.082	12
Circalittoral coarse sediment	121	0.035	29
Circalittoral mixed sediment**	90	0.031	32
Circalittoral mud	68 +10 outside EEZ	0.027	37
Circalittoral rock*			
Circalittoral rock and biogenic reef*			
Circalittoral sand	805	0.040	25
Offshore circalittoral coarse sediment	90	0.040	25
Offshore circalittoral mixed sediment**	75	0.025	40
Offshore circalittoral mud	547 +10 outside EEZ	0.024	42
Offshore circalittoral rock and biogenic reef*			
Offshore circalittoral sand	694	0.043	23
Upper bathyal sediment			
Complete subregion	4,126 +20 outside EEZ	0.043	23

Figure 4.3 illustrates the coverage of the broad habitats in the subregions. It shows that in the three largest habitat types, *Offshore circalittoral sand* and *Circalittoral sand* had a high sample number, while the number of samples for *offshore circalittoral mud* was relatively low. The areas in Kattegat were in general much smaller, but the number of samples for *Infralittoral sand* was comparable to the highest sample numbers in the North Sea and Skagerrak. In the Baltic Sea, *Infralittoral sand* was the best monitored broad habitat type, while the similarly widely distributed *Offshore circalittoral mud* was only represented by ten samples. (Figure 4.3, Table 4.3)

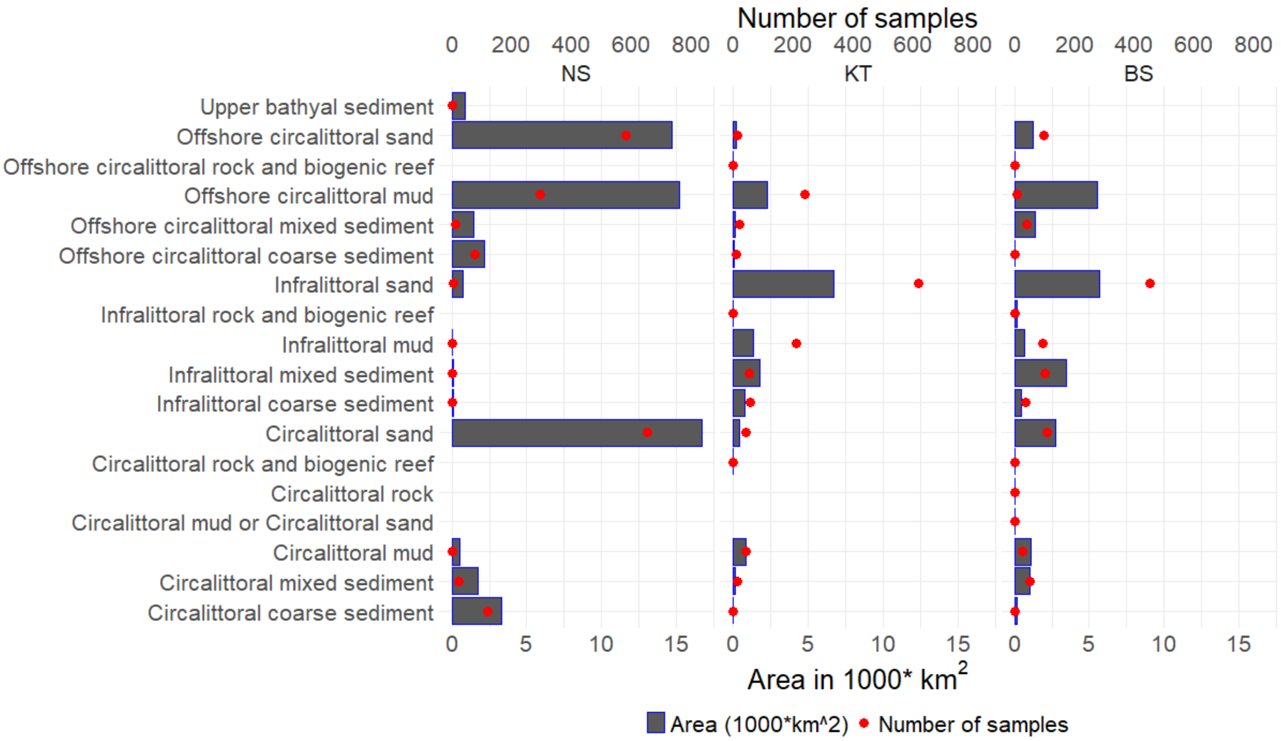


Figure 4.3. Comparison of area and number of samples in the MSFD broad habitat types in each of the three subregions. The red dots indicate the number of softbottom samples in relation to the top axis and the bars the size of the respective broad habitat (bottom axis). (BS=Baltic Sea, KT=Kattegat and NS=North Sea and Skagerrak)

Table 4.3. Number of soft bottom samples and density of samples. The samples taken outside the EEZ are not included in the density. The areas used to calculate density are from table 4.1. (BS=Baltic Sea, KT=Kattegat and NS=North Sea and Skagerrak), ---: broad habitat not present in the subregion

MSFD broad habitats	NS		KT		BS	
	Number of samples	Density (sample/km^2)	Number of samples	Density (sample/km^2)	Number of samples	Density (sample/km^2)
Infralittoral coarse sediment	0		58	0.07	38	0.09
Infralittoral mixed sediment	0		55	0.03	103	0.03
Infralittoral mud	0		209	0.15	94	0.15
Infralittoral rock and biogenic reef	---		0		1	0.01
Infralittoral sand	5	0.007	619	0.09	454	0.08
Circalittoral coarse sediment	120	0.036	1	0.09	0	
Circalittoral mixed sediment	24	0.014	15	0.15	51	0.05
Circalittoral mud	0		43	0.05	25+10 outside EEZ	0.02
Circalittoral rock	---		---		0	
Circalittoral rock and biogenic reef	---		---		0	
Circalittoral sand	654	0.039	42	0.09	109	0.04
Offshore circalittoral coarse sediment	78	0.035	12	0.42	0	0.00
Offshore circalittoral mixed sediment	12	0.008	21	0.12	42	0.03
Offshore circalittoral mud	296	0.019	241 +10 outside EEZ	0.11	10	0.00
Offshore circalittoral rock and biogenic reef	---		---		0	
Offshore circalittoral sand	580	0.039	15	0.07	99	0.08
Upper bathyal sediment	0		---		---	
Complete subregion	1,769	0.031	1,331 +10 outside EEZ	0.09	1,026 +10 outside EEZ	0.04

4.2.2 Hard bottom flora and fauna monitoring data

A total of 581 dive samples and 35 ROV samples were available for the complete study area. The samples collected by a diver covered app. 25 m^2. The samples collected using a ROV covered app. 100m^2.

Hard bottom flora and fauna were collected in specific reef sites within the habitat types with mixed sediment or at the seabed type rock. The sample distribution on subregions and broad habitats are given in table 4.4.

Table 4.4. Number and distribution of hardbottom flora and fauna samples using diver and ROV in the three subregions.

Location and biological zone	Seabed type	Method	
North Sea/Skagerrak		Dive	ROV
Infralittoral	Mixed Sediment	35	
Circalittoral	Mixed Sediment		14
Offshore circalittoral	Mixed Sediment		15
Kattegat			
Infralittoral	Mixed Sediment	267	10
Baltic Sea			
Infralittoral	Mixed Sediment	273	
	Rock	12	
Offshore circalittoral	Mixed Sediment	3	

The highest sampling density on hard substrate was done in areas mapped as *Infralittoral mixed substrate* in the Baltic Sea and Kattegat (Table 4.5). Less sampling was done at the same seabed type in the North Sea, however, the area covered of this type is considerably smaller (Table 4.1), giving a higher density (Table 4.5)

No sampling was conducted in habitats mapped as *Infralittoral rock* and *Rock and biogenic reef* in Kattegat. This habitat type refers mainly to an area in the southern part of The Sound and a very small area of limestone around Grenå that extends over the coastal zone of 1 km. Bubbling reefs might be included in this category and, in that case, some sampling is conducted, but not included in this gap analysis.

Hard substrate sampling was also missing within *Circalittoral mixed sediment* and *Offshore circalittoral mixed sediment* in Kattegat and the Baltic Sea as well as in *Offshore circalittoral rock and biogenic reef* in the Baltic Sea.

Table 4.5. Total number of dive and ROV samples and density of samples taken on hard bottom locations within areas mapped as mixed sediment and rock. 0 indicates that areas of the particular type are present without sampling.

MSFD broad habitats	NS		KT		BS	
	Number of samples	Density (sample/km^2)	Number of samples	Density (sample/km^2)	Number of samples	Density (sample/km^2)
Infralittoral mixed sediment	35	0.412	267	0.148	273	0.079
Infralittoral rock and biogenic reef			0	0	12	0.072
Circalittoral mixed sediment	14	0.008	0	0	0	0
Circalittoral rock					0	0
Circalittoral rock and biogenic reef					0	0
Offshore circalittoral mixed sediment	15	0.010	0	0	3	0.002
Offshore circalittoral rock and biogenic reef					0	0

4.3 Sensitivity analysis

The areal distribution of the broad habitats shows that the three most common habitat types lay in the North Sea/Skagerrak and the most common types were sand and mud. The least common habitat types were coarse sediments, *Circalittoral rock and biogenic reef*. *Rock* and R*ock and biogenic reef* were mostly mapped in the Baltic Sea around Bornholm and, to a lesser extent, in Kattegat. The upper bathyal zone only occurred in the northernmost part of Skagerrak. (Table 4.1)

The sensitivity analysis was based on the percentage of a habitat type within its respective subregion. The resulting sensitivity range per subregion is shown in figure 4.4.

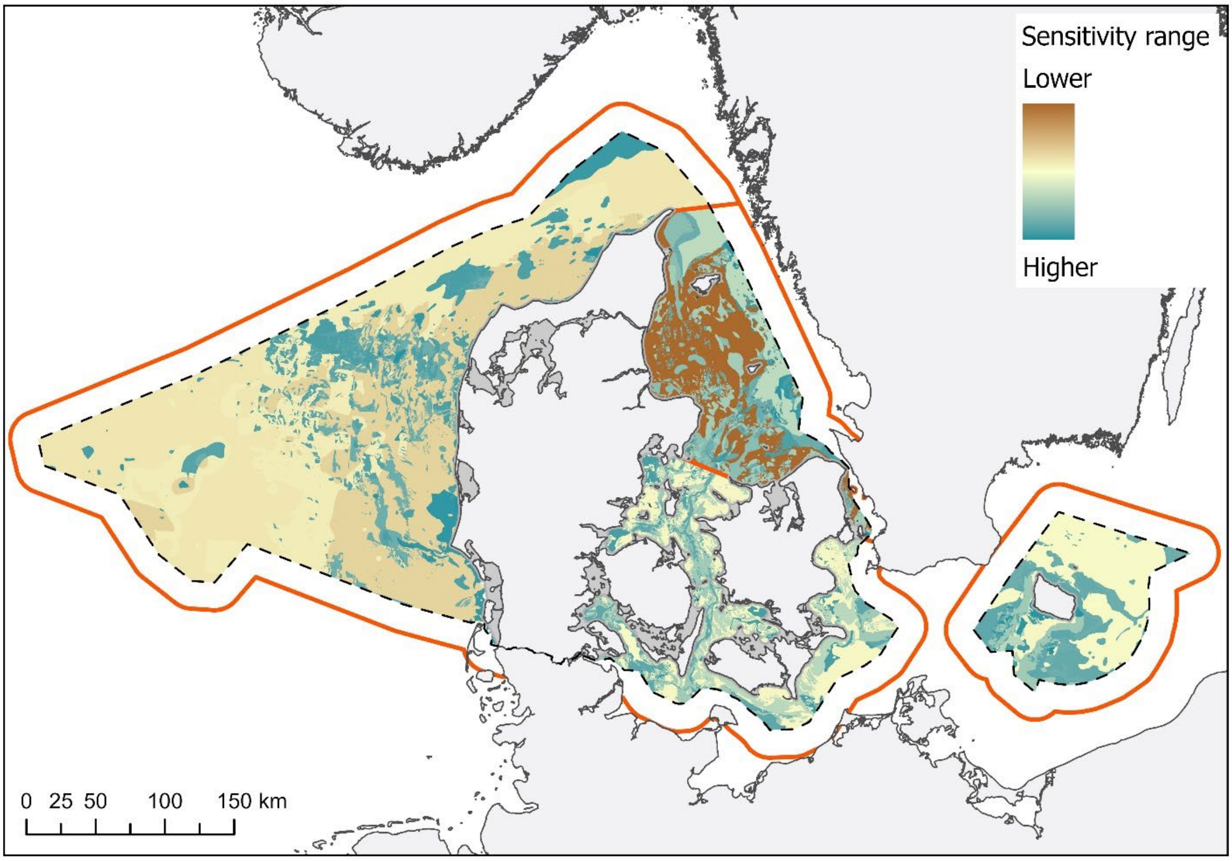


Figure 4.4. Sensitivity range of the MSFD broad habitat types on a linear scale in all three subregions. The highest sensitivity is found for *Circalittoral rock* in the Baltic Sea (dark petrol). The lowest sensitivity is found for *Infralittoral sand* in Kattegat (brown).

The thresholds of an extent of 5% within a subregion for higher sensitivity and 15% for medium sensitivity led to different broad habitats being classified into different sensitivity classes in the three subregions. *Circalittoral mixed sediment* and *Offshore circalittoral coarse sediment* were of higher sensitivity in all three subregions, and *Offshore circalittoral mud* was of lower sensitivity in all three subregions. All other broad habitats varied in their sensitivity or were not present in all three subregions. The number of the different broad habitat types and their total percentages that fall into the respective sensitivity classes also varied among the three subregions (Tables 4.6, 4.7).

Table 4.6. Sensitivity of the broad habitat types according to their area percentage within a subregion. HS: higher sensitivity, MS: medium sensitivity, LS: lower sensitivity

Subregion	NS	KT	BS
Infralittoral coarse sediment	**HS**	**MS**	**HS**
Infralittoral mixed sediment	**HS**	**MS**	**MS**
Infralittoral mud	**HS**	**MS**	**HS**
Infralittoral rock and biogenic reef		**HS**	**HS**
Infralittoral sand	**HS**	**LS**	**LS**
Circalittoral coarse sediment	**MS**	**HS**	**HS**
Circalittoral mixed sediment	**HS**	**HS**	**HS**
Circalittoral mud	**HS**	**MS**	**HS**
Circalittoral rock			**HS**
Circalittoral rock and biogenic reef			**HS**
Circalittoral sand	**LS**	**HS**	**MS**
Offshore circalittoral coarse sediment	**HS**	**HS**	**HS**
Offshore circalittoral mixed sediment	**HS**	**HS**	**MS**
Offshore circalittoral mud	**LS**	**LS**	**LS**
Offshore circalittoral rock and biogenic reef			**HS**
Offshore circalittoral sand	**LS**	**HS**	**MS**
Upper bathyal sediment	**HS**		

Tabel 4.7. Number and area percentage of the sensitivity classes in each subregion

Subregion	NS	KT	BS
Numbers			
HS	9	7	10
MS	1	4	4
LS	3	2	2
Percentage			
HS	13.4	6.6	15.3
MS	5.8	32.6	37.2
LS	80.8	60.8	47.5

North Sea/Skagerrak

In the North Sea/Skagerrak, appr. ¾ of the broad habitats were of higher sensitivity, while they covered only 13.4 % of the subregion area. The broad habitats with the smallest extent were *Infralittoral coarse sediment*, *Infralittoral mixed sediment* and *Infralittoral mud,* which were all below or equal to 0.1%. The infralittoral zone was reduced by the removal of the coastal zone. It is therefore not surprising that *Infralittoral sand* also only reached 1.3%. *Circalittoral mud,* with 0.9%, and *Upper bathyal sediment,* with 1.5%, were in a same range.

Offshore circalittoral mixed sediment, *Circalittoral mixed sediment* and *Offshore circalittoral coarse sediment* range from 2.6% to 3.8%. *Circalittoral coarse sediment* was, with 5.8%, of medium sensitivity, while the remaining types were of lower sensitivity and covered 80.8% of the subregion. (Tables 4.6, 4.7, Figure 4.5)

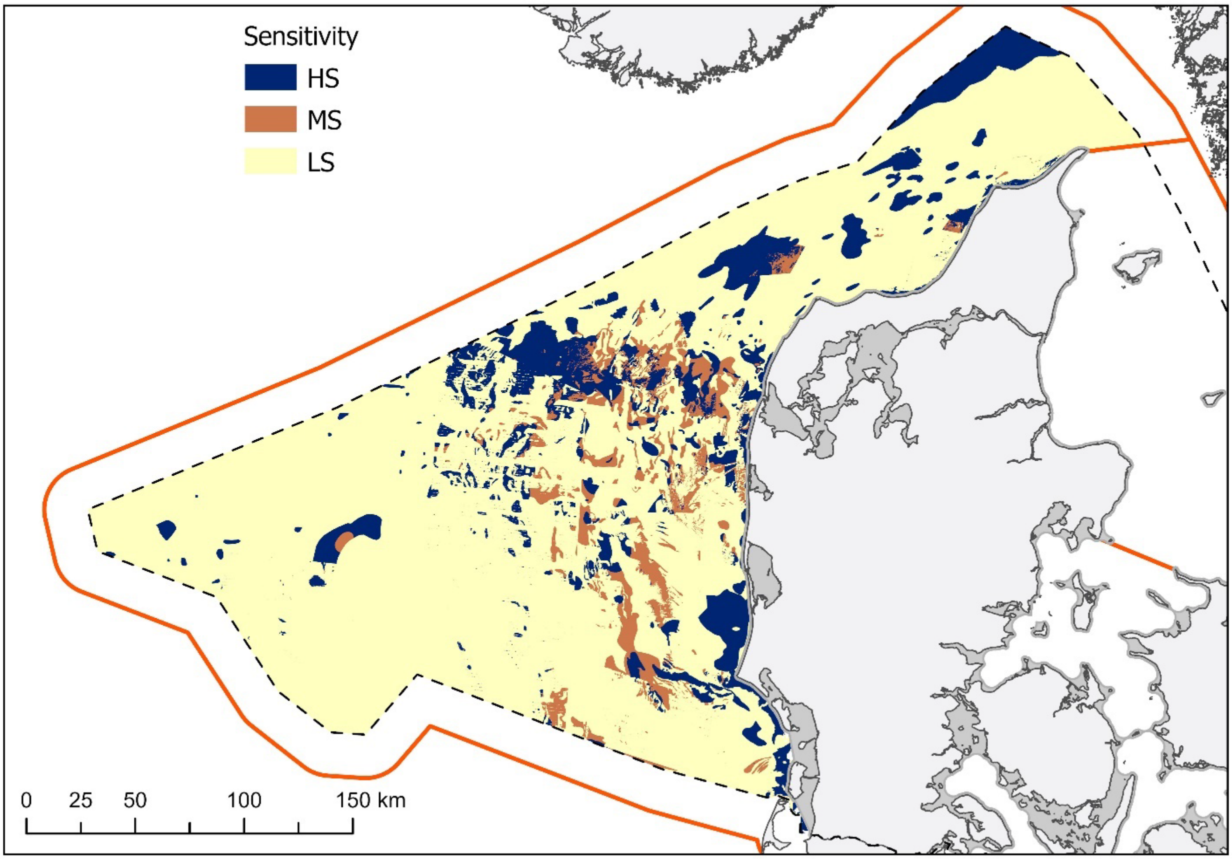


Figure 4.5. Sensitivity of the broad habitats in the North Sea/Skagerrak. Blue: Higher sensitivity (HS), Red-brown: Medium sensitivity (MS), Yellow: Lower sensitivity (LS)

Kattegat

With 6.6% of the subregion, Kattegat had the smallest percentage of higher sensitivity habitats, and one third of the subregion had medium sensitivity.

The definition of infralittoral is different in the Kattegat from the North Sea and covers a much bigger area. It is still the infralittoral zone that was affected by the removal of the coastal area in the analysis, but the only habitat type in the infralittoral zone of higher sensitivity was *Infralittoral rock and biogenic reef* with 0.1%. *Offshore circalittoral coarse sediment* and *Circalittoral mixed sediment* were also below 1.0%. *Offshore circalittoral mixed sediment, Offshore circalittoral sand* and *Circalittoral sand* lay between 1.1% and 3.0%.

Infralittoral coarse sediment, Infralittoral mixed sediment, Infralittoral mud and *Circalittoral mud* were of medium sensitivity, and *Infralittoral sand* had low sensitivity. Four broad habitat types were not present. (Tables 4.6, 4.7, Figure 4.6)

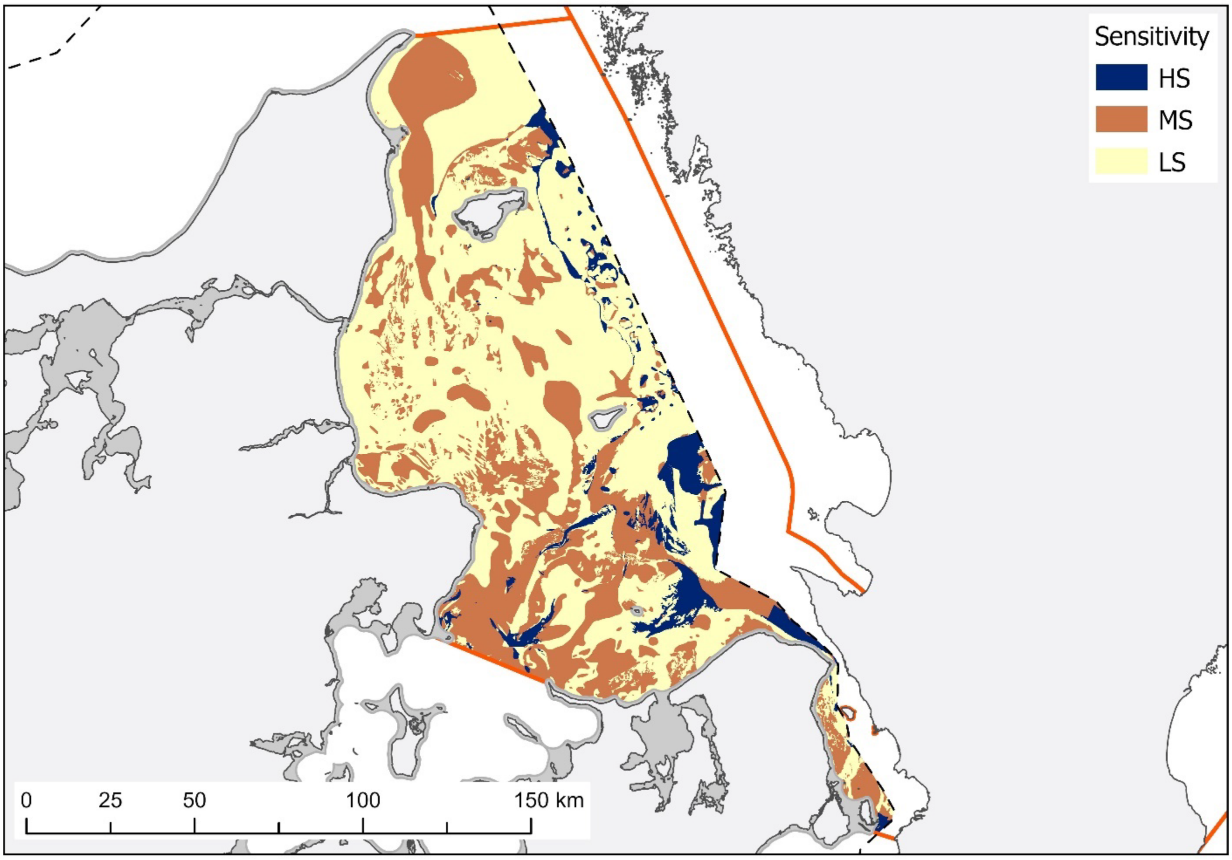


Figure 4.6. Sensitivity of the broad habitats in the Kattegat. Blue: Higher sensitivity (HS), Red-brown: Medium sensitivity (MS), Yellow: Lower sensitivity (LS)

Baltic Sea

The Baltic Sea had the highest amount of habitat types that were categorised as more sensitive (10), and in total they cover 15.3% of the area.

Circalittoral rock and biogenic reef, Offshore circalittoral coarse sediment, Circalittoral coarse sediment and *Infralittoral rock and biogenic reef* each covered less than 1.0% of the subregion. Another 4 types, *Infralittoral coarse sediment, Infralittoral mud, Circalittoral mixed sediment* and *Circalittoral mud,* were below 5.0%. For the infralittoral, we note, again, that the coastal zone was not included in the analysis. In the Baltic Sea, the lower limit of the infralittoral had a similar definition for euhaline and polyhaline waters as in Kattegat.

Infralittoral mixed sediment, Circalittoral *sand*, O*ffshore circalittoral mixed sediment* and *Offshore circalittoral sand* were of medium sensitivity. Two broad habitats had a lower sensitivity, and one type was not present. (Tables 4.6, 4.7, Figure 4.7)

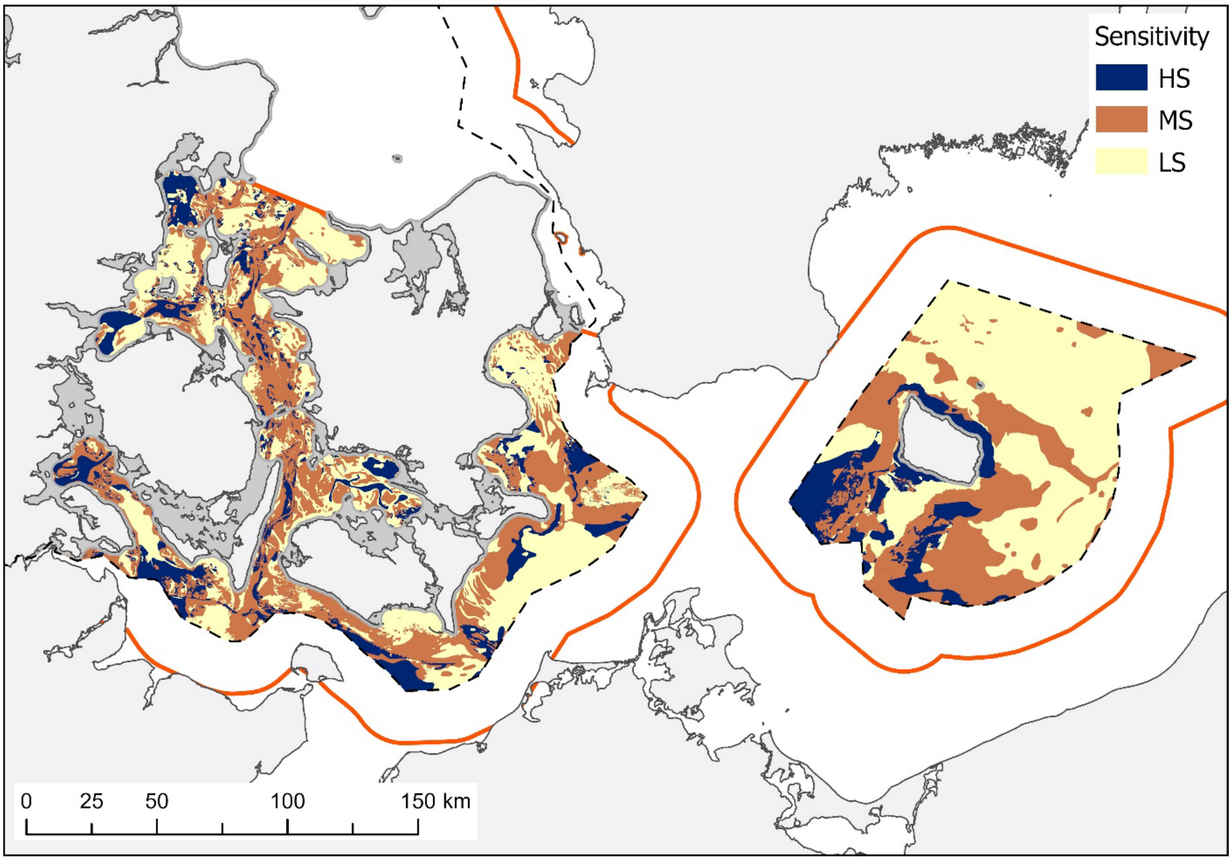


Figure 4.7. Sensitivity of the broad habitats in the Kattegat. Blue: Higher sensitivity (HS), Red-brown: Medium sensitivity (MS), Yellow: Lower sensitivity (LS)

4.4 Potential loss of and impact on broad habitats by the 2030 scenario

In the Baltic Sea, the planned scenario for OWF areas covered 1,184 km^2 or 5.0 % of the subregion, while it was lower (2.6-2.7%) for the other two subregions. (Table 4.8). Sensitivity assessments are calculated on the extent of current broadscale habitats (Section 4.3), with this impact scenario derived from current OWF and future OWF based on Scenario 2030. Changes to future OWF windfarm projects may result in changes to the impact assessment.

Table 4.8. Percentage and size in km^2 of the park area of the planned scenario and subregion area

	NS	KT	BS
Scenario 2030 %	2.7%	2.6%	5.0%
Scenario 2030 area	1567	385	1184
Total subregion area	57816	14742	23632

Type 1: Direct construction impact

Our findings indicated that the direct construction effect would result in less than 0.071% loss in all broad habitats (figure 4.9, table 4.10). The impact by the construction effect in the North Sea/Skagerrak and Kattegat was much lower, with a maximum of 0.015% in the North Sea and 0.008% in the Kattegat. In the North Sea, *Infralittoral sand* is most affected broad habitats, while in the Kattegat, the impact is distributed over several types in the infra- and circalittoral zones. (Table 4.9)

Circalittoral rock in the Baltic area had the overall highest impact. *Offshore circalittoral coarse sediment* had the second highest percentage in the Baltic Sea and, in general, the affected areas were predominantly in the circalittoral zone in the Baltic Sea.

Type 2: Reef effect

The simplified approach to calculate the construction effect and the reef effect resulted in the same broad habitats getting affected. However, the area considered for the reef effect was larger. The affected areas by the reef effect were approximately 16.4 times larger than the construction effect. The highest reef effects were 0.24% in the North Sea for *Infralittoral sand,* 0.13% in Kattegat with highest value for *Circalittoral coarse sediment* and 1.15% for *Circalittoral rock* in the Baltic Sea. (Figure 4.8, Table 4.9)

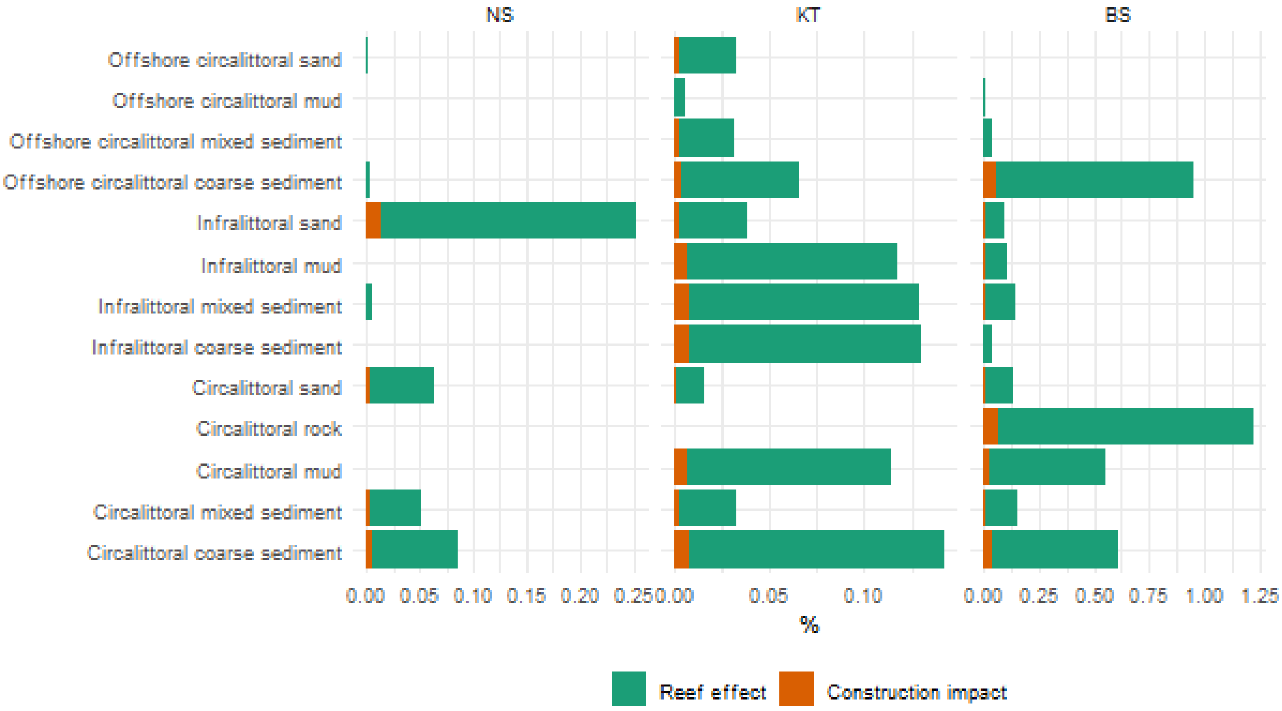


Figure 4.8. Area affected by construction (type 1) and reef effect (type 2) as percent of the respective broad habitat within a subregion. The scaling of the x-axes vary.

Table 4.9. Area percentages of those broad habitats within a subregion that are affected by construction (type 1), reef effect (type 2) and all potential effects as sum of type 1-3.

	NS			KT			BS		
	type 1	type 2	type 1-3	type 1	type 2	type 1-3	type 1	type 2	type 1-3
Circalittoral coarse sediment	5.00E-03	8.10E-02	1.01E+01	8.00E-03	1.34E-01	8.60E+00	3.50E-02	5.76E-01	5.00E+01
Circalittoral mixed sediment	3.00E-03	5.00E-02	9.56E-01	2.00E-03	3.00E-02	1.88E+00	9.00E-03	1.46E-01	1.09E+01
Circalittoral mud	0.00E+00	0.00E+00	1.00E-03	7.00E-03	1.07E-01	7.07E+00	3.20E-02	5.19E-01	2.31E+01
Circalittoral rock							7.00E-02	1.15E+00	1.00E+02
Circalittoral sand	4.00E-03	6.10E-02	6.85E+00	1.00E-03	1.50E-02	9.49E-01	8.00E-03	1.33E-01	1.13E+01
Infralittoral coarse sediment				7.00E-03	1.22E-01	5.41E+00	2.00E-03	3.80E-02	1.41E+00
Infralittoral mixed sediment	0.00E+00	5.00E-03	5.40E-02	7.00E-03	1.22E-01	4.17E+00	8.00E-03	1.35E-01	3.12E+00
Infralittoral mud				7.00E-03	1.11E-01	6.85E+00	6.00E-03	1.05E-01	2.52E+00
Infralittoral sand	1.50E-02	2.38E-01	2.11E+00	2.00E-03	3.60E-02	1.36E+00	6.00E-03	9.30E-02	3.57E+00
Offshore circalittoral coarse sediment	0.00E+00	3.00E-03	6.07E-01	4.00E-03	6.20E-02	3.79E+00	5.50E-02	8.98E-01	7.73E+01
Offshore circalittoral mixed sediment				2.00E-03	3.00E-02	1.86E+00	2.00E-03	3.70E-02	3.15E+00
Offshore circalittoral mud				0.00E+00	5.00E-03	3.14E-01	0.00E+00	6.00E-03	5.07E-01
Offshore circalittoral sand	0.00E+00	1.00E-03	2.72E-01	2.00E-03	3.00E-02	1.87E+00	0.00E+00	4.00E-03	3.18E-01

All potential impacts (type 1, 2 and 3)

The coverage was much higher for the potential other effects (type 3). In figure 4.9 and table 4.9, we sum all three effects (type 1 - 3) to provide an overview over the potential total effect.

In the North Sea/Skagerrak, the OWFs of scenario 2030 were distributed among a few, but the largest, broad habitat types (fig. 4.9). The three most highly affected broad habitats were *Circalittoral coarse sediment,* with 10.1%, *Circalittoral sand,* with 6.9%, and *Infralittoral sand,* with 2.1%. The other were covered to less than 1.0% or not affected at all. In the North Sea/Skagerrak, one of the higher sensitivity broad habitats (*infralittoral sand*) was affected more than 2 %.

In the Kattegat, the OWFs were more evenly distributed over the broad habitat types. *Circalittoral coarse sediment* was the most highly affected habitat, with 8.6%, followed by *Circalittoral mud,* with 7.1%, and *Infralittoral mud,* with 6.8%. In the Kattegat, two of the higher sensitivity broad habitats (*Circalittoral coarse sediment* and *Offshore circalittoral coarse sediment*) were affected more than 2.0 %.

In the Baltic Sea, three habitat types were impacted more than 25 %. The highest coverage was found for *Circalitoral rock* in the Baltic Sea, where the mapped area was completely covered by the scenario extent, *Offshore circalittoral coarse sediment* 77 % and *Circalittoral coarse sediment* 50 %. All three of these habitats had a very low extent, namely 2, 20 and 149 km^2, and they therefore fell into the highest sensitivity class. The two remaining circalittoral habitats, *Circalittoral mixed sediment* and *Circalittoral sand,* were also affected to more than 10%, so that all circalittoral types were affected by more than 10%.

When examining the sensitivity of the broad habitat types in the Baltic Sea, it was found that all three types with a coverage of over 25%, showed higher sensitivity. Additionally, three of the broad habitats affected by > 2 %, namely *Circalittoral mixed sediment*, *Circalittoral mud* and *Infralittoral mud*, were of higher sensitivity.

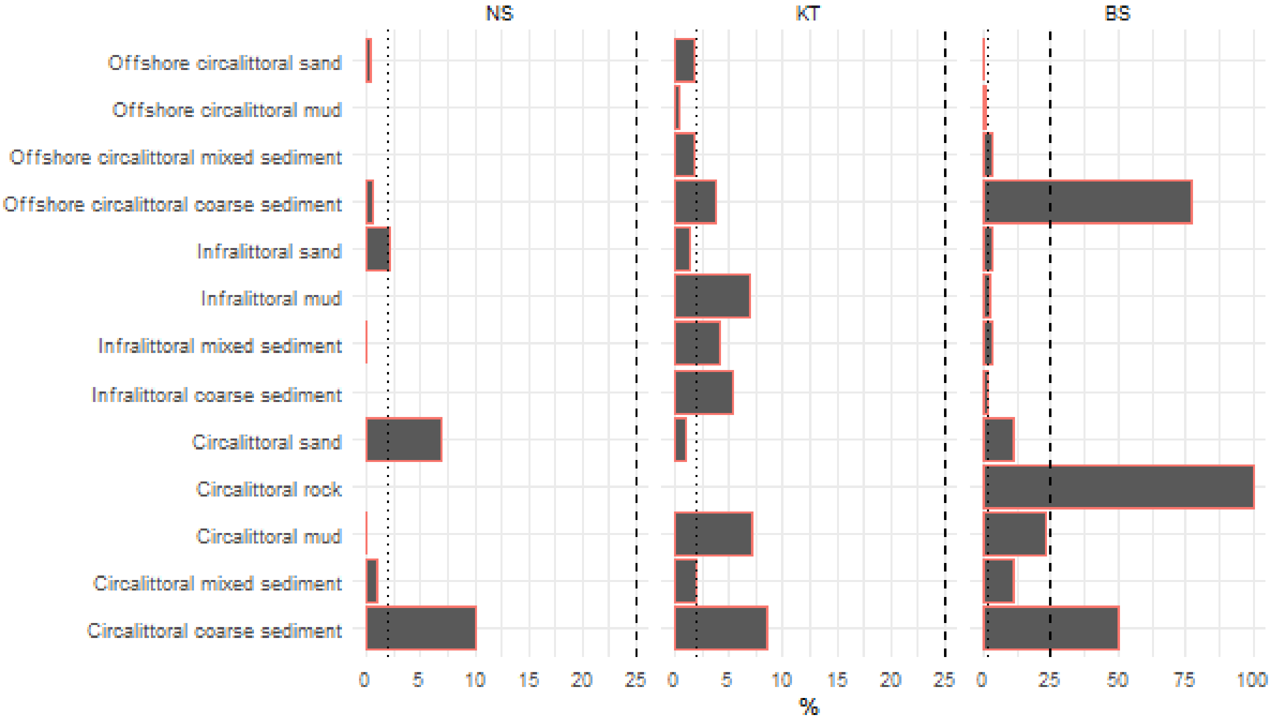


Figure 4.9. Coverage of the broad habitats with the complete OWF area (type 1-3). The x-axes are varying. The 2% and 25% thresholds represent the limits established by the MSFD for what is permitted to be irreversibly lost and adversely affected, respectively.

4.5 Community composition

4.5.1 Soft bottom fauna

Soft sediment benthic biodiversity analysis revealed differences in biodiversity between the three subregions (Figure. 4.10). Kattegat generally had the highest average biodiversity at 3.05 ± 0.42 SD Shannon diversity Index, followed by North Sea/Skagerrak subregion 2.30 ± 0.31 SD Shannon diversity Index and, finally, the Baltic Sea subregion 1.55 ± 0.44 SD Shannon diversity Index. As the area of broad habitats decreased, the number of soft sediment sampling stations decreased, and the North Sea subregion had the greatest number of broad habitats without sufficient samples for analysis.

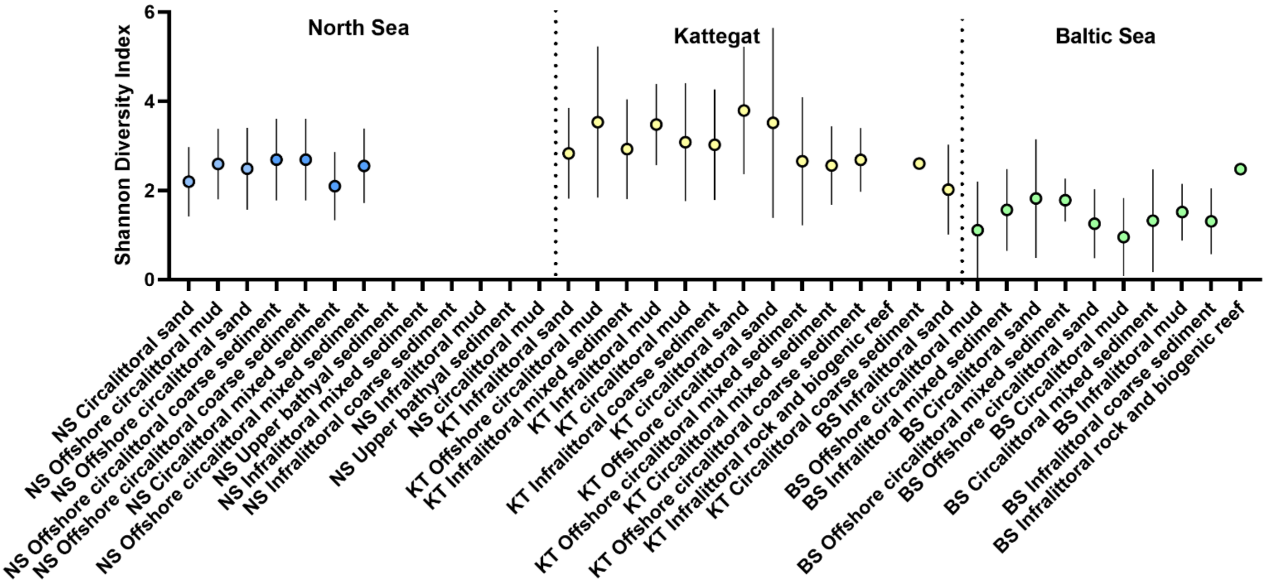


Figure 4.10. Average Shannon diversity index for all broad habitats for each subregion: NS – North Sea/Skagerrak, KT – Kattegat, BS –Baltic Sea. Error bars are standard deviation. Broad habitat types with no sample point contain no soft sediment samples.

Multivariate ANOSIM analysis of similarity are reported in table 4.10. All subregions within both global and pairwise tests showed significant difference in all combinations. Global tests for broad habitat differences in similarity reported a significant result (r = 0.189 p=0.1%). The majority of pairwise tests across the broad habitats showed significant difference, however, a few did not. Of note, *Offshore circalittoral mixed sediment* was not significantly different from several other broad habitat types.

Table 4.10. Reporting the 2-way crossed ANOSIM global (**bold**) and pairwise results with 999 permutations testing for significance difference between subregion and broad habitats. Significant results (≤ 5 %) are denoted with a "*". KT=Kattegat, NS=North Sea/Skagerrak, BS = Baltic Sea. O=Offshore, CL=Circalittoral, IL=Infralittoral.

Subregions	**Statistic**	**R significance Level %**
Global test	**0.324**	**0.1***
KT, NS	0.212	0.1*
KT, BS	0.422	0.1*
NS, BS	0.345	0.1*
Broad habitats	**Statistic**	**R significance Level %**
Global test	0.189	0.1*
O CL mud, O CL mixed sed.	0.276	0.3*
O CL mud, CL mud	0.093	0.1*
O CL mud, CL mixed sed.	0.358	0.1*
O CL mud, O CL sand	0.046	0.1*
O CL mud, CL sand	0.186	0.1*
O CL mud, IL mixed sed.	0.456	0.1*
O CL mud, CL coarse sed.	0.542	0.1*
O CL mud, IL sand	0.346	0.1*
O CL mud, O CL coarse sed.	0.337	0.1*
O CL mud, IL mud	0.243	0.1*
O CL mud, IL coarse sed.	0.528	0.1*
O CL mud, IL rock and biogenic reef	0.689	9.1
O CL mixed sed., CL mud	0.313	0.1*
O CL mixed sed., CL mixed sed.	0.331	0.1*
O CL mixed sed., O CL sand	0.021	33.1
O CL mixed sed., CL sand	0.077	14.8
O CL mixed sed., IL mixed sed.	0.313	0.1*
O CL mixed sed. CL coarse sed.	-0.086	93.8
O CL mixed sed., IL sand	0.364	0.1*
O CL mixed sed., O CL coarse sed.	-0.052	89.3
O CL mixed sed., IL mud	0.740	0.1*
O CL mixed sed., IL coarse sed.	0.583	0.1*
O CL mixed sed., IL rock and biogenic reef	0.933	2.3*
CL mud, CL mixed sed.	0.281	0.1*
CL mud, O CL sand	0.486	0.1*
CL mud, CL sand	0.338	0.1*
CL mud, IL mixed sed.	0.315	0.1*
CL mud, CL coarse sed.	-0.018	45.5
CL mud, IL sand	0.368	0.1*
CL mud, O CL coarse sed.	-0.036	62.4
CL mud, IL mud	0.580	0.1*
CL mud, IL coarse sed.	0.463	0.1*
CL mud, IL rock and biogenic reef	0.022	50.0
CL mixed sed., O CL sand	0.079	1.8*
CL mixed sed., CL sand	0.108	1.9*
CL mixed sed., IL mixed sed.	0.293	0.1*
CL mixed sed., CL coarse sed.	-0.094	99.4
CL mixed sed., IL sand	0.389	0.1*
CL mixed sed., O CL coarse sed.	0.056	3.3*
CL mixed sed., IL mud	0.752	0.1*
CL mixed sed., IL coarse sed.	0.543	0.1*
CL mixed sed., IL rock and biogenic reef	0.698	3.8*
O CL sand, CL sand	0.127	0.1*
O CL sand, IL mixed sed.	0.404	0.1*
O CL sand, CL coarse sed.	0.265	0.1*
O CL sand, IL sand	0.271	0.1*
O CL sand, O CL coarse sed.	0.096	0.1*
O CL sand, IL mud	0.599	0.1*
O CL sand, IL coarse sed.	0.617	0.1*
O CL sand, IL rock and biogenic reef	0.856	1.0*
CL sand, IL mixed sed.	0.240	0.1*
CL sand, CL coarse sed.	0.258	0.1*
CL sand, IL sand	0.116	0.1*
CL sand, O CL coarse sed.,	0.220	0.1*
CL sand, IL mud	0.304	0.1*
CL sand, IL coarse sed.	0.216	0.1*
CL sand, IL rock and biogenic reef	0.465	2.7*

Table 4.10. continued. Reporting the 2-way crossed ANOSIM global (**bold**) and pair-wise results with 999 permutations testing for significance difference between subregion and broad habitats. Significant results (≤ 5 %) are denoted with a "*". KT=Kattegat, NS=North Sea/Skagerrak, BS = Baltic Sea. O=Offshore, CL=Circalittoral, IL=Infralittoral.

IL mixed sed., CL coarse sed.	0.657	1.8*
IL mixed sed., IL sand	0.059	0.3*
IL mixed sed., O CL coarse sed.	0.539	0.1*
IL mixed sed., IL mud	0.532	0.1*
IL mixed sed., IL coarse sed.	0.064	2.8*
IL mixed sed., IL rock and biogenic reef	0.448	8.7
CL coarse sed., IL sand	0.225	0.7*
CL coarse sed., O CL coarse sed.	0.017	8.3
CL coarse sed., IL mud	0.892	1.0*
CL coarse sed., IL coarse sed.	0.736	5.1
IL sand, O CL coarse sed.	0.585	0.1*
IL sand, IL mud	0.125	0.1*
IL sand, IL coarse sed.	0.032	11.8
IL sand, IL rock and biogenic reef	0.452	4.4*
O CL coarse sed., IL mud	0.855	0.1*
O CL coarse sed., IL coarse sed.	0.616	0.1*
IL mud, IL coarse sed.	0.604	0.1*
IL mud, IL rock and biogenic reef	0.489	1.1*
IL coarse sed., IL rock and biogenic reef	0.601	5.1

Each nMDS ordination (Figures 4.11 – 4.14) was constructed using 50 permutations and concurred with the statistical results described in table 4.10. Interpretating these results should be done with caution, as stress values (a measure of accuracy of nMDS) are high across all nMDS, with all values of 2D stress >0.15 but <0.20, a broad interpretation of the data and subdivision is appropriate. These results will be presented with a focus on ANOSIM (Table 4.10) and nMDS providing guidance. However, the limitations imposed by the stress values will be considered when interpretating results.

Figure 4.11 concurs with the ANOSIM results, showing a clear separation between the subregions within the study, there is a degree of overlap between subregions and, particularly, the Kattegat, which occupies the margin between the Baltic and North Sea/Skagerrak. The North Sea/Skagerrak appears to have the largest spread in data points, indicating a greater degree of soft sediment fauna difference amongst its stations, which is particularly surprising, since it has the least number of broad habitats present within its region. The Kattegat and Baltic Sea appear to cover the same volume of multi-dimension spaces within the nMDS plots, suggestion a similar and high degree of variability.

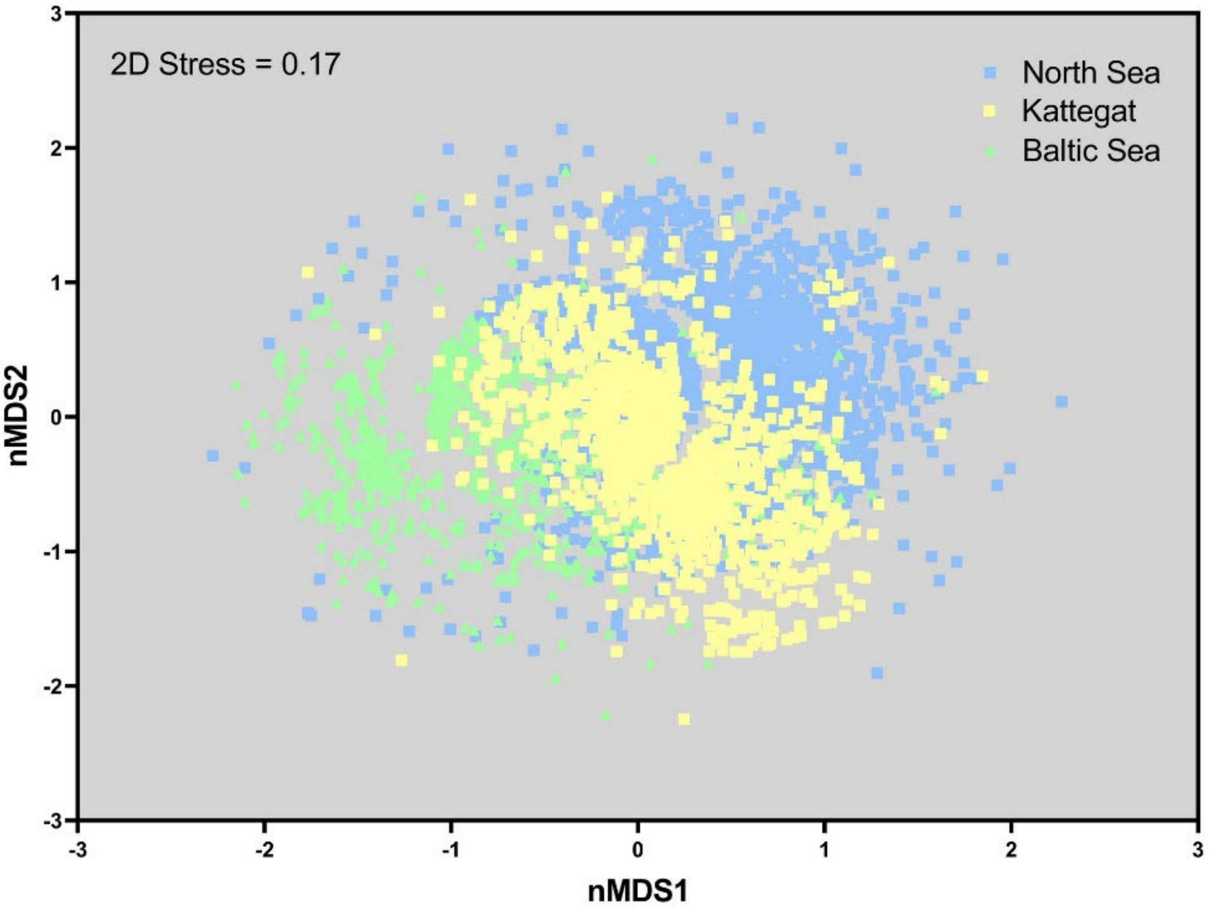


Figure 4.11. nMDS displaying all samples compared using a bray-Curtis similarity index from all subregions. Ordination was constructed using 50 permutations, with all data fourth root transformed.

The North Sea nMDS (Figure 4.12), shows a broad spread of multiple broad habitats with a large degree of overlap notably, *circalittoral sand* habitats, *offshore circalittoral mud* and *circalittoral coarse sediment,* which constitute many stations within the North Sea. All *circalittoral sand*, *offshore circalittoral mud* and *circalittoral coarse sediment* tend to have distinct benthic communities when compared against all other broad habitats.

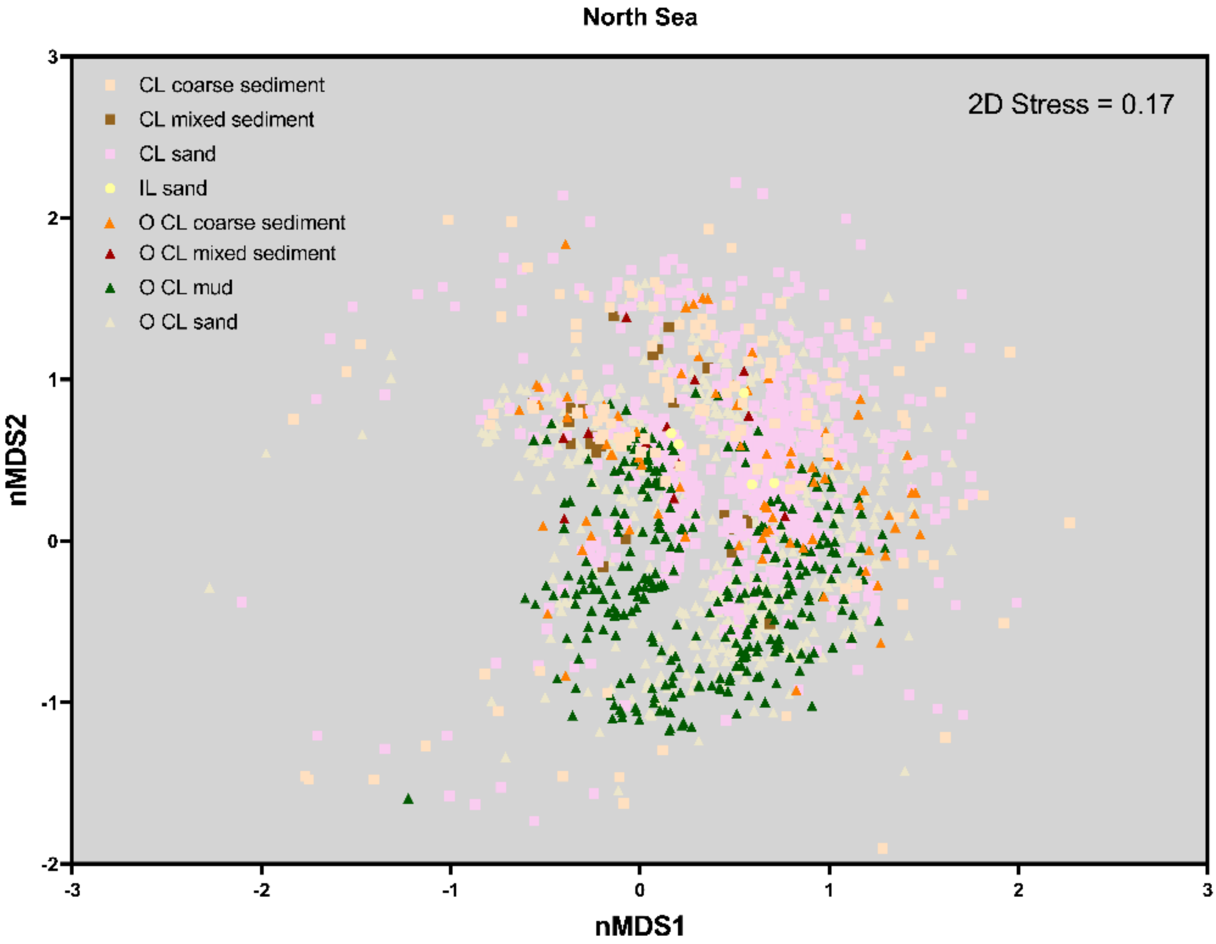


Figure 4.12. nMDS displaying all samples from North Sea/Skagerrak compared using a bray-Curtis similarity index. Ordination was constructed using 50 permutations, with all data fourth root transformed.

The Kattegat nMDS (Figure 4.13) has a spread of multiple broad habitats showing a large degree of overlap, including *offshore circalittoral sand*, *infralittoral sand* and *offshore circalittoral mud*. A few broad habitat types, such as *infralittoral mixed sediment* and *offshore circalittoral coarse sediment*, have fewer samples and are tightly clustered. However, *circalittoral coarse sediment* and *circalittoral mud* show a high degree of overlap, which is reflected within the ANOSIM pairwise test, revealing a non-significant change between the two (r = 0.018, p=45.5%).

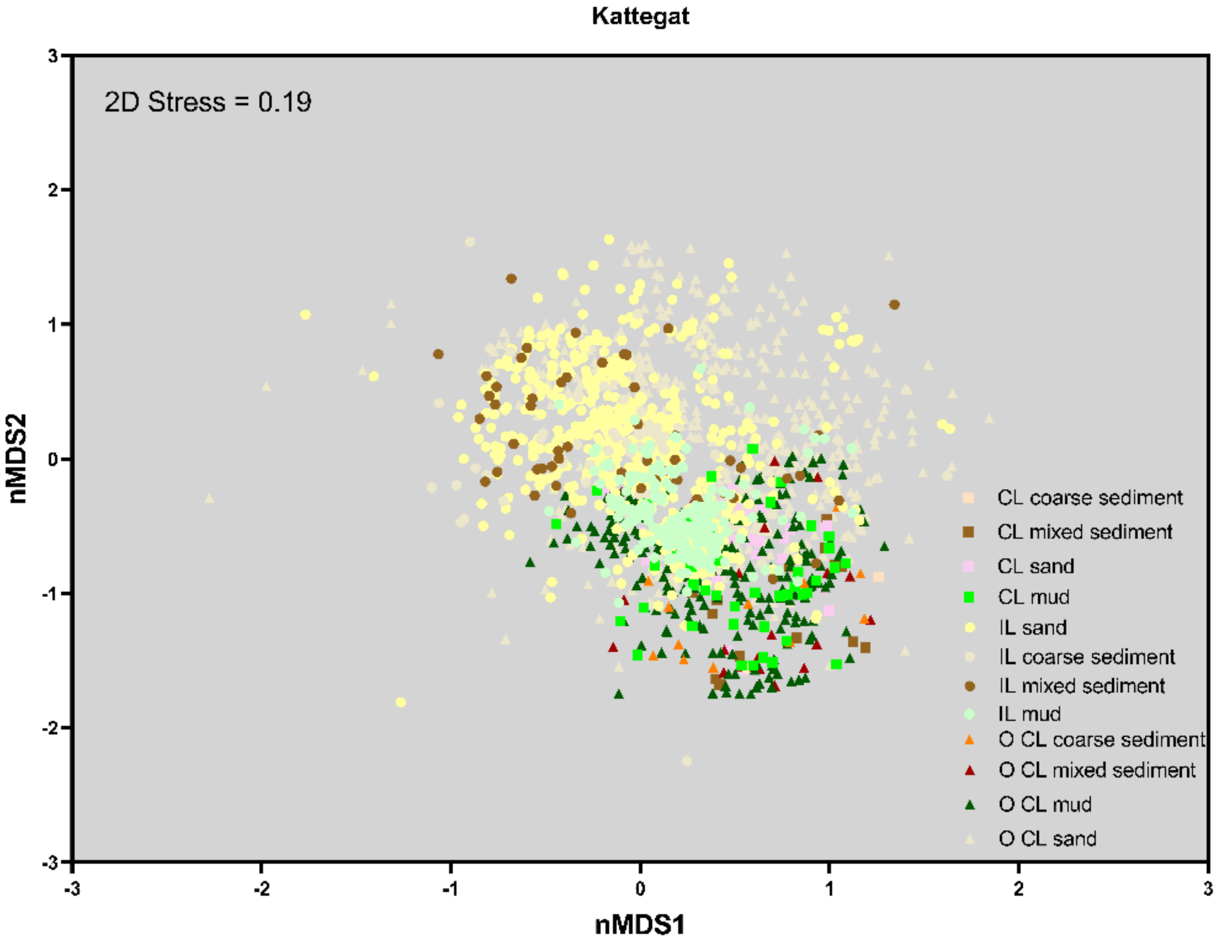


Figure 4.13. nMDS displaying all samples from Kattegat compared using a bray-Curtis similarity index. Ordination was constructed using 50 permutations, with all data fourth root transformed.

The Baltic Sea nMDS (Figure 4.14) has broad habitats with a high degree of overlap with other broadscale habitats. However, *Offshore circalittoral mixed sediment* and *Offshore circalittoral sand* show a degree of clustering and strong overlap with each other and no other broadscale habitat, which reflects a similar soft sediment benthic community between the two (0.021, p=33.1%).

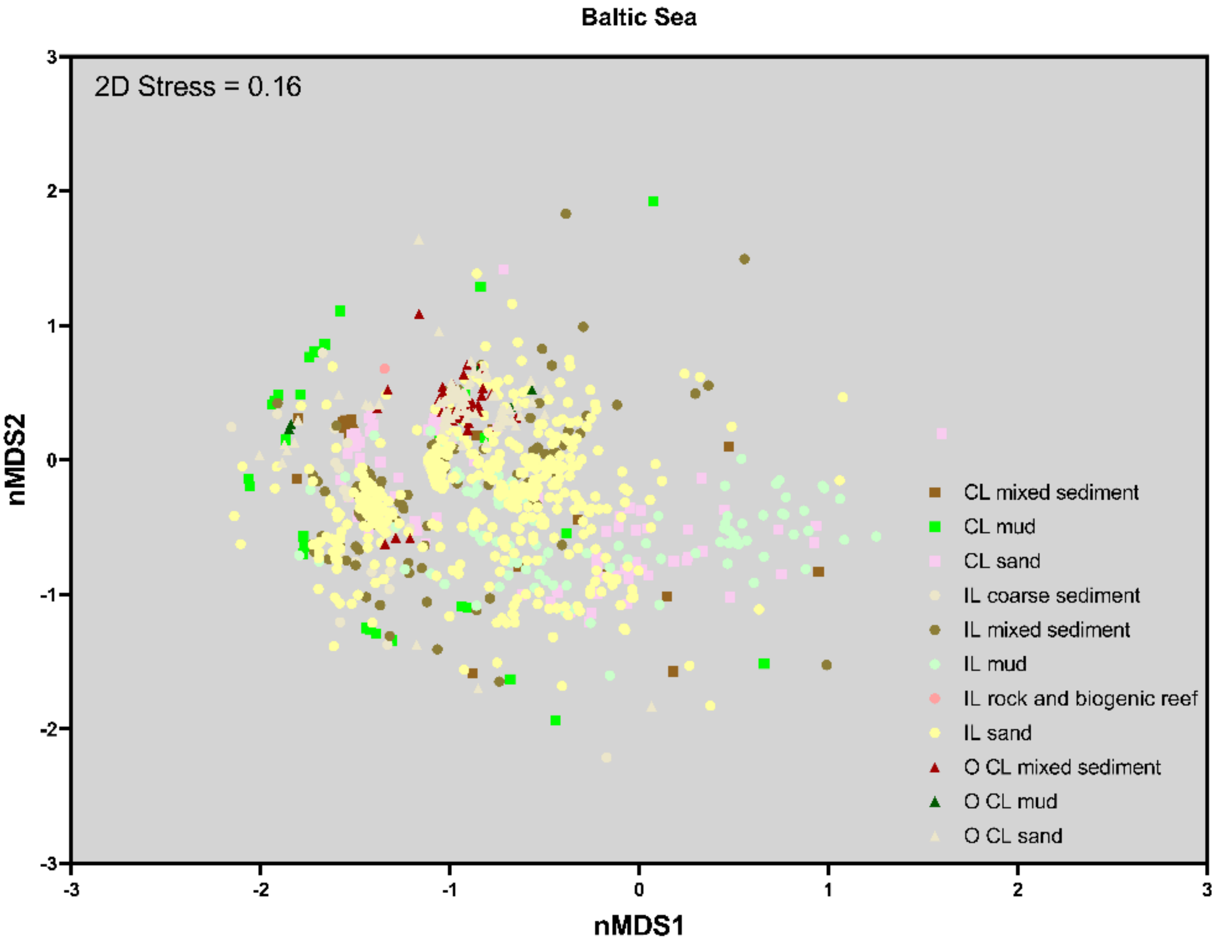


Figure 4.14. nMDS displaying all samples from the Baltic Sea compared using a bray-Curtis similarity index. Ordination was constructed using 50 permutations, with all data fourth root transformed.

ANOSIM results and nMDS ordination both agree that most broad habitats contain a significantly distinct soft sediment benthic community, and that the same broad habitats are distinct between subregions. Only a few pair-wise tests reported non-significance between broad habitats.

Within the North Sea/Skagerrak (Table 4.11), *Circalittoral coarse sediment* and *Circalittoral mixed sediment* are dominated by *Echinocyamus pusillus* (sand urchin), a common species in sand and coarse sediment environments. Overall, the North Sea/ Skagerrak broad habitats have a generally low average broad habitat similarity, indicating a wide range in variability across the area. The exception is *Infralittoral sand*, with an average similarity of 54.03, and dominated by two species *Magelona mirabilis* and *Sigalion mathildae* (polycheata), the former of which is also found in high abundance at all North Sea and Skagerrak stations.

Within the Kattegat broad habitats, *Amphiura chiajei* (brittle star) is dominant in *Offshore circalittoral mixed sediment*, *Circalittoral mud*, *Circalittoral mixed sediment* and *Offshore circalittoral coarse sediment*, with the latter also dominated by *Abra nitida* (bivalve). *Scoloplos armiger* was found to dominant infralittoral broad habitats, including *Infralittoral mixed sediment*, *Infralittoral sand* and *Infralittoral coarse sediment*. However, it was not listed in dominant species in *Infralittoral mud*.

The Baltic Sea is characterised by a generally high average broad habitat similarity and reduced numbers of common and high abundance species, leading to a reduced list of dominant taxa. Again, *S. armiger* was a dominant species across multiple broad habitats, including *Offshore circalittoral mud*, *Offshore circalittoral mixed sediment* and *Offshore circalittoral sand*, the latter of which was also dominated by *Macoma balthica*, a species found in many sites across the Baltic Sea. *Circalittoral mixed sediment* and *Circalittoral sand* share the same two dominant species *M. balthica* and *Pygsio elegans* (spionidae worms), the latter of which was also dominant in *Offshore circalittoral mixed sediment*. *Infralittoral mixed sediment* is dominant by *P. ulvae,* another species that is found in high presence across all Baltic Sea samples. Finally, *Circalittoral mud*, was dominated by a single species *Tubificoides benedii* (sludge worm), a species often found in mud and nearly accounting for all the similarity found within this environment. (Table 4.11)

Table 4.11. Results of 2-way crossed SIMPER analysis on subregions and broad habitats.

Subregions		
North Sea/Skagerrak	**Av. Abundance**	**Av. Similarity**
Overall group similarity	-	12.18
Magelona mirabilis	0.31	1.29
Spiophanes bombyx	0.38	1.20
Amphiura filiformis	0.43	1.08
Phoronis sp.	0.41	0.90
Scoloplos armiger	0.30	0.87
Tellina fabula	0.18	0.63
Kattegat	**Av. Abundance**	**Av. Similarity**
Overall group similarity	-	17.92
Scoloplos armiger	0.55	3.24
Amphiura filiformis	0.76	1.68
Phoronis sp.	0.63	1.54
Kurtiella bidentata	0.61	1.53
Nucula nitidosa	0.40	0.88
Nemertini indet.	0.39	0.88
Baltic Sea	**Av. Abundance**	**Av. Similarity**
Overall group similarity	-	**18.69**
Peringia ulvae	0.69	4.34
Scoloplos armiger	0.62	3.72
Pygospio elegans	0.61	2.11
Macoma balthica	0.43	1.44
Hediste diversicolor	0.25	1.16
Mya arenaria	0.23	0.78
North Sea/Skagerrak		
Circalittoral sand	**Av. Abundance**	**Av. Similarity**
Overall group similarity	-	**12.21**
Magelona mirabilis	0.61	2.47
Spiophanes bombyx	0.50	1.64
Tellina fabula	0.42	1.28
Phoronis sp.	0.48	0.72
Nephtys hombergii	0.26	0.68
Lanice conchilega	0.25	0.51
Echinocardium cordatum	0.22	0.44
Circalittoral coarse sediment	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**7.46**
Echinocyamus pusillus	0.45	2.34
Spiophanes bombyx	0.29	0.69
Nemertini indet.	0.28	0.64
Scoloplos armiger	0.23	0.57
Magelona mirabilis	0.21	0.39
Nematoda indet.	0.24	0.38
Branchiostoma lanceolatum	0.16	0.33

Table 4.11. continued

Results of 2-way crossed SIMPER analysis on subregions and broad habitats.

Offshore Circalittoral Sand	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**10.73**
Amphiura filiformis	0.65	1.77
Scoloplos armiger	0.35	1.35
Phoronis sp.	0.53	1.23
Edwardsia sp.	0.33	0.84
Spiophanes bombyx	0.31	0.76
Echinocyamus pusillus	0.23	0.50
Nemertini indet.	0.20	0.35
Offshore Circalittoral coarse sediment	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**10.42**
Echinocyamus pusillus	0.40	1.47
Spiophanes bombyx	0.39	1.27
Scoloplos armiger	0.32	1.07
Nematoda indet.	0.42	1.04
Amphiura filiformis	0.25	0.53
Edwardsia sp.	0.25	0.49
Nemertini indet.	0.21	0.47
Circalittoral mixed sediment	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**23.50**
Echinocymas pusillus	0.98	8.72
Scoloplos armiger	0.55	2.59
Kurtiella bidentata	0.55	1.39
Nemertini indet.	0.35	1.24
Prionospio fallax	0.32	1.24
Nephtys caeca	0.33	1.18
Nucula nitidosa	0.50	1.08
Offshore Circalittoral mud	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**18.42**
Amphiura filiformis	0.88	3.55
Galathowenia oculata	0.81	3.44
Scoloplos armiger	0.41	1.36
Diplocirrus glaucus	0.41	1.12
Nemertini indet.	0.34	0.96
Kurtiella bidentata	0.34	0.82
Phoronis sp.	0.32	0.69
Offshore circalittoral mixed sediment	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**13.74**
Scoloplos armiger	0.67	3.70
Spiophanes bombyx	0.59	2.45
Owenia fusiformis	0.54	1.87
Nemertini indet.	0.41	1.07
Nematoda indet.	0.36	0.94
Infralittoral sand	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**54.03**
Magelona mirabilis	1.69	17.59
Sigalion mathildae	1.20	12.62
Tellina fabula	1.27	8.98

Table 4.11. continued

Results of 2-way crossed SIMPER analysis on subregions and broad habitats.

Kattegat		
Offshore circalittoral mud	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**17.90**
Amphiura filiformis	1.15	4.35
Amphiura chiajei	0.73	3.34
Kurtiella bidentata	0.40	0.71
Terebellides stroemi	0.39	0.66
Nemertini indet.	0.37	0.58
Thyasira flexuosa	0.34	0.55
Pholoe baltica	0.34	0.53
Offshore circalittoral mixed sediment	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**21.35**
Amphiura chiajei	1.18	12.91
Nucula nucleus	0.45	2.35
Circalittoral mud	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**19.47**
Amphiura chiajei	0.87	6.06
Phoronis sp.	0.63	2.32
Amphiura filiformis	0.66	2.02
Abra nitida	0.43	1.82
Maldanidae indet.	0.30	0.86
Praxillella affinis	0.25	0.55
Glycera rouxii	0.24	0.54
Circalittoral mixed sediment	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**29.91**
Amphiura chiajei	1.34	16.50
Glycera rouxii	0.53	3.43
Polychaeta indet.	0.40	1.88
Offshore circalittoral sand	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**14.53**
Amphiura chiajei	0.79	2.86
Amphiura filiformis	0.72	2.06
Abra nitida	0.49	1.45
Maldanidae indet.	0.48	1.33
Spiophanes kroyeri	0.61	0.95
Nemertini indet.	0.54	0.89
Phoronis sp.	0.46	0.77
Circalittoral sand	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**24.96**
Amphiura filiformis	1.38	6.55
Phoronis sp.	1.11	4.54
Kurtiella bidentata	0.86	2.85
Astrorhiza limicola	0.69	1.29
Rhodine gracilior	0.42	0.89
Spiophanes kroyeri	0.41	0.69
Praxillella praetermissa	0.41	0.67

Table 4.11. continued

Results of 2-way crossed SIMPER analysis on subregions and broad habitats.

Infralittoral mixed sediment	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**14.36**
Scoloplos armiger	0.83	4.88
Phoronis sp.	0.59	1.31
Spio filicornis	0.48	1.09
Pygospio elegans	0.33	0.61
Thyasira flexuosa	0.34	0.53
Kurtiella bidentata	0.39	0.51
Nemertini indet.	0.32	0.50
Infralittoral sand	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**16.32**
Scoloplos armiger	0.82	4.07
Phoronis sp.	0.67	1.62
Kurtiella bidentata	0.57	1.39
Tellina tenuis	0.41	1.10
Nemertini indet.	0.41	0.94
Amphiura filiformis	0.48	0.79
Nucula nitidosa	0.36	0.61
Offshore circalittoral coarse sediment	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**31.61**
Amphiura chiajei	1.52	14.92
Abra nitida	0.82	4.90
Phascolion strombi	0.42	1.80
Nucula nucleus	0.48	1.41
Infralittoral mud	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**31.76**
Amphiura filiformis	1.42	5.79
Nucula nitidosa	1.11	4.51
Kurtiella bidentata	1.23	4.08
Phoronis sp.	0.88	2.28
Thyasira flexuosa	0.73	2.24
Notomastus latericeus	0.63	1.75
Phoronis muelleri	0.60	1.19
Infralittoral coarse sediment	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**19.32**
Scoloplos armiger	0.95	4.59
Spio filicornis	0.78	2.12
Nemertini indet.	0.65	1.98
Chaetozone setosa	0.61	1.51
Phoronis sp.	0.60	1.47
Kurtiella bidentata	0.53	1.37
Ampelisca brevicornis	0.51	1.83

Table 4.11. continued

Results of 2-way crossed SIMPER analysis on subregions and broad habitats.

Baltic Sea		
Infralittoral sand	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**16.76**
Peringia ulvae	1.07	4.68
Scoloplos armiger	0.68	3.20
Pygospio elegans	0.61	1.50
Hediste diversicolor	0.43	1.35
Mya arenaria	0.38	0.89
Cerastoderma glaucum	0.36	0.82
Infralittoral mixed sediment	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**20.70**
Peringia ulvae	1.20	9.92
Pygospio elegans	0.59	2.69
Scoloplos armiger	0.43	1.63
Macoma balthica	0.35	1.55
Infralittoral mud	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**19.61**
Phoronis sp.	1.10	4.29
Kurtiella bidentata	0.65	3.47
Peringia ulvae	0.64	2.84
Lagis koreni	0.44	1.86
Abra alba	0.54	1.46
Circalittoral mud	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**27.26**
Tubificoides benedii	1.15	20.33
Circalittoral mixed sediment	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**46.83**
Macoma balthica	1.46	23.11
Pygospio elegans	1.09	14.57
Circalittoral sand	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**22.86**
Pygospio elegans	1.29	10.76
Macoma balthica	0.66	4.31
Scoloplos armiger	0.38	1.39
Infralittoral coarse sediment	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**26.13**
Pygospio elegans	0.64	6.63
Peringia ulvae	0.86	4.01
Marenzelleria viridis	0.63	3.91
Oligochaeta indet.	0.39	2.79
Hediste diversicolor	0.50	2.74

Table 4.11. continued

Results of 2-way crossed SIMPER analysis on subregions and broad habitats.

Offshore circalittoral sand	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**38.07**
Scoloplos armiger	1.14	21.37
Macoma balthica	0.82	11.62
Offshore circalittoral mixed sediment	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**40.44**
Scoloplos armiger	1.18	14.61
Pygospio elegans	0.78	7.44
Corophium crassicorne	0.62	4.48
Aricidea suecica	0.62	3.96
Offshore circalittoral mud	**Av. Abundance**	**Av. Similarity**
Overall group similarity	**-**	**40.04**
Scoloplos armiger	0.94	34.69

4.5.2 Hard bottom flora and fauna

Flora and fauna investigations on hard bottom target specifically reef sites in areas classified as *mixed substrate* and, principally, all areas classified as *rock and biogenic reef*. The communities are highly controlled by the level of light present at the seabed.

North Sea/Skagerrak

Infralittoral mixed substrate

Reef sites are investigated between 8 and 18 m depth. The communities are highly dominated by perennial macro algae vegetation. The vegetation grows in multilayers at shallow waters with different species adapted to specific layers. The communities include a mix of red and large brown species. Larger epifauna species occur in increasing amount with increasing water depth.

Circalittoral mixed substrate and *Offshore circalittoral mixed substrate*

The community is almost entirely dominated by fauna species, with the soft coral dead man's finger (*Alcyonium digitatum*) and leaf forming bryozoans being the most dominant species attached to the hard substrate (Hansen & Høgslund 2023). Investigations are carried out from close to the infralittoral boundary to 62 m water depth.

Kattegat

Infralittoral mixed substrate and *Rock*

Reef sites are investigated between 4 and 24 m depth. The communities are highly dominated by perennial macro algae vegetation to approximately 22-24 m (Dahl et al., 2003). The vegetation grows in multilayers to 15-18 m water depth, with different species adapted to specific layers. The communities include a mix of red and large brown species. Larger epifauna species occur in increasing amounts with increasing water depth. The species diversity changes from the northern to the southern part of Kattegat given the same light conditions due to decreasing salinity (Dahl et al., 2001). If chalk-sandstone formations, known as bubbling reefs, are considered rock, there are observations from app 8 to 16 m depth. The communities on bubbling reefs are like boulder reefs on the horizontal upper part dominated by macro algae vegetation, but are highly different in their vertical structures, where fauna like sea anemones, the soft coral dead man's finger (*A. digitatum*) and hydrozoans are the dominant biota.

Baltic Sea

Infralittoral mixed substrate and *Rock-biogenic reef*

In the Danish part of the Baltic Sea region, large changes in biota occur along the change in salinity, given the same light conditions (Dahl et al., 2003). Information of communities exists from 4 m water depth to the circalittoral border in the Belt Sea area. Multi-layered diverse vegetation with red algae and large brown algae species occurs in the northern Belt Sea region. Sponges and leaf-forming bryozoans may occur with relatively high biomasses as well on water depths >15 m in areas with high currents in the Belt Sea. East of the Gedser-Dars sill and south of the Drogden sill in Øresund, the salinity drops to a level impacting the survival of Common Sea star (*Asterias rubens*). Lack of sea stars favour the survival of blue mussels (dominated by *Mytilus trossolus*). Below the very shallow water, mussels most often form dense carpets on boulders and rock (Dahl et al., 2025a) with few red algae species growing in between and often in a dwarf form caused by the low salinity. Large brown algae species are almost completely lacking south-east of the sills on depths >4 m, although the two large brown algae species blather wrack (*Fucus vesiculosa*) and toothed wrack (*Fucus serratus*) grow in very shallow waters.

Offshore circalittoral mixed sediment

According to the seabed sediment map, the reef location Davids Banke, located northwest of Bornholm, should be considered *Offshore circalittoral*. However, the depths investigated during monitoring, as well as the algae vegetation present (although sparse), indicate that this specific location is misclassified in the seabed map. Davids Banke is likely infralittoral.

5 Discussion

The sensitivity analysis presented in this report is based on the areal extent of the broad habitats. In this way, it is well aligned with EU's MSFD procedure describing good environmental status for the descriptor benthic integrity.

Broad habitats and biological data

To improve the database for the broad habitats, we updated the substrate map with available new data of high spatial coverage. The broad habitats are produced with several methods and over a long period of time. Both the sediment information and the bathymetry, which is an important parameter for the biological zones, are additionally interpolated between survey points and lines. Newer data tends to have a better coverage and more detail in the mapping. Few areas in Danish waters, like sand and gravel extraction sites and construction sites like OSW's and Natura 2000 sites, have very detailed and up to date maps with full or high cover between the hydroacoustic survey lines. In other areas, habitat maps rely on interpolation/modelling between widely spaced survey lines and scattered sediment sampling, which results in seabed maps with varying degrees of confidence. As survey resolution increases, a greater degree of detail is provided. Artifacts of this are evident on Figure **2.2**, with areas of extreme complexity describing multiple marine habitats within a small area and other areas given broad generalised coverage.

Broad habitats use generalised substrate classes, which, in some cases, contain different degrees of hard and soft substrate within a single habitat. Bedrock is a separate class, while boulder reef, the dominant form of hard bottom substrate, is part of the mixed sediment left by glaciers.

Most often, dense numbers of boulders (reef sites) are a result of erosion processes after the glacial period, making them much more likely to find at shallow areas or along ancient riverbeds or in areas with strong currents today. The chance of finding hard substrate in the substrate type mixed sediment is therefore less likely at circalittoral and offshore circalittoral seabeds compared to infralittoral ones. Making an expert judgement, the distribution of biological hard bottom sampling reflects the expected depth distribution of hardbottom habitats on mixed sediment. *Circalittoral rock and biogenic reef* and *Offshore circalittoral rock and biogenic reef* in Kattegat and the Baltic have no hard bottom sampling at all. In general, those areas are small.

Even though several of the broad habitats can contain both hard and soft substrate to different degrees, we address the communities individually within this report, since hard and soft substrate flora and fauna monitoring use different sampling techniques, making it impossible to combine the data for analysis. Broad habitats, with a high presence of hard substrate, present a particular challenge for soft-sediment sampling techniques such as Haps corer or Van-Veen grabs. This often leads to low opportunistic sampling in these areas or no sampling at all. On the other hand, hard bottom sampling targets most often areas defined as reef sites with a high degree of stable hard substrate present.

Delineations

For an area-based approach, the chosen delineations have a direct influence on the areal extent of the broad habitats. At the start of the project, no decision had been taken for the Danish management of the MSFD as to which subregion delineation to choose. It was decided to use three subregions, as was used in the first phase of the Danish implementation of the MSFD. The subdivision has an influence on the area percentage of the broad habitats. The biology in fjords and other coastal area differs from the open sea, and nearshore areas have so far not been allocated to large wind farms. Thus, it was decided to exclude fjords and near coastal areas. Due to the placement of the OWFs, we could not exclude 1 nm from the baseline, as is sometimes done for the MSFD, and chose 1 km from the coast instead. This reduced the resulting areas of those broad habitats that overlap with the coastal zone and has both influence on the sensitivity analysis and the coverage of the scenario 2030. Since we removed the coastal zone, mainly the infralittoral habitat types have been reduced.

Sensitivity analysis

With the above-described limitations, the sensitivity can be based on the percentage distribution of the broad habitat areas within a subregion. With this method, we describe a continuous range from higher sensitivity, described by the lowest occurring percentage, to lower sensitivity, described by the highest occurring percentages. To be able to distinguish between higher, medium and lower sensitivity, thresholds had to be chosen. The thresholds of 5 and 15% are not based on scientific data, but are chosen to provide balanced input to the overall sensitivity mapping of nature, environmental, wind and hydrodynamic conditions. Use of sensitive benthic communities and indicator species in Danish waters would have been a preferable approach to describe sensitivity, but is hampered by lack of biological (detailed habitat classification) and geophysical data and knowledge of wind farms' impacts on specific communities and species.

Potential loss and impact

Similarly, the impact analysis is strongly influenced by the above-described decisions for the area delineations. The cut-off of the coastal zone and the fjords influences the calculated infralittoral percentages.

We have made a preliminary assessment of the 2030 wind farm plans in relation to the thresholds for achieving good environmental status, as defined by the MSFD. For benthic habitats, these thresholds are set at a maximum of 2% for the extent of loss and 25% for adverse effects on seabed habitats. Even though the European commission has defined those targets, it is still unknown what the baseline is for permanent loss in terms of starting year, and the term "adversely affected" is also open for discussion. A full assessment would need to include effects of all pressures, like fishery, sand and gravel extraction, and land reclamation projects, like (beach park south of Lolland, and the projects Nordhavn and Lynetteholm in The Sound). A full assessment was beyond the scope of this project.

There is still a significant lack of scientific evidence regarding the extent and magnitude of the effects on benthic biota when small artificial reef sites are established on a sandy seabed, known as the reef effect. The unsolved questions include whether it is an adverse effect, the size of the effect and the differences from subregion to subregion. In our assessment, we have assumed an adverse effect to 100 m distance from the centre of the turbine tower.

Even more uncertain are the other potential effects (type 3). We have decided to make a worst-case scenario based on the assumption that adverse effects on the benthic biota might build up over years in the entire farm area. This would for example cover effects of cables, changes in hydrography and fisheries. Comparing with current environmental conditions, established wind farms might improve conditions in those cases where parks exclude fishery with bottom contacting fishing gear. We hoped to document this effect in another study (Dahl et al., 2025b), but were unsuccessful.

Construction of windfarms in areas with boulder reefs have so far been avoided in Danish waters. If this should happen, one could argue that the reef effect would not be a problem. The same can be argued building on the habitat type rock. However, we know from two studies at Anholt Windfarm (Dahl et al., 2025b) and Krigers Flak Wind farm (Dahl et al., 2025a) that the biology is different on the tower compared to natural reefs, especially in Kattegat. In general, the turbines favour hard bottom fauna at the expense of algae communities in both studies. Blue mussels seem to thrive in the upper part of the turbine tower to the extent that beds of dead shells can build up around the towers. The development of shell beds was observed at Anholt Wind Park (Dahl et al., 2025b).

The estimates of the affected areas for the direct impact, the reef effect and the whole OWF as an area are therefore only a rough estimate to show the possible range. While it is expected that the entire OWF areas might not be affected, the effects are, on the other hand, not necessarily limited to the OWF area.

Benthic community composition

There is no observed trend between Shannon diversity index and sensitivity (Figure 4.10), however, there is a lack of biological samples at higher sensitivities. High sensitivity habitats (i.e. *Circalittoral rock* or *Offshore circalittoral rock and biogenic reef*) are likely rarely sampled, as operating a sediment core sampler in areas with increasing hard substrate is unreliable, as sediment cores' success relies on hitting random patches of sediment within a hard substrate environment.

The analysis of the soft sediment benthic community broad habitats confirms that the report's approach of treating each broad habitat and subregion separately was appropriate. This is further supported at the subregional level by the biodiversity measurements. The Kattegat's overall higher diversity is likely due to its position as a boundary region and the fact that it spans across large abiotic gradients (i.e. salinity, depth, temperature) (Göransson, 2017; Obst et al., 2018). This was evident in the shared similar species between the North Sea and Kattegat, however, interestingly, this overlap was not evident with the Baltic Sea, suggesting a possible zonation between these two regions.

A broad habitat exception was *Offshore circalittoral mixed sediment*, which was not distinct from several other broad habitats in species composition. The lack of distinct soft sediment benthic community in the offshore circalittoral habitat is likely due to the mixed sediment, categorising a mix of the sediment types quaternary clay, silt, till and diamicton, including boulders.

The North Sea has a wide range of soft sediment benthic community structures, even with relatively few broad habitats (Figure 4.12). This is likely due to the large area that the North Sea subregion encompasses within this study. The majority of collected samples include *Circalittoral sand* and *Circalittoral coarse sand*, which reflect this wide range of soft sediment benthic communities and is indicative of regional shifts from the South to the North within the North Sea. The North Sea/Skagerrak also contained most broad habitats without soft-sediment community sampling, limiting what can be observed about the community structure.

The Kattegat had the greatest number of recorded broad habitats, likely due to the environmental gradients that run across it and resulting in the higher diversity across most Kattegat broad habitats. Across the Baltic Sea, the broad habitats have a large degree of overlap with similar biodiversity, however, *offshore circalittoral mixed sediment* and *offshore circalittoral sand* were strongly clustered together and had a similar benthic community.

The Baltic Sea contained the lowest number of characteristic species, indicating that very few relatively high abundance species are responsible for the community structure. Previous studies have made an inventory of benthic macrofaunal communities in the entire Baltic Sea, which found 10 major communities (Gogina et al., 2016). Although these communities do not match the broad habitats described here, a good number of the same species have been highlighted, including *Macoma balthica* and *Pygosop elegans*, as well as others.

A species of note across all stations is *Scoloplos armiger* (bristle worm), which was relatively prevalent. This is not surprising due to it cosmopolitan nature being one of the most common macrofauna species of the eastern North Atlantic (Hartmann-Schröder et al., 1996). Other work has shown the ability of this species to form sub-populations within different environments (Kruse et al., 2004) and adaptation to deal with hypoxic conditions (Schöttler & Grieshaber 1988).

Furthermore, it is worth considering the limitations of the soft-sediment monitoring data within this report, which were collected using multiple different methods and across a large temporal scale, and which do not contain the wider marine community, including meiofauna and the neckto-benthic fish populations. Within the realms of a screening report, however, this compromise in the data is appropriate, and the report will hopefully provide context and information for any potential offshore wind farm projects within these locations.

6 Conclusion

With the above discussed limitations, we estimated the percentages of the broad habitats within the region and applied threshold values to identify sensitivities values. We classified broad habitats with less than 5% coverage as having higher sensitivity, those with more than 15% coverage as having lower sensitivity, and the remaining habitats as moderately sensitive, based on their coverage within each of the three subregions. The threshold values were selected to identify areas, where potential conflicts with the EU Maritime Strategy Framework Directive (MSFD) targets could be highest in the future. However, these values were also chosen to leave sufficient space with lower sensitivity, so that other factors, such as seabed construction suitability and higher sensitivity areas for other biological components, can be taken into account in the strategic planning for new wind farms. The threshold values were determined through an iterative process that identified areas of highest sensitivity, while also allowing space for future wind farms that will be constrained by other factors as well. The threshold values are easily adjusted if needed. Using the 5% threshold, we found that 13.4% of the North Sea/Skagerrak 6.6% of Kattegat and 15.3% of the Baltic Sea could be considered having the higher sensitivity according to spatial extent of the broad habitats. With the 15% threshold, we found a lower sensitivity in almost 81% of the North Sea, 61% in Kattegat, but only 48% in the Baltic Sea. The medium sensitivity made up the rest, being very low in the North Sea/Skagerrak (app 6%), but covering about 1/3 in Kattegat and the Baltic Sea.

This assessment is closely aligned with the area-based approach of descriptor 6, seabed integrity, under MSFD. As requirements for good environmental status, two thresholds are set so that no more than 25% of each broad habitat type should be adversely affected by human pressures and no more than 2% should be irreversibly lost. More targets for additional indicators are expected to be decided upon by the EU in the future. We assessed the potential overall impact of the existing and planned OSWs until 2030 as defined for the overall screening project. The assessment distinguished three types of impact: direct construction impact, resulting in habitat loss; reef effect, potentially having an adverse effect of the seabed habitats biota; and, as a proxy, an overall park effect, which includes both the construction effect, the reef effect and the more hypothetic effects on benthos due to e.g. changed hydrography and other wind farm related pressures.

We found that the construction effect (the area covered by the turbines and the scour protection) would result in a less than 0.071 % loss in all broad habitats. For *Circalittoral rock* in the Baltic area, being the highest impacted, this corresponds to 1337 m^2. The threshold level of habitat loss of 2% was far from reached in all cases. It is important for managing good environmental status in accordance with the MFSD to include loss from all pressures and over the timespan that (apparently) still needs to be decided by the member states. However, the contribution of direct, construction-caused loss from wind farms is minor.

The turbines and scour protections are likely to have a reef effect, i.e. have an effect on benthic communities in the vicinity of the scour protection. This change might turn out as an adverse effect. Keeping in mind that, although it is decided at EU level that no more than 25% should be adversely affected by human pressures, it remains to be defined what 'adversely' means in this context. Assuming an impact distance of maximum 100 m from the centre of the turbine, this effect was less than 0.25% in the North Sea, with the highest value for *Infralittoral sand*, less than 0.15% in Kattegat, with highest value for *Circalittoral coarse sediment,* and less than 1.25% for *Circalittoral rock* in the Baltic Sea. The importance of a reef effect can be questioned at the broad habitats defined by the substrate rock or in specific parts of the broad habitats defined by the substrate class mixed sediment holding reef sites. Again, a potential reef effect needs to be assessed with effects of other benthic pressures in relation to the MFSD targets.

If new research provides knowledge on important, negative bottom-up processes (type 2 and 3 – reef effect and all other potential impacts), they may result in adverse effects on seabed ecology and, potentially, on larger scales.

If adverse effects are to be considered on the overall wind farm scales, then the habitat type *Circalittoral rock* is 100% affected in the western Baltic, but also *Offshore circalittoral coarse* sand and *Circalittoral coarse sand* highly exceed the MFSD 25% target for good environmental quality in this area, and *Circalittoral mud* is close to the limit, with 23%. These broad habitats are, at the same time, of higher sensitivity (sparser occurrence) in the Baltic Sea. Three other broad habitats of higher sensitivity (*Circalittoral mixed sediment*, *Circalittoral mud* and *infralittoral mud)* would be affected by more than 2%.

The 25% target is not exceeded for any habitats in Kattegat or the North Sea/Skagerrak, but several habitats could potentially be affected between 5 and 10%. In Kattegat and the North Sea/Skagerrak, there are three broad habitats of higher sensitivity that are covered by the park area of the existing and planned OWFs until 2030 by more than 2%. In the Kattegat, these are *Circalittoral coarse sediment* and *Offshore circalittoral coarse sediment,* and in the North Sea/Skagerrak it is *Infralittoral sand*.

It should be noted that within the scope of the project, we only assessed the impact of the OWFs. Adding other stressors, like sand and gravel extraction or bottom trawling in the North Sea and Kattegat to this potential wind farm effect, would increase the total impact per broad habitat. Finally, it is important to note that excluding fishery with benthic contacting gear in wind parks might have a positive effect on large parts of the benthic communities within the park area – and potentially beyond. The exclusion of benthic contacting gear is based on safety zones around cables that are defined in the Executive Order on the Protection of Submarine Cables and Submarine Pipelines (BEK nr 939 af 27/11/1992) to 200 m on both sides of a cable or combined cable fields.

Across all three subregions, the soft sediment broad habitat communities are different between subregions, but with similar key species. This could be interpretated as shaped by fishing pressure, with the observed communities representing an early successional stage and lack of climax species. These pioneering species will dominate across all habitats regardless of sediment due to the fishing pressure. This adds complexity when analysing the post construction effects of OWFs, as it is the combined effect of fishing pressure removal and OWF disturbance that results in the observed community. Monitoring the development of seafloor communities following construction is crucial, as is interpretation, since removal of fishing pressure might allow the development of a more natural (less anthropogenically influenced) community, regardless of OWF impacts.

It is important to keep in mind that sensitivity ranking and the proposed identification of areas with three different classes of effect rely on the available broad-scale habitat maps with varied spatial confidence due to differences in survey intensities. From a biological point of view, the broad habitats defined by mixed sediment are not ideal as a management unit, as they can include hard stable boulder reefs as well as a range of other sediments (clay, sand and coarse sand), each with very distinct biological communities. But this is currently the only available data and aligns with the approach of the MSFD.

It is also important to keep in mind that the assessment of potential impacts builds on several assumptions, since the state of knowledge of ecological effects of wind turbines and wind parks are still insufficient. Especially the assessment of the park effects should be considered as a worst-case scenario and should be adjusted to reflect a growing knowledge base. On the other hand, factors such as larval production and dispersal could lead to non-local impacts, hence potentially leading to an underestimation of the impacts from OWF.

7 References

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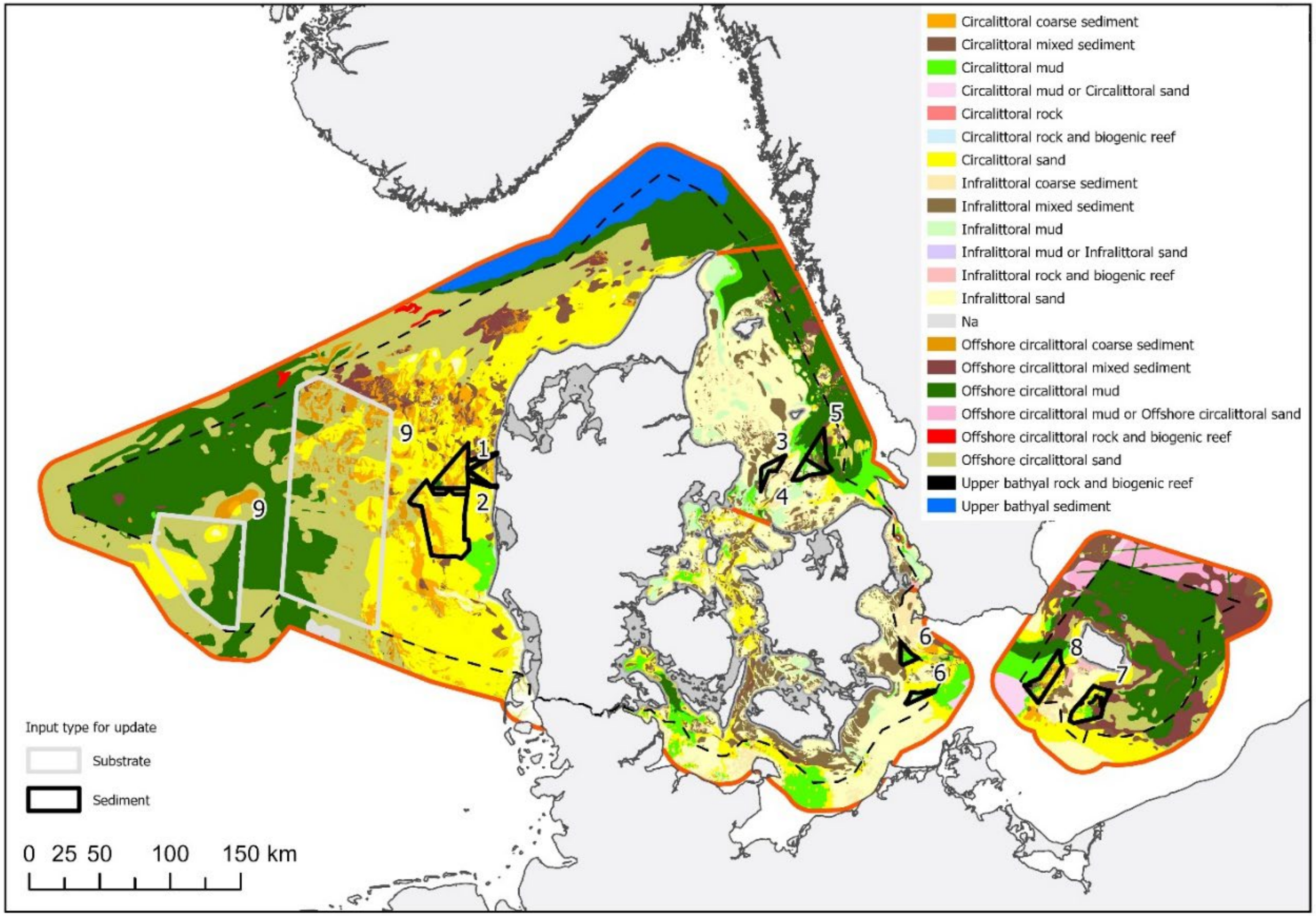
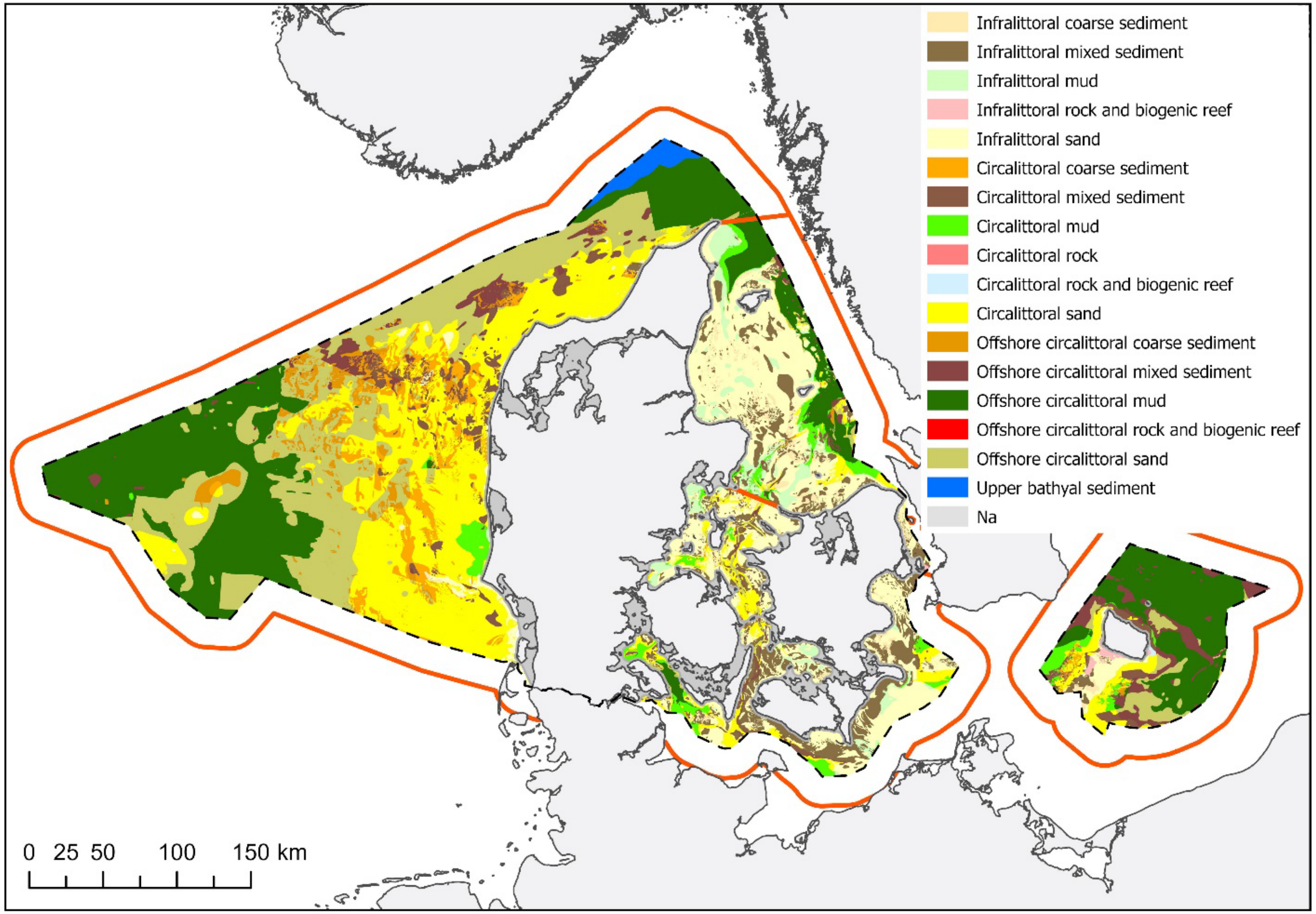
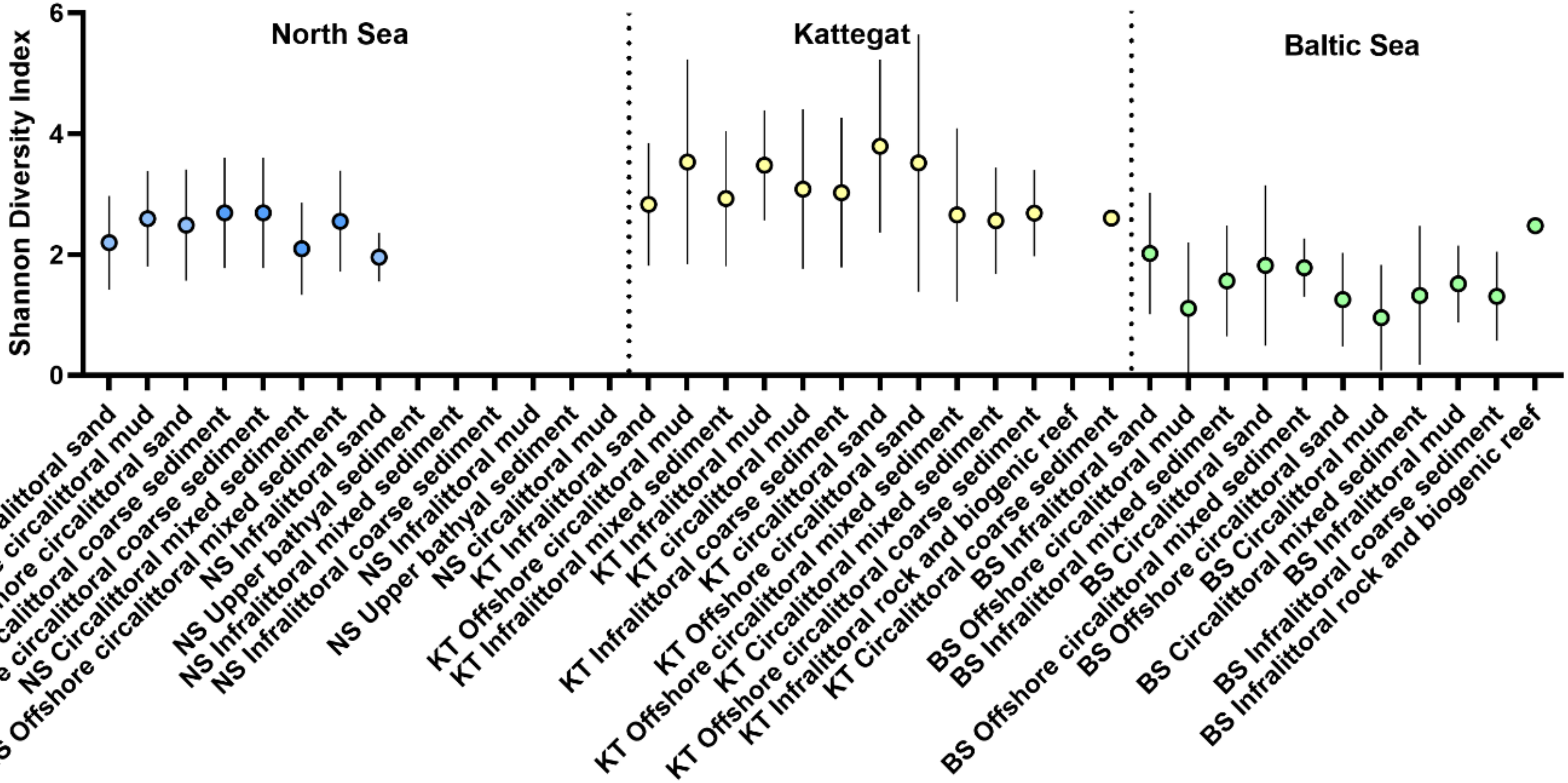
9 Appendix



Figur 9.1. Broad habitat types and the nine areas (table 3.1) where the sediment information was updated



Figur 9.2. MSFD broad habitat types in the Danish EEZ.



Figur 9.3. Average Shannon diversity index for all broad habitat types for each sub-region: NS – North Sea, KT – Kattegat, BS –Baltic Sea. Error bars are standard deviation. Broad habitat types with no sample point contain no soft sediment samples.

Glossary

Seafloor is defined as a key compartment for marine life. It includes both the physical and chemical parameters of seabed (e.g. bathymetry, roughness (rugosity), substratum type, oxygen supply, etc.) as well as the biotic composition of the benthic community. Different kinds of habitats for sedentary and mobile marine species are formed inside and above the seabed.

Integrity is interpreted as comprehending both (i) natural spatial connectivity (avoiding unnatural habitat fragmentation or connectivity), and natural ecosystem processes functioning in their characteristic ways.

Not adversely affected means that the cumulative effect of pressures associated with human activity are at a level that ensures the ecosystem maintains its respective components (structure) along with its natural levels of diversity, productivity, and dynamic ecological processes (functioning). Levels of disturbance (intensity, frequency, and spatial extent) must be at a level that ensures a dynamic recovery potential is maintained.

Recovery means that the impacted seafloor attributes show a clear trend towards their pre-perturbation conditions, and the trend is expected to continue (if pressures continue to be managed) until the attributes lie within their range of historical natural variation. Benthic communities are not static entities, and thus recovery does not re-quire that the ecosystem attributes return to their exact prior state.

Rapid must be interpreted in the context of the life histories of the species and natural rates of change in the community properties being perturbed. For some seafloor habitats and communities, recovery dynamics from perturbation would require multiple decades or more, and in such cases management should strive to prevent perturbations.

Impairment of an ecological component occurs if the ecological consequences of the direct or indirect perturbations extend widely through the ecosystem in space and/or time, or if the normal ecological linkages among species act to extend and amplify the effects of a perturbation rather than to dampen its effects.

Source: European Commission. 2024

ENVIRONMENTAL MAPPING AND SCREENING OF THE OFFSHORE WIND POTENTIAL IN DENMARK

Sensitivity mapping: Benthic habitats and associated biological communities

This report assesses the sensitivity of benthic habitats and biological communities to establishment of offshore wind farms in Danish waters. Sensitivity was estimated as the percentage of each broad habitat within the North Sea/ Skagerrak, Kattegat, and Baltic Sea basins. The study's purpose is to inform overall sensitivity mapping of natural, environmental, wind, and hydrodynamic conditions for future wind farm planning.

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