# BENSO

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WAARDEN BURG Ecology

WAGENINGEN UNIVERSITY & RESEARCH

WATER PROOF Marine Consultancy & Services BV.

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# Preface

In spring 2019, the BENSO initiators came up with the idea that taking the developments on scour protection developments a step further could give a major boost to making offshore wind initiatives truly nature inclusive. And apart from the design of scour protection, monitoring the success of such nature-inclusive initiatives had to become easier and therefore cheaper. The project idea for Scour protection design for **B**iodiversity **E**nhancement in **N**orth **S**ea **O**ffshore Wind farms was thus born. It was then a small step to set up a project and submit it to RVO for a financial contribution from the TKI Wind op Zee (WoZ) program.

After the grant was awarded in autumn 2019, the collaboration between Waardenburg Ecology (then Bureau Waardenburg), Wageningen Marine Research and Waterproof B.V. was a fact.

The present report reflects this more than 4.5 years of collaboration. It has become a unique project in which each partner contributed its own knowledge and experience, and which jointly resulted in absolute added value.

Apart from the authors of this document, many collaborators have made this project possible, in the development of innovative techniques, during fieldwork expeditions, sparring sessions and during consortium meetings.

The authors are more than grateful to the following persons:

At Waardenburg Ecology: Wouter Lengkeek (co-initiator, diver & quality assurance), Joost Bergsma (innovator & diver), Udo van Dongen (cameras and underwater photographer), Tom van Gemert (the electro genius), Rebecca Bakker (support on pebbles research), Karin Didderen (critical follower and author) & José van Zundert (financial support).

At WMR: Oscar Bos (co-initiator + diver), Enzo Kingma (lead author pebble article), Ninon Mavraki (co-worker from first hour), Afra Asjes (project management), Oliver Bittner & Babeth van der Weide (both lab work).

At Waterproof B.V.: Luitze Perk (co-initiator), Marijke Olivierse (logistics), Joost Brinkkemper (computer wizard) & Daan Nieuwendijk (field wizard).

We also had the necessary collaborations with people outside our organizations: the crew of the Tender I (especially skipper Frank Loonstra), employees of Programma de Rijke Noordzee (Marjolein Kelder, Frank Jacobs & Renate Olie), employees of ARK Rewilding (Karel van den Wijngaard, Ernst Schrijver & Marijke van de Staak), employees of van Oord (Remment ter Hofstede, Nathalie Strookman, Miriam Schutter), fellow divers like Ben Stiefelhagen, Klaudie Bartelink, Peter van Rodijnen and Melchior Stiefelhagen. in case we forgot anyone, apologies, but super thanks to you too!

And of course, thanks also to RVO & TKI Offshore Wind (grant TEWZ119010) for making this project financially possible.

**In memoriam**

In February 2025, during the completion phase of this project, Roelant Snoek passed away. The death of Roelant, initiator and co-author of the Benso project, saddens us deeply. Roelant was a great inspirator for innovative marine research as reflected in the Benso project. He connected biology with engineering. His technical approach to ecological issues created a close bond between the Benso partners and beyond. Offshore wind, offshore monitoring programmes, nature restoration and innovations in shoreline maintenance: all fascinating projects in which we worked energetically together. We thank Roelant immensely for his inspiration and legacy. The loss is immense. This report is dedicated to his remembrance.

# Contents

# Summary


**Background**

As part of the transition from fossil fuels to renewable energy, the Dutch government aims to realise five offshore wind farms of 700 MW before 2023 and an additional 1,000 MW between 2023 and 2030. A further increase to more than 35 GW in 2050 by offshore wind energy is needed to reach climate goals. The Dutch government identified several challenges to the successful scaling-up of offshore wind energy. One of these is the ecological impact of OWF's on the North Sea ecosystem, which can be either negative (bird collisions, disturbance, construction effects) or positive (introducing hard substrate in a mainly soft sediment ecosystem, bottom-trawling ban). There is increasing international evidence for the ecological opportunities and positive effects of offshore wind farms (OWF's) on subsurface marine ecosystems. Scour protection functions as settling substrate for marine organisms and habitat for fish, crabs and lobsters. This has motivated the Dutch Ministry of Agriculture, Nature and Food Quality to use the development of OWF's to strengthen the North Sea ecosystem by enhancement of ecological functioning in OWF's to improve the status of policy-relevant species.

**Objectives**

The BENSO-project contributes to Programme line 3 of the TKI-WOZ programme Integration of offshore wind energy in the environment (ecology and multi-use) and aims to:

1) To create economical value by developing, testing and implementing smart ecological design for scour protection in offshore wind farms to enhance biodiversity locally and in the wider ecosystem.
2) Implement smart monitoring techniques in monitoring programmes and maintenance operations.

**Activities**

The BENSO project aimed to develop and implement methods and techniques for biodiversity enhancement within offshore wind farms. The positive impacts of scour protection on species and ecosystem scale will be quantified by desk studies, field experiments in OWF's. Smart monitoring techniques were implemented in experiments, regular monitoring and in maintenance operations. Smart ecological design of scour protection will be developed and tested. An approach to select smart ecological designs is made available to the OWF industry.

## Results

Positive impact of scour protection on species and ecosystem scale

The creation of a joint dataset (BISAR) to which the BENSO project contributed, has proven valuable for the increase of scientific understanding of benthic effects of offshore wind farms.

Results demonstrate that abundant and diverse communities are present on all SPLs. On a regional scale, communities are mainly affected by depth and location. Increasing habitat complexity has significant and positive effects on species richness yet was non-significant for biomass and abundance of the biofouling community. Nature inclusive design of the SPL habitat can effectively promote biodiversity by manipulating the physical complexity of the structure.

Smart monitoring techniques

Smart monitoring techniques are primarily developed to enable easy application by non-ecologically trained personnel. In this way, maintenance personnel of wind farms, for instance, can be offered the possibility to collect ecological data. In addition, the devices should be applicable on small (fast) CTVs, so that costs can be saved on the deployment of large ships.

Within the BENSO project, the dropcam, for instance, turned out to be an alternative for ROV applications. The system is robust and can be applied on different substrates. Baited cams are suitable for collecting images in wind farms, with special focus on mobile species like fishes, crabs and other invertebrates. Apart from the design of the hardware of the cam also the baited used will influence the success of the results. Using different kind of baits will increase the attraction to a variety of organisms.

The use of an unmanned vessel can lead to the collection of a lot of hydrological data but also can be adjusted to make recordings of marine mammals. The challenge for devices like the AUV is the range in which they can operate.

The use of the DOME device is gives special insight in the epibenthic fauna and the use and production of nutrients and biomass.

Habitat complexity

The different biogenic reef types differ in various aspects of morphology, structural components, interstitial spaces and fractal dimension, A common aspect of all reefs is the interaction between the reefs and surrounding soft sediments: mobile species can dig burrows in the sediment and acquire a stable cover from the hard substrate. The structural complexity is lowest in encrusting polychaete reefs (e.g., *Sabellaria alveolata*) and higher in serpulid reefs which form hemispherical structures (*Serpula narconensis*). The habitat complexity is highest in the irregular and hemispherical oyster reefs and corymbose and branching corals. The reefs with high structural complexity substantially increase turbidity and create wakes, which leads to higher retention of food and larvae. On the other hand, corymbose and branching corals are sensitive for hydrodynamic disturbances. In theory, the overall conclusion is that fractal dimension is a very good parameter to describe habitat complexity in biogenic reefs.

Apart from the habitat complexity, the kind of hard substate defines what kind of organisms occur on a certain location. Different organisms seem to attach to different kind of rocks as shown in the experiment where 3 kind of potential scour protection material was subjected to offshore conditions. The type of material appears to select for different groups of organisms (e.g. more tube dwelling organisms on marble and more free-living, epi/endobiotic and crevice dwelling organisms in concrete samples). And on top of that the when it comes down to epibenthic species: more surface area will lead to more space for settlement and potential diversity in species. For mobile species it is the interstitial space between rocks and other substrate that provides crevises for hiding and finding food.

Smart, nature-inclusive design available to OWF industry

Offshore wind turbine scour protection is evolving to integrate more sustainable and nature-inclusive designs, mimicking natural reef habitats. Concrete structures are widely promoted for their cost-efficiency and complex designs that support biodiversity. However, the challenging offshore conditions require stable, hydrodynamic designs. The proposed approach merges hydrodynamic analysis with ecological needs, using habitat complexity measures (like fractal dimensions) to enhance biodiversity. The five-step design process includes identifying ecological functions, selecting solutions through multi-criteria analysis, and testing stability and ecological interactions. This method aims to provide smart ecological scour protection to the Offshore Wind Farm industry.

**Conclusions**

Based on the above, we conclude that the following parameters should be taken into account in the design of scour protection:

- Increase the size ranges of the stones of the armour layer in a conventional scour protection design;
- Make use of various types of material within the armour layer (mix of various rock types, as well as wood and other natural materials);
- Use material that contributes to an optimal balance between lots of surface area for settling and at the same time creates lots of space between the material for foraging and hiding of mobile species;
- Design or select scour protection according to the principle of trait-based industrial design for maximum biodiversity gain within industrial requirements
- Consider omitting filter layers for creating extra space between sediment and hard substrate for infaunal species which contributes to the overall biodiversity.

For the successful monitoring several devices have been developed which can be easily applied with smaller vessel like CTV’s. It is now important to further roll out the knowledge gained in BENSO so that in time, staff, who are already on board of CTVs to maintain the park's hardware, can collect ecological data. Apart from that, further development in data analysis and management. In that aspect AI is promising in analyzing collected video and photo images.

# 1 Introduction

## 1.1 Background

As part of the transition from fossil fuels to renewable energy, the Dutch government aims to realise five offshore wind farms of 700 MW before 2023 and an additional 1,000 MW between 2023 and 2030. A further increase to more than 35 GW by offshore wind energy is needed to reach climate goals (Ros and Daniëls, 2017). The Dutch government identified several challenges to the successful scaling-up of offshore wind energy. One of these is the ecological impact of offshore wind farms on the North Sea ecosystem, which can be either negative (bird collisions, disturbance, construction effects) or positive (introducing hard substrate as settling substrate for marine organisms in a mainly soft sediment ecosystem, cessation of bottom-trawling). In addition, large-scale extraction of wind energy may affect local wind patterns and hydrodynamic conditions (Boon et al., 2018) and the scour protection may attenuate the noise generated by the wind turbines.

There is increasing international evidence for the ecological opportunities and positive effects of offshore wind farms on subsurface marine ecosystems (Ashley et al., 2014; Hammar et al., 2016). Scour protection, for example, can function as settling substrate for marine organisms or habitat for fish, crabs and lobsters. This has motivated the Dutch Ministry of Agriculture, Nature and Food Quality to use the development of offshore wind farms to strengthen the North Sea ecosystem by enhancement of ecological functioning in offshore wind farms to improve the status of policy-relevant species. This is part of the North Sea 2050 Spatial Agenda (Min I&M and Min EZ, 2014) and is being operationalized through permit-obligations. In addition, if biodiversity enhancement by offshore wind farms can be realized, this will generate public support for the scaling-up of offshore wind, in an area where a variety of sectors compete for space (fisheries, mining, recreation, transport).

*Problem definition* The governmental challenge for the realisation of offshore wind energy is how to mitigate the negative impacts (e.g. birds strikes) and to increase successfully the ecological value of offshore wind farms (OWF's) and to implement that in current and new OWF's on a relatively short time scale in a cost-effective way. This challenge is shared between the public and private partners: the policy goals of the government overlap with the market opportunities of the OWF industry and related consultancies.

## 1.2 Objectives

The BENSO project aimed to:

1) Create economical value by developing, testing and implementing smart ecological design[1] for scour protection in offshore wind farms to enhance biodiversity locally and in the wider ecosystem (see figure 1.1).
2) Implement smart monitoring techniques[2] in monitoring programs and in maintenance operations.

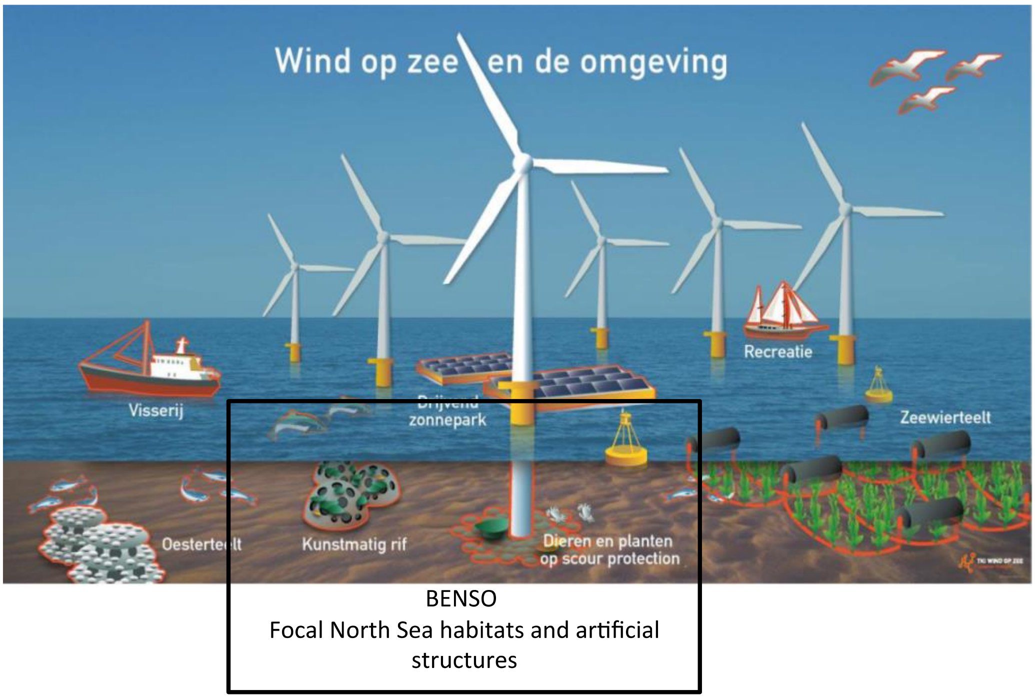


*Figure 1.1. Wind at Sea and the Environment: ecological values, habitats and multi-use (source: www.noordzeeloket.nl).*

## 1.3 Results and impacts

The expected results and impacts from the BENSO project were:

1) Ecological scour protection design and technology available for OWF industry. (reports and an approach to select smart ecological design of scour protection).

The expected impacts are:

2) *Economical* – Support of multi-use of OWF's by enhancement of populations of commercial species of fish, lobster and crab.
3) *Economical* - The development and implementation of smart ecological design for scour protection will lead to significant cost-reduction if scour protection can remain on the seafloor after decommissioning;

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[1] Smart, ecological design: cost-effective adjustments of scour protection (as attachment substrate for organisms) with a large ecological effect

[2] Smart monitoring techniques are methods which replace diving operations and reduce monitoring costs, for example, eDNA methods, video cameras with bait to attract mobile species, ROV which can take scratch samples from hard substrates.

4) *Economical* - Cost-efficient methods developed to enhance and monitor biodiversity will provide competitive advantage for Dutch research organisations and offshore wind industry;
5) *Ecological* – Enhancement of biodiversity of the North Sea ecosystem is an important goal of national and international policy and legislation (Marine Strategy, OSPAR);
6) *Scientific* – Improved knowledge of biodiversity enhancement by artificial structures will contribute to our understanding of the functioning of marine ecosystems and to marine conservation worldwide.

| WP | Short description | Contractors | Results / Deliverables |
|---|---|---|---|
| 1 | Quantify impact on (1) macrobenthos and (2) fish and large, mobile crustaceans | **Wageningen Marine Research,** Waardenburg Ecology, WaterProof | Data analysis, impact described, report published |
| 2 | Implementing smart monitoring techniques, including in maintenance infrastructure | **Waardenburg Ecology,** WaterProof Wageningen Marine Research, | Methods developed, tested and resulting data analysed and report published |
| 3 | Develop and test smart ecological design by monitoring | **Waardenburg Ecology,** Wageningen Marine Research, WaterProof | Design and methods developed, tested and results analysed and report published |
| 4 | An approach to select smart design available to OWF industry | **Waardenburg Ecology,** Wageningen Marine Research, WaterProof | An approach to select nature-inclusive scour protection and reports published |

# 2 Quantify positive impact of scour protection on species and ecosystem scale

## 2.1 Background

The presence of offshore wind turbines provides habitat for many species associated with the submerged hard surfaces of the turbine foundation and surrounding scour protection layer (SPL; Coolen et al. 2022). Many of these hard substrate species are rare in sandy sediments (Coolen et al. 2020). As a result of the addition of hard substrates during construction of a wind farm, local species richness of macrobenthic species, may double in comparison to soft sediments without windfarm (Coolen et al., 2019). The biomass of these species can increase 10- to 20-fold compared to the soft sediments. At the scale of an offshore wind farm (72 $km^2$) this increase was estimated to be about 5% (Coolen et al., 2019). This change is likely to affect local ecosystem functioning (Degraer et al., 2020) but since offshore wind farms have only been present for ~20 years, which is short on an ecological time scale, many effects remain unknown and much better understanding of wind farms with the benthic environment is needed (Dannheim et al., 2020).

In all North Sea countries with offshore wind farms, ecological effects monitoring programmes have been carried out. Data was collected on the fouling communities associated with the turbine foundation and (in most countries) the SPL. For most programmes, fauna was scraped from the foundation and SPL rocks were collected, after which the fauna was identified, counted, and weighed. Most of the programmes' results have been published and are publicly available (Leonhard & Christensen, 2006; Bouma & Lengkeek, 2013; Vanagt & Faasse, 2014; Zupan et al., 2023; Gutow et al., 2014). However, the data of these separate programmes had been formatted in different ways, limiting the potential for higher level analysis, and thus understanding of effects on larger scales than individual wind farms or countries. A joint dataset including results from many of these different programmes in a standardised format was needed (Coolen et al. 2022).

With the increasing body of data available from these monitoring programmes, it had become clear that the effects of the SPL were not identical to the foundation effects. SPLs are more complex habitats, with variations in substrate orientation, holes between rocks and a coarser surface area compared to the straight, smooth, vertical surfaces of the turbine foundations (Coolen et al., 2020; Spielmann et al., 2023). However, a better understanding of the effects of SPL on benthic ecology was needed to be able to guide offshore wind farm developers in the optimisation of SPL for wind turbine stability as well as ecology.

## 2.2 Aims

To better understand the effects of scour protection layers on benthic ecology, the aim in this chapter was to quantify the densities and species richness of macrofauna on different types of scour protection (as settling substrate for marine organisms), based on existing data from different monitoring programmes. Furthermore, the project aimed to quantify the abundance of large, mobile species (fish, crustaceans) in relation to different types of scour protection and spatial design.

## 2.3 Activities

To meet the aims of the project, desk studies were carried out and data from different monitoring programmes and scientific studies were collected. The activities were carried out in 3 clusters:

A. In collaboration with an international group of scientists collaborating via the International Council of Exploration of the Sea (ICES) as part of the Working Group on Marine Benthal and Renewable Energy Devices (WGMBRED) a dataset was created, collating all published monitoring data from benthic monitoring programmes in Belgium, the Netherlands, Germany and Denmark using a standardised format. This dataset was named Biodiversity Information of benthic Species at ARtificial structures (BISAR) and made use of the infrastructure of the Alfred Wegener Institute in Germany, where a the Critterbase data system (https://critterbase.awi.de) hosts large amount of benthic species data from all over the world.
B. Using the data from A. in collaboration with scientists from Belgium, an analysis of the SPL data from several wind farms and oil and gas platforms was used to assess differences in species composition between different SPL designs, exploring effects of different rock sizes, surface area and rock types.
C. We reviewed the available literature on abundance of finfish and other mobile species in offshore wind farms in the North Sea. This study included of almost 20 studies of 10 different offshore wind farms in the period 2005-2017. Focus of the study was the effect size of the wind farm in relation to the type of SPL design and other factors.

## 2.4 Project results

The BISAR dataset as well as the analysis of effects of different SPL designs have been included in two scientific manuscripts that are currently under review. Here we present the abstracts of each manuscript. Further details can be obtained from Dannheim et al. (under review) and Zupan et al., (under review).

A. Abstract: Biodiversity Information of benthic Species at ARtificial structures (BISAR)

Understanding the effects of artificial structures in marine landscapes is required for ecosystem-based management. Global demand for oil and gas and accelerated commitments to renewable energy development has led to the proliferation of marine artificial structures. Investigating the cumulative effects of these structures on marine ecosystems requires data on the benthic community over large geographical and long-time scales. It is imperative to share the data collected by many stakeholders in an integrated information system to benefit science, industry and policy. BISAR is the first data product containing harmonised and quality-checked international data on benthos from artificial structures in the North Sea. BISAR was compiled from environmental impact assessment studies and scientific projects (3864 samples, 890 taxa). Data derive from 17 artificial structures and surrounding soft sediments (years: 2003 to 2019). Structures include offshore wind turbines, oil and gas platforms and a research platform. Data from a geogenic reef, allow comparison of natural and artificial reef communities. We aim to host future BISAR data dynamically at http://critterbase.org.

More information: Dannheim, Jennifer, Paul Kloss, Jan Vanaverbeke, Ninon Mavraki, Mirta Zupan, Vanessa Spielmann, Steven Degraer, Silvana N.R. Birchenough, Urszula Janas, Emma Sheehan, Katharina Teschke, Andrew B. Gill, Zoe Hutchison, Drew A. Carey, Michael Rasser, Jolien Buyse, Babeth van der Weide, Oliver Bittner, Paul Causon, Roland Krone, Marco Faasse, Alexa Wrede, Joop W.P. Coolen (n.d.). Biodiversity Information of benthic Species at ARtificial structures – BISAR (under review).

B. Abstract: Effects of SPL design on benthic macrofauna

The scour protection layer (SPL) is a layer of large stones placed around man-made structures in the marine environment, preventing sediment scouring while also providing new hard substrate and potentially increasing the structural complexity of the original environment. This fosters development of diverse benthic communities, supporting high abundance of organisms. Future SPLs are therefore a potential tool for the ecological enhancement of degrading marine habitats following the principles of nature-inclusive design. Yet, factors that shape the benthic communities on SPLs are poorly understood. Here, we analysed existing data from SPLs from offshore wind farms and a gas platform in the southern North Sea to determine how SPL characteristics affect the biofouling community structure. We combined this analysis with an *in-situ* experiment testing for the effects of habitat complexity on SPL communities. Our results demonstrate that abundant and diverse communities are present on all SPLs. On a regional scale, communities are mainly affected by depth and location. Increasing habitat complexity has significant and positive effects on species richness yet was non-significant for biomass and abundance of the biofouling community. If (judiciously) applied, nature inclusive design of the SPL habitat can effectively promote biodiversity by manipulating the physical complexity of the structure.

More information: Zupan, M., Coolen, J.W.P., Mavraki, N., Degraer S., Moens, T., Kerckhof F., Lopez Lopez, L., Vanaverbeke J. (n.d.) Life on every stone: Characterising benthic communities from scour protection layers of offshore wind. Under review.

C. The literature review of showed that in the 20 studies ten different types of sampling gear were used, including visual scuba diving, trawling, fyke nets, remote video, hook and line, gill net, scallop dredge, acoustic methods (sonar, didson). In addition, the effect size was measured in at least seven different units, including CPUE (mass), N/1000m$^2$, N/hr, N/ha, N/m$^3$, N/transect and catch / m$^3$, preventing further quantitative analysis.

## 2.5 Discussion

The creation of a joint dataset (BISAR) to which the BENSO project contributed, has proven valuable for the increase of scientific understanding of benthic effects of offshore wind farms. Not only were they included in the SPL study reported here (Zupan et al. n.d.) but they have also been used to different decommissioning scenarios for offshore wind farms (Spielmann et al., 2023) and as part of a life cycle analysis of offshore wind (Li et al., 2023). Furthermore, the dataset is currently being used as part of a functional trait analysis carried out by the ICES WGMBRED and by multiple PhD students from different institutes. However, even though BISAR contains data from 3864 samples obtained in 18 hard substrate sites (including 7 wind farms), still the available data is often too limited to draw clear conclusions. Even within a local region of the southern North Sea, the variations in species composition are known to be large. Furthermore, during the lifetime of an offshore wind farm, the species community will change as a result of succession and seasonal patterns such as winter storms. To separate this natural variation from the effects under study, such as the SPL effects investigated here, more data is needed than is currently available in BISAR. It is therefore recommended to continue the monitoring programmes in offshore wind farms and extend the sharing of data between countries and wind farms via shared datasets such as BISAR.

Within the data available in BISAR, for 4 wind farms SPL data was available to explore the effects of different designs on benthic ecology. Variation in SPL species composition in the BISAR dataset was strongly related to the wind farm sites together with the age of the structures. Unfortunately, with only 4 wind farms with different SPL designs, it was not possible to distinguish between the effects of the location and the SPL designs. However, the analysis did suggest that rock type (e.g. granite vs limestone) had limited influence on the species composition.

Since no certain advice on how to design SPLs in the future could be extracted from the BISAR data, it is recommended to keep expanding the dataset with SPL observation so in future analysis of SPL designs it may become possible to separate the SPL designs from any location effects.

Although the effect size of offshore wind farms on the abundance of finfish is overall positive on demersal species in particular, the high variation in sampling methods and metrics prevailed further analysis of environmental factors.

# 3 Implementing smart monitoring techniques in monitoring programmes and maintenance operations

## 3.1 Background

In the development within offshore wind farm construction, there is an increasing focus on biodiversity enhancement. This results, among other things, in the design of ecologically friendly scour protection and/or other techniques designed to enhance or enrich local biodiversity. In addition to such active restoration objectives, passive developments of nature can also be expected within wind farms on the Dutch seabed. Partly because of less disturbance of at least the seabed (after all, no fishing is allowed within wind farms), nature can recover or develop locally.

Whether the measures aimed at increasing biodiversity produce results must be closely monitored. The costs of monitoring can be considerable. Using (specialized) ship's equipment that sails out explicitly to carry out such monitoring is relatively expensive. Especially in the light of the daily sailing back and forth of crew tender vessels for the daily maintenance of the wind turbines and other infrastructure.

Therefore, the BENSO project aims to develop monitoring techniques that can be launched relatively easily from smaller vessels, such as CTVs.

The premise here is that devices should be easy to handle, relatively light and safe to operate.

## 3.2 Aims

Within the project, with respect to smart monitoring, the following goals have been established:

1. Implement smart monitoring techniques in OWF's.
2. Reduce monitoring costs of scour protection experiments by using the maintenance operations infrastructure and logistics.

## 3.3 Activities

The techniques developed have focused on the design of a research cage and on the application of two video monitoring techniques that can visualize local presence of benthic life and mobile species.

Design of monitoring devices:

1. Demonstration and instruction of simple monitoring techniques to maintenance crew.
2. Analysis of costs and benefits of different monitoring techniques.

3. Adapt monitoring methods and techniques to be used at small vessels and Crew Tender Vessels.
4. Implementation and field tests within at least one (up to five) OWF's.

## 3.4 Project results

### 3.4.1 Smart cage: Werc-dock

Within marine biodiversity restoration, biogenic reefs play an important role. Such reefs form an ideal location for a countless number of species to settle, spawn, forage or flee if threatened. Reef formers such as (flat) oysters are therefore in the spotlight for large-scale restoration in various parts of our North Sea and elsewhere in the world. Prior to large-scale restoration initiatives, the first thing we want to investigate is whether organisms such as the flat oyster are at all capable of surviving in a specific (marine) environment. To this end, oysters are placed in research cages. The cages must be lifted out of the water with some regularity to see if the target organisms survive and if there is growth. Until recently, such cages were solidly dimensioned to withstand the harsh marine environment and to ensure that the cages could be found again. The lowering and retrieval of such cages requires working vessels which, especially within the confines of an OWF, should also have DP system.

Work has been done within BENSO on a cage construction in which deployment and retrieval by a relatively small vessel can be applied. During interim assessment of the oysters and/or other organisms, a part of the construction can be hoisted on board by means of a small vessel and refilled with new research material. The research components themselves can be (dis)assembled.

The construction consists of several parts (see figure 3.1a):

The base of the construction consists of four legs, which can be made longer or shorter depending on the expected conditions at the location to be deployed.

The ends of the legs contain perforated plates. The plates prevent the structure from sinking into the seabed, but at the same time provide the rigidity that prevents the cage from tilting in case of (light) sanding. The plates are hinged so that when the total structure is retrieved, the sand can slide off gradually and retrieval is simplified.

In the center of the base is a pole over which the final racks can be slid. The pole has a diameter of 76 mm and is mounted on the base by via a strong spring. The spring gives the pole some flexibility when exposed to currents.

Racks can be slid over the pole onto which baskets (see figure 3.1b) containing target organisms can be attached. In the center of each rack is a hole which can slide precisely over the pole. Each rack is provided with a lifting eye by which the rack can be lifted to the water surface.

<u>Application:</u>

So far, one test cage has been deployed at an offshore location, namely at the offshore test site (OTS), about 12 km off the coast of Scheveningen. The cage was successfully deployed in May 2021 (see figure 3.1b). The site was visited several times (September 2021, September 2022 and September 2024) to see how the device behaved under water and whether the structure remained upright. To date, the structure has remained in place, the structure is still fully intact and is completely overgrown with all kinds of marine sessile

organisms (figure 3.1c). In addition, it provides habitat for several crab species and many dozens of pout (see figure 3.1d) that roam around it on every visit.
The attachment of the research baskets has so far proved to be the weak link, the baskets have disappeared from the structure, the contents have been found scattered around the site.

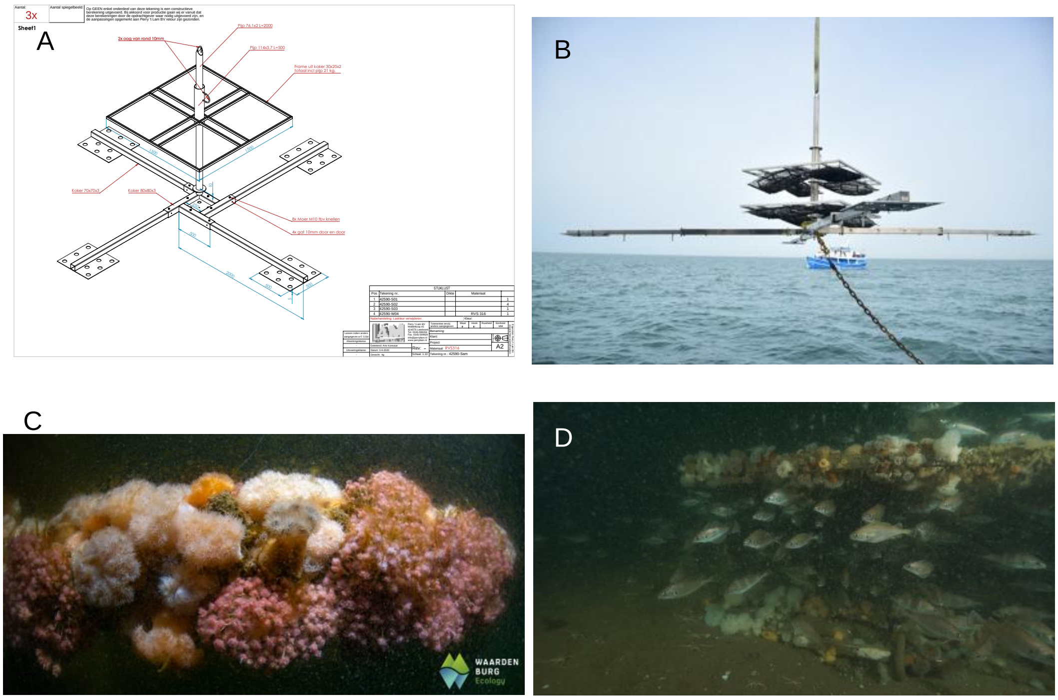



*Figure 3.1. a) technical drawing of the device, b) deployment of the cage with two racks and the extended legs c) biodiversity growing on the cages after 2 years, d) the cages accomodating large school of pout after 3 years*.

<u>Lessons learned</u>:
Initially, the legs were designed short for the expected conditions at the offshore location. Based on model tests an additional calculations it was decided to make the legs extendable, as a result the dveice is less manageable.
In addition, the original design assumed 3 racks on top of each other. This too turned out not to benefit the stability and made the cnstruction more sensitive to (laminar) flow, resulting in falling over.
Retrieving and replacing the loose racks using a small ROV has so far not been tested in offhsore conditions, this is still on the program during the decommisioning of the device.

### 3.4.2 Droppable camera system

For surveying the North Sea floor in large areas such as the (upcoming) wind farm lots, it is important that a robust methodology is applied. Typically, such surveys are conducted using ROVs. ROVs suitable for this work are of considerable size and require a suitable vessel that can facilitate the work. In addition, ROVs work optimally when there is sufficient water column visibility (>0.5m).

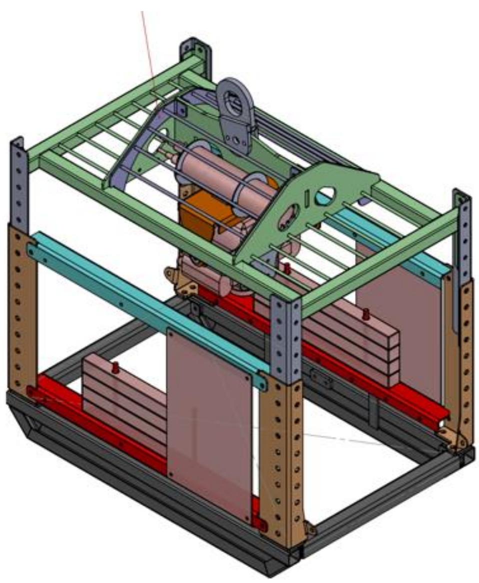
An alternative to a decent ROV is the use of a dropable camera system. Such a system is placed on the seabed from a ship and will be moved over the seabed as a result of the movement of the ship (due to currents). Each time the system touches the bottom, a clear recording of the bottom and all life is made. The recordings then serve as the basis for further analysis of the biodiversity and condition of the bottom.

Work was done within the BENSO project to optimize the dropable camera system. A number of assumptions were made:

- Manageable using (small) crane + winch
- Robust system
- Height adjustable in relation to the seabed
- High resolution camera (4K)

These principles led to a stainless-steel cage construction (figure 3.2 a-b) in which the height is adjustable in relation to the seabed, and which is suitable for a decent camera that can also be tilted if necessary. In addition to the camera, the construction contains sufficient lighting where no wires or arms protrude outside the frame. The weight of the construction is approx. 80 kg (in air) and thus manageable with crane systems as generally present on CTVs. The camera system (4k) used is remotely controlled and places in a dedicated underwater housing, the lighting used in the system consist of dimmable and diffused LED lighting.

A



C D

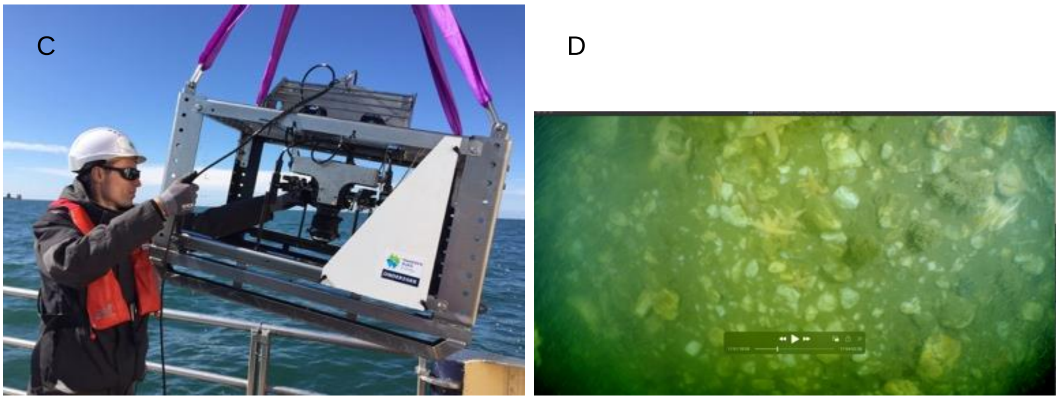


*Figure 3.2. a) technical drawing of the design, b) the first real life prototype, c) the fully equipped device in action offshore, d) the result of the recordings.*

Application:
The system has been successfully tested and subsequently applied in various studies (see figure 3.2c). This involved surveying large parts of the Dogger Bank. In addition, the system has also been applied for surveying cable crossings where OWF cables cross existing transport pipelines. In addition to biodiversity, the latter study also focused on the state of the scour protection (see figure 3.2d) as applied to and around the crossings.

Lessons learned:
The cage structure worked properly. During the recordings, the underwater cage construction did appear to be able to rotate on the current, this gave an unsettled picture during the analysis. By placing two (Perspex) plates on the side of the cage construction, this was eventually prevented (see figure 3.2 c).
The cables running from the camera to the deck of the ship can be subjected to the necessary force during drift. Reinforcing the connection of the cable to the camera prevents the connection from becoming loose or damaged.

### 3.4.3 Baited camera's

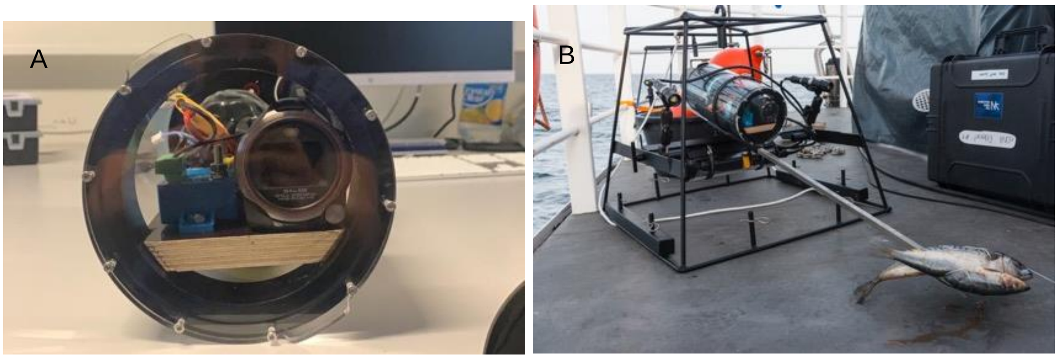
In addition to surveying bottom life, it is also desirable to understand which mobile species reside near the sandy seabed or near hard substrates such as the scour protection around monopiles or cable crossings.
Techniques such as diving ROVs or dropable camera systems can disturb locally occurring mobile species. The presence of the organisms is thus underestimated.
In order to gain insight into locally occurring mobile species such as crabs, lobsters and fish species, there are so-called baited camera systems. Such systems are placed on the seabed where they record the environment for at least one hour. To attract wandering species, a bait is placed in front of the camera.
Within the BENSO project, work was done to optimize previously described systems (Cappo et al., 2007). The challenge was to build a system that also works properly in rough conditions (wave action, limited visibility, currents and sufficient depth) such as those prevailing in the North Sea.

The developments can be divided into several steps:

- Waterproof system
- Suitable camera + power supply that can record long enough
- Good lighting
- Cage construction in which system is adequately protected
- Construction manageable, but heavy enough to stand firmly on the ground
- Solid system for placing and retrieving the camera + cage construction

The developments have led to a system that has been proven to work, with good recordings being made at a depth of approximately 20-25 meters in which various species have been captured. Even in rougher North Sea conditions (wave height ca. 3 m.), the construction has remained in place and successfully retrieved.
The system now consists of the following components:

- Perspex tube with both front and back covers fitted with double O-rings (see figure 33 a). One of the lids is fitted with a valve to force the lid out of the tube using air pressure.
- A mini video camera (Panasonic) + a lithium battery pack, with sufficient memory capacity for at least 3 hours of recording (see figure 3.3 b)).
- Two dimmable LED lights connectable to battery pack (lithium) (see figure 3.3 b).
- Cage structure of rebar (diameter 10 mm) and coated matte black to prevent undesirable reflection and the ability of putting weights on the structure (see figure 3.3 b).
- A lifting structure using a submerged buoy to prevent excessive direct forces on the cage structure (see figure 3.3 c).



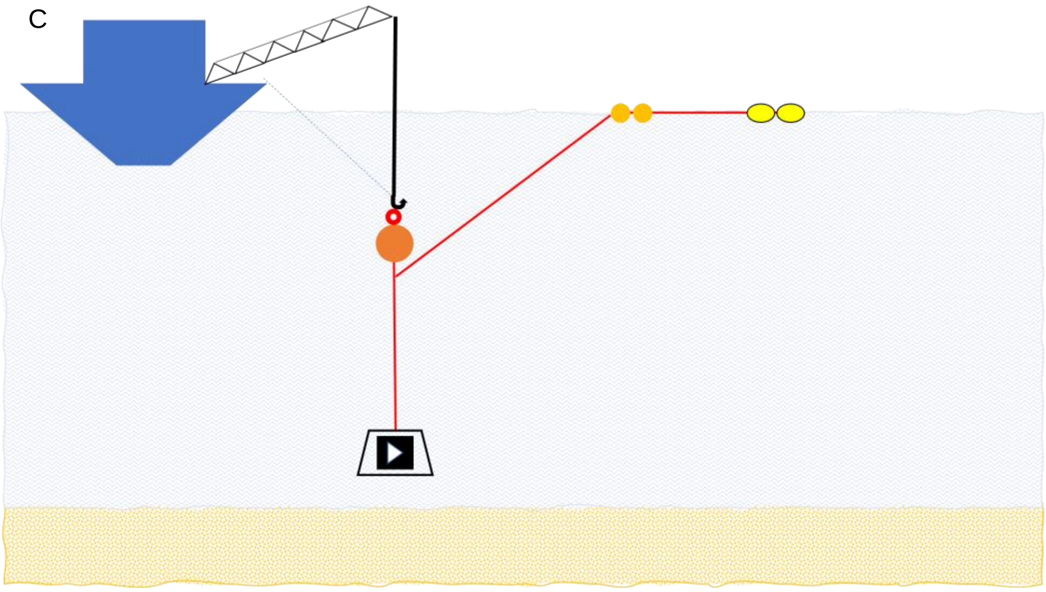



*Figure 3.3. Developments steps in creating a robust baited cam device that can be deployed in full offshore conditions. a) the waterproof body of the camera, b) the prototype with bait and weight blocks on the site, c) the conceptual design of the buoy system.*

Application:
The system has been successfully tested and subsequently applied in several studies. Its stability and image quality are sufficient for further analysis of the occurrence of mobile species, even in limited visibility (see figure 3.4). The system has been deployed around wrecks as a test for hard substrate in a sandy environment. It has also been deployed elsewhere in the North Sea including around the Klaverbank and Borkum reef ground. Recently the system has also been used to observe the diversity around a scour protection of monopiles of a wind farm off the Dutch coast. During one of the expeditions, the system was left alone overnight during which it withstood waves of about 3 meters. At the end of the rough weather conditions, the device was found back at the same location.
In this way, several species particularly fish were imaged including stone pout, whiting, juvenile cod, dab, horse mackerel and also a shorthorn sculpin (see figure 3.4). Other mobile species that appeared in front of the camera include various crab species (including velvet swimming + brown crab), hermit crabs and even a predatory snail (the whelk).

Lessons learned:
The camera system with its combination of lights and batteries appears to work well. Sufficiently longer recordings can be made that collect footage of sufficient quality for further image analysis. Success in attracting organisms depends not only on the location but also on the type of bait used. For example, recordings have been made on which hardly any fish are detectable, while at another location the same type of bait attracted a high density of fish. For more diversity in front of the camera, offering several types of bait has been shown to work better than offering 1 type of bait. The combination of fresh fatty fish (including mackerel) combined with squid-like fish gave good results. It is not closed than further experimenting with different baits can positively influence the success on attracting more entrenched organisms.

Another lesson is that although the entire system (incl 16 kg weighting) weighs about 30 kg, it is difficult to handle by hand. Especially when retrieving the system, the necessary manpower is needed to lift the device back on board. A small crane with a folding block and a capstan are recommended to pick up and put down this system properly. Such systems are well suited to a CTV.

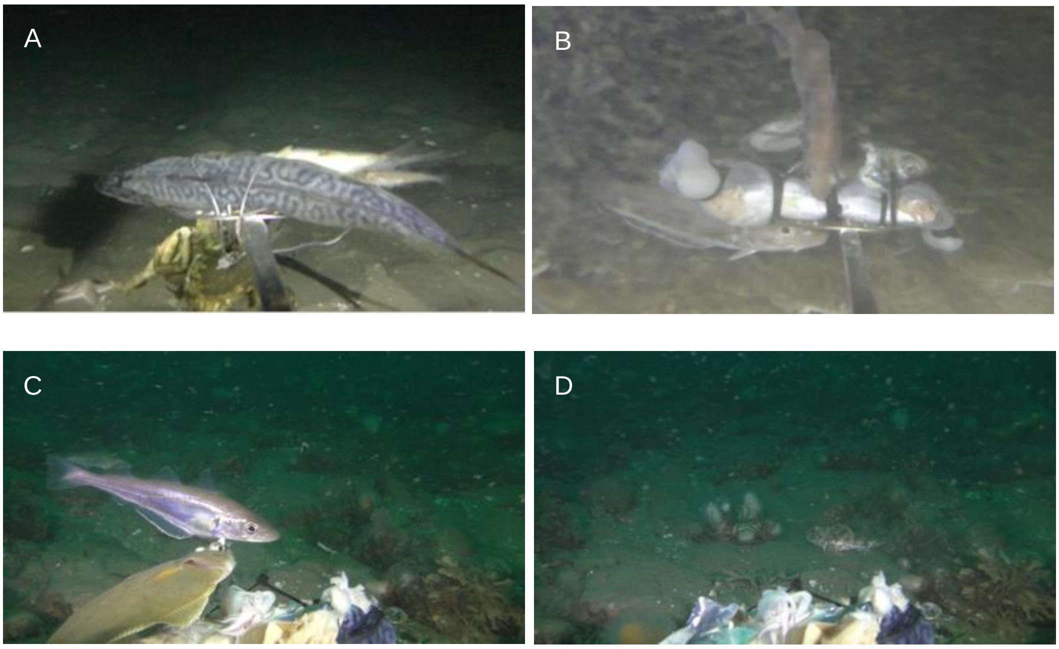



*Figure 3.4. Impression of the different kind of organisms, including fish, crabs and seastars, attracted by the bait in front of the camera.*

### 3.4.4 Mobile DP system

In general, working in OWFs, especially near the monopiles, should be performed with vessels equipped with a dual Dynamic Positioning (DP2) system.

Such systems are mainly found on the larger (and therefore more expensive) vessels. To make the smart monitoring techniques described above truly successful the use of small research vessels would be ideal. Especially if a small vessel is equipped with a DP system. BENSO has been working on the development of a DP system that can be used both on a small vessel and mobile (i.e. transferable to different vessels).

Using our in-house developed software and 4 acquired trusters an unmanned services vehicle was build. First the system was tested on a small dingy, see below pictures (figure 3.5 a-d).


*Figure 3.5 a-d) testing the portable DP system on small dinghy in the marina of Lelystad*.

Tests have been performed on various locations; Rodby (Denmark), Lelystad (Netherlands) and Eastern Scheldt (Netherlands)

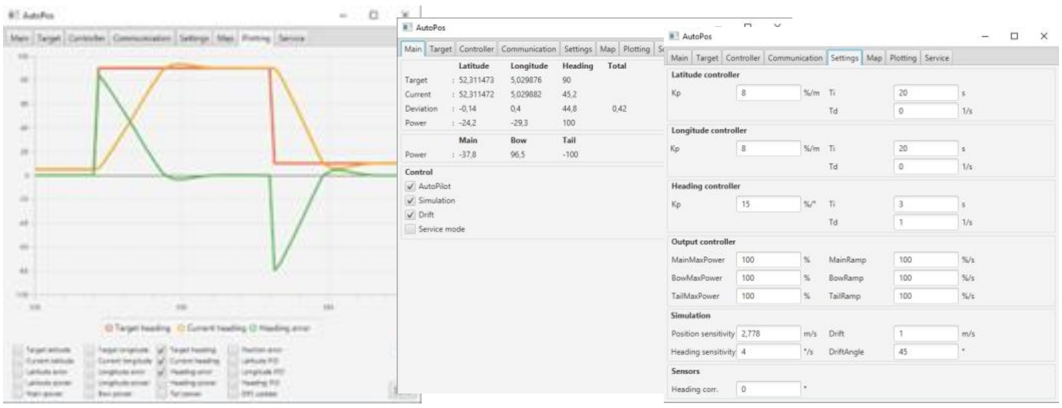


*Figure 3.6. Screen dumps of the results of testing the DP system*

During testing phases, the software was improved such that the system could both keep track on a pre-set programmed sailing track and could also hold itself stable on a pre-set location. Some windows of the developed software and output / input is presented above (figure 3.6). The main challenge was to overcome the “overshooting” of the system (while approaching the set coordinates the vessel first approached it too fast and was not on time to stop).

The next step was to build it on a USV and perform tests on larger waters. Tests have been performed on Lake IJssel and Eastern Scheldt. Images of the test on Eastern Scheldt and the performance of the USV to follow a pre-set track is presented in below photos (figure 3.7 a-d).

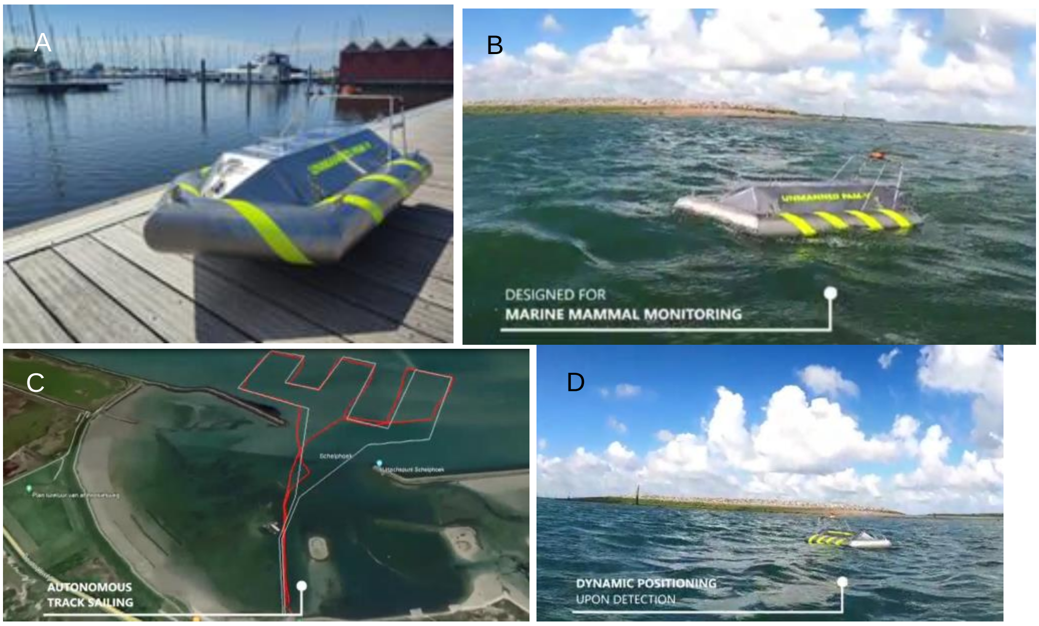



*Figure 3.7. a-d) impression of the unmanned dinghy sailing in open water and equipped with different types of sensors.*

<u>Application</u>:
The system has been applied for 2 purposes:

Marine mammal monitoring in the Eastern Scheldt. Therefore, the USV was equipped with a recorder, hydrophone and harbour porpoise click detector. By measuring the presence of porpoises using a mobile platform more insight could be gained on the location of these porpoises.

Bathymetrical survey monitoring in the Wadden Sea. Therefore, the system was equipped with a sonar system and measures the seabed bathymetry. The system has been applied to measure the bathymetry of the PrinsHendrikZanddijk in the Waddensea. An example of the measured seabed in the very shallow waters of the tidal lagoon in the PHZD is presented in below figure 3.8).

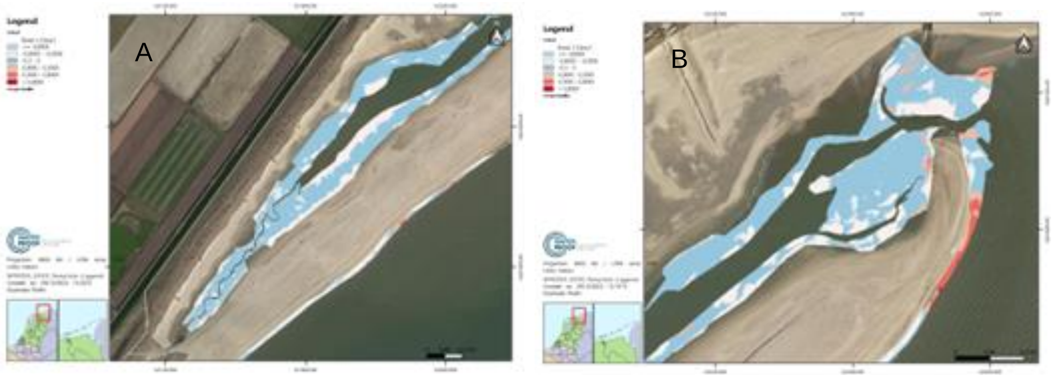



*Figure 3.8. Result of the application of the unmanned vehicle equipped with SONAR.*

Lessons learned:
The USV platform has been developed very successfully. Both hardware and software have been coupled which allowed to produce a system which can be further build out in near future. The main challenge lies in scaling up. When enlarging the vessel, the trusters need a lot more power and consume considerably more battery capacity. Moreover, relative strong (electrical) engines are required to keep a vessel in a tidal flow which can become as large as 1.0 m/s. Based on the developed prototypes, experience gained we expect that a “mobile DP-system” which can just be clicked-on and off a vessel will be challenging and more steps need to be taken to further detail this.

### 3.4.5 Underwater GPS

At sea, one’s position can be determined relatively simple by making use of a gps system. Underwater however, such a system is not available, making it much more difficult to determine one’s position accurately. For the underlying project, a so-called underwater-gps (Waterlinked UGPS) has been applied, improved and tested.

The Waterlinked underwater GPS is a standalone hardware and software application without extended logging and visualization functionality.

We developed a custom Python-based connector designed to split and create two local virtual ports, to which an external GPS antenna was connected. The virtual ports split the raw NMEA data string: one was sent to the water link top unit, and the other to a logging application. The connector also requested the underwater GPS position every second and combined this data with the external GPS data to calculate latitude, longitude, and height relative to a specified coordinate system.
As the detection distance and angle of the transducers were sometimes limited, we experimented with and adjusted the signal-to-noise ratio to improve the ability to locate the underwater transducer. Finally, the connector included an integrated data parser that could interface with an open-source QGIS plugin (PosiView), allowing for real-time visualization of both the boat's position and the underwater transducer position.
In below figure some characteristics of the setup of the antenna and sensors are presented.

1. Topcase unit
2. Connection topcase - antenne
3. Antenna
4. Transponder
5. 12V Accu
6. 12V connection topcase
7. 12V connection GPS
8. External GPS / Lowrance
9. Connections GPS laptop
10. Laptop
11. Cable GPS

*Figure 3.9. Overview of parts of the underwater GPS system.*

The resulting improved measurement system is presented in below figure (3.10).

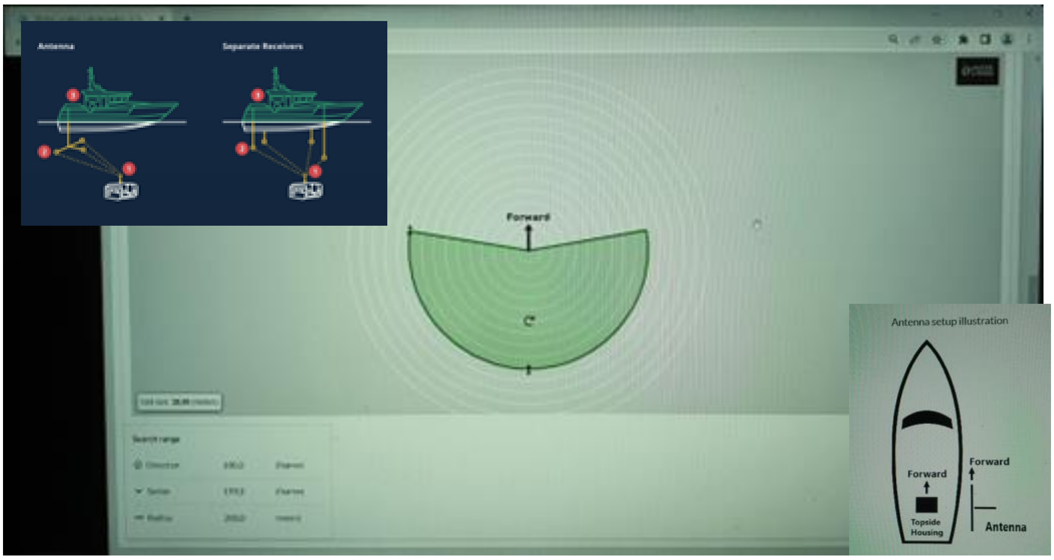



*Figure 3.10. Screen dump of the orientation of the GPS signal.*

<u>Application</u>

The system has been tested multiple times in various projects, both by WaterProof as well as Waardenburg Ecology. One of the tests performed was for Electromagnetic Field (EMF) monitoring on the Northsea. For the Export cables of Borssele it is unknown what the EM-fields are at various wind velocities. To measure these, an EMF sensor on a measurement sledge (see figure 3.11a) has been pulled over the seabed. At the sledge also the GPS transponder (figure 3.11 b) was positioned in order to be able to track the sledge location in relation to the position of the Export cables. An example of the measured tracks is presented in figure 3.12.

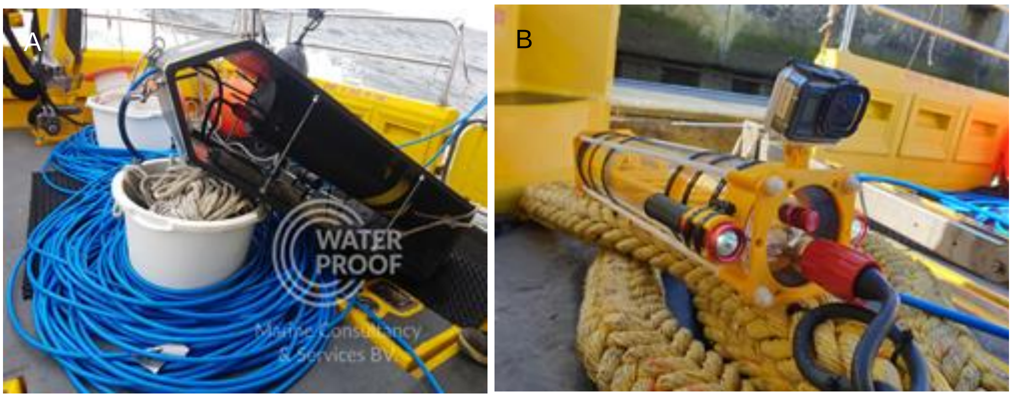



*Figure 3.11. a) EMF sensor on measurement sledge, b) GPS transponder.*

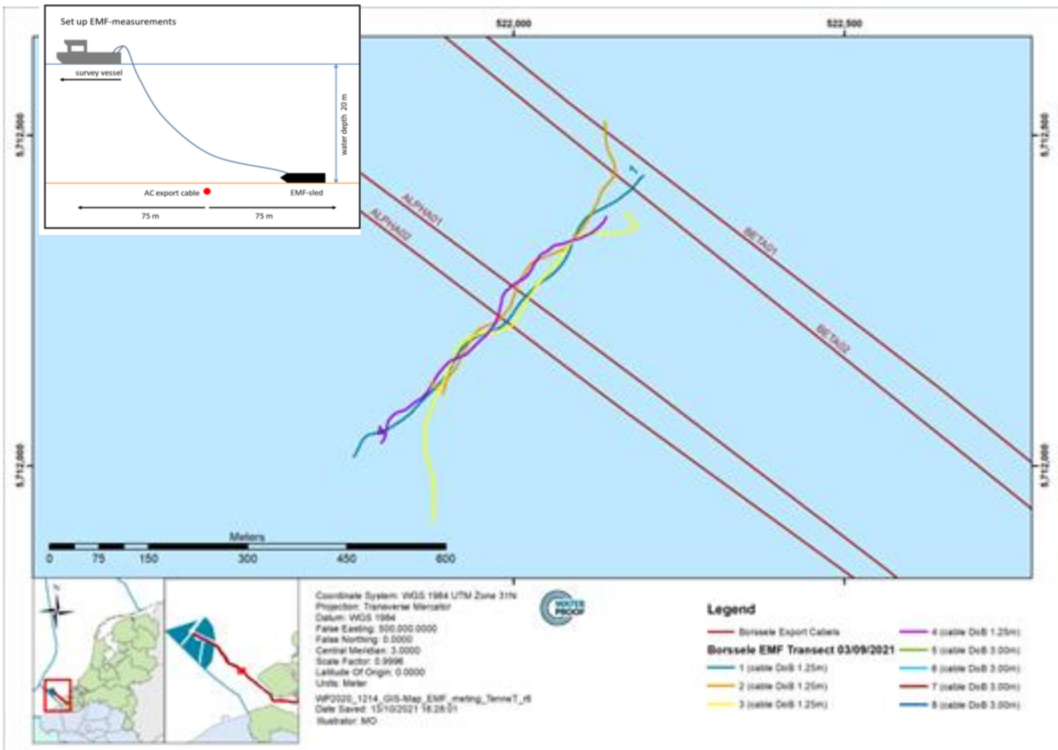



*Figure 3.12. Result of th tracks sailed with EMF devices in combination with underwater GPS system.*

<u>Lessons learned</u>:

- Top side unit is connected via Wifi which sometimes crashes or is instable.
- The top side unit has an integrated GPS, which is not accurate so an external GPS should always be used.
- The receiver frame and receiver might be too close to each other limiting the range and detection area.
- Transducer is quickly out of range or out of the horizontal angle of detection

### 3.4.6 Development and tests of DOME

A system was developed to perform *in situ* incubations to measure exchange of oxygen and nutrients between macrofauna organisms and the water. The dome shaped measurement chamber (DOME) has been applied on various substrates inshore as well as offshore. In BENSO, the application of the DOME to experimental settlement plates was developed and tested. As part of this an 'Artificial hard substrate garden' test site was developed and placed in the Marina of Texel, facilitated by Watersportvereniging Texel.
The artificial hard substrate garden (AHSG, see figure 3.13 a) and DOME allow for the placement of settlement plates in frames (3.13 b), which can be relatively easily manipulated and measured, compared to offshore conditions. The aim was to develop the method and make it available for experiments in projects following BENSO.

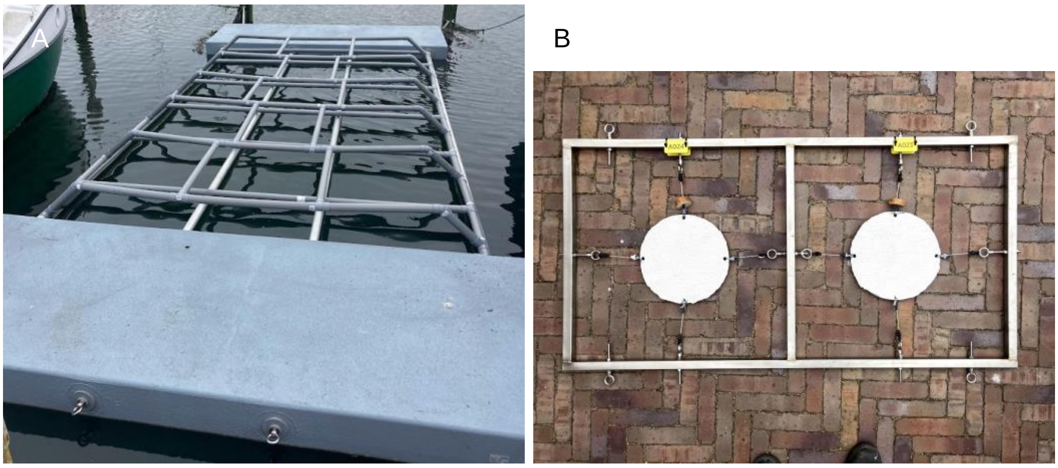



*Figure 3.13. a) the AHSG as deployed in the Marina on Texel, b) settlement plates with BESE reef paste in frames before placement.*

Currently the AHSG is being used to test the seasonal patterns in nitrogen fluxes of species colonising hard substrates. An example of such substrates is BESE reef paste. (DEI pilotproject: Pilot ontwikkeling van biocomposiet voor erosiewerend rifherste, BIERI, DEI221015). In the AHSG, the use of BESE reef paste on the settlement plates was tested (figure 3.14 a-b). For this purpose, PVS settlement plates were covered with BESE reef paste and the colonisation of biofouling organisms followed and compared to concrete covered plates and plates without cover. For this purpose, frames were developed that allowed settlement plates to be placed in the AHSG.

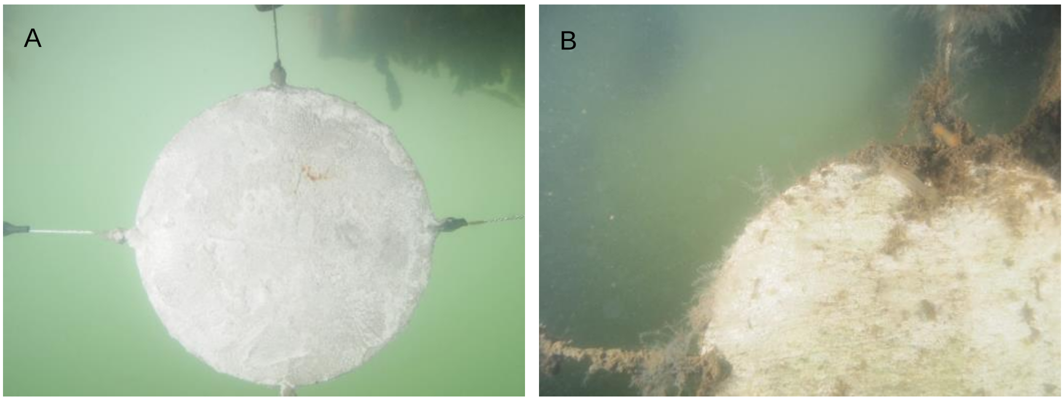



*Figure 3.14. a) reef paste disc after placement, b) reef paste disk after incubation for multiple weeks*

<u>Application:</u>
The DOME was furthermore also tested and applied during the cruises carried out in 2022 and 2023, during which measurements were taken on shipwrecks and the Halfweg GBS. Additionally, the development of a method to use the DOMES on the underside of floating offshore solar systems was started.

<u>Lessons learned:</u>
Since scuba divers exhale bubbles (figure 3.15), which collect in the biofouling communities on the underside of the floaters, initial tests of the DOME failed. A solution for this was seen in the use of closed-circuit rebreathers, since using these systems, divers do not produce bubbles which collect under the floaters. The development of this methods is ongoing work and will be continued after the end of the BENSO project.


*Figure 3.15. The dome is applied on a shipwreck in the North Sea.*

## 3.5 Discussion

Smart monitoring techniques are primarily developed to enable easy application by non-ecologically trained personnel. In this way, maintenance personnel of wind farms, for instance, can be offered the possibility to collect ecological data. In addition, the devices should be applicable on small (fast) CTVs, so that costs can be saved on the deployment of large ships, see table 3.1 for a summarizing overview of techniques developed in BENSO.

Within the BENSO project, a number of such devices have been (further) developed and are ready for application. The dropcam, for instance, turned out to be an alternative for ROV applications. The system is robust and can be applied on different substrates.

The baited cams are suitable for collecting images in wind farms, with special focus on mobile species like fishes, crabs and other invertebrates. Apart from the design of the hardware of the cam also the baited used will influence the success of the results. Using different kind of baits will increase the attraction to a variety of organisms. An additional feature which may improve the traceability of the baited cams is to add a portable AIS responder on the buoy system.

The use of an unmanned vessel can lead to the collection of a lot of hydrological data but also can be adjusted to make recordings of marine mammals. The challenge for devices like the AUV is the range in which they can operate. An optimalisation between power and the battery pack needed may improve the ranges.

Where the above-mentioned techniques focus on larger organisms, the use of the DOME device is gives special insight in the epibenthic fauna and the use and production of nutrients and biomass. Sofar, the DOME is installed by divers, and since diving is not promoted within wind farms the application on e.g. monopiles will probably not take place. However, the device can be applied on monopile-like structures in near coast or harbor settings. In this way insight can be gained in the in-situ processes on such hard substrates.

*Table 3.1. Summarizing overview of methods developed in the BENSO project.*

| Method | Reearch questions | Vessel requirements | Applicable in wind farms |
|---|---|---|---|
| Werc-dock | survival of target organisms / biodiversity enhancement success of different | small crane (1,5 T) + winch, suffiecient deskspace, small ROV | Yes, proofed to be stable |
| Drop cam | biodivesitiy of the sea floor / artifical structures | small crane (1,5 T) + winch | Yes |
| Baited cam | local diversity of mobile species | small crane (1,5 T) + winch + capstan | Yes |
| Underwater GPS | Exact location of devices and offshore infrastructure | small crane (1,5 T) + winch | Yes |
| AUV | widely applicable and equipped with different | small crane (1,5 T) | Yes |
| DOME | in-situ measurements of primary production and consumption of nutrients | Vessel equipped for diving operations | No, since diving is not allowed OWF |

# 4 Development and tests of smart ecological design of scour protection to enhance positive impact of OWF’s

## 4.1 Background

More than a century ago, the current sandy bottom of the North Sea was largely covered with boulders, stones and hard peat. Such hard substrates were ideal attachment sites for all kinds of sessile organisms but also provided space for organisms to find shelter, spawn and forage. With the deployment of scour protection around monopiles and other wind farm infrastructure, the opportunity arises to create similar hard structures. This creates new habitat similar to habitats lost. Scour protection brings back the function of hard substrate and allow associated species to (re)establish themselves. What type of substrate and shape will potentially help determine the success of habitat development. In this part of the BENSO project, the development of that knowledge was elaborated, inspired by extant natural reefs, both theoretically and in practical applications.

## 4.2 Aim

To optimize ecological design of scour protection (as settling substrate for marine organisms) for biodiversity enhancement during operation life of turbines and after decommissioning.

## 4.3 Activities

- First, we review habitat complexity in biogenic reefs to the design of nature inclusive scour protection;
- Second, we designed and deployed several field tests of habitat complexity and species richness with stones of varying size and different kind of stone type.

## 4.4 The theory: habitat complexity and fractal dimension in biogenic reefs

The Dutch part North Sea is dominated by soft sediment habitats with species living in the sediment (infauna) and on the sediment (epibenthos). Many infaunal species rework the sediment causing bioturbation, several epibenthic species such as tube worms and bivalves form biogenic reefs, which stabilize the sediment and create hard substrate and structural complexity.

In this report we focus on biogenic and geogenic reefs which form large-scale structures with high structural complexity in coastal and offshore areas. This structural complexity will be used to inspire design solutions for artificial structures, to enhance biodiversity in and on the scour protection of wind turbines. The focal biogenic reefs in this report are formed by polychaete worms, bivalves and corals. Species groups which form only small-scale reefs are not included, such as bryozoa, cold-water corals, and sponges. Canopies with high structural complexity formed by flexible species, such as kelp, are also not included.

### 4.4.1 Habitat complexity

Habitat complexity is an important factor structuring biotic assemblages in both aquatic and terrestrial ecosystems. It is intuitively attractive because it matches also how we as humans perceive habitats with respect to predation threat, foraging opportunities and social interactions. In marine environments clear examples of habitat complexity are biogenic reefs, ranging from rather simple, predominantly two-dimensional structures like Sabellaria- and Lanice-reefs to complex three-dimensional structure like coral reefs and mangroves (Kovalenko et al., 2012; Figure 4.1). Rocks commonly used as scour protection around wind turbines are an example of an artificial reef resembling cobbles in riverbeds (figure 4.1).

The effects of habitat complexity on aquatic biotic structure and ecosystem processes listed and discussed by Kovalenko et al. (2012) are essential in understanding the relationship between biodiversity in relation to OWF artificial reefs and for improving the biodiversity enhancement potential of scour protection.

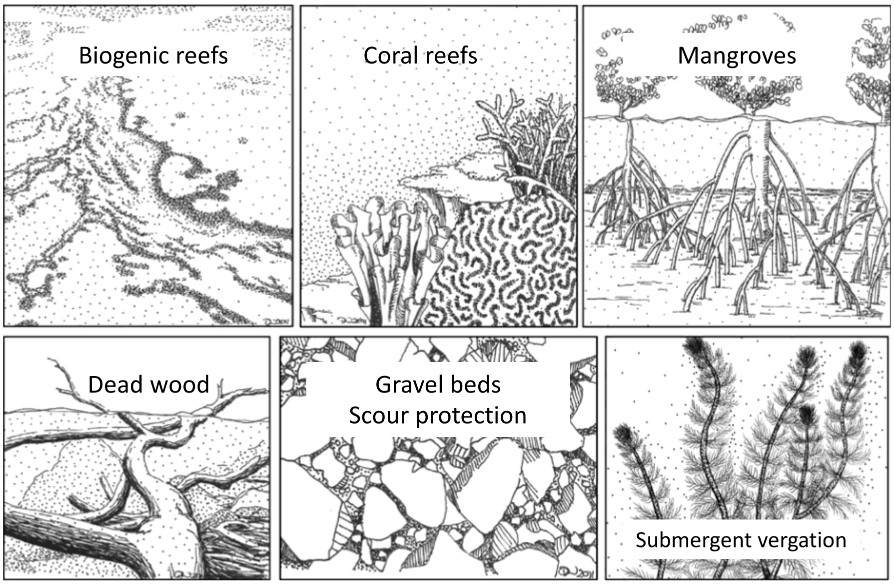



*Figure 4.1. Examples of habitat complexity in marine and aquatic ecosystems provided by biogenic reefs in soft sediment areas (Lanice and oyster reefs), three-dimensional coral reefs (in detail), mangroves (3D), dead wood (3D), riverbed rocks or gravel beds and scour protection in the North Sea (3D) and macrophytes (3D; adapted from Kovalenko et al., 2012).*

### 4.4.2 Fractal dimension

The ecological paradigm that structurally complex habitats harbour more species than simple habitats is rooted in basic principles: species richness increases with area and surface area and niche density increase with three-dimensional complexity. Surface area habitats are typical for marine ecosystems where (epi)benthic organisms attach to a surface or substrate.

Torres-Pulliza et al. (2021) propose a geometric basis for surface habitats that unifies ecosystems and spatial scales. Their theory is based on the fundamental constraints between three descriptors of structure: surface height *H*, rugosity *R* and fractal dimension *D*. This theory has value for predicting the consequences of natural and human modifications of surface structure. In addition, it may lead to cost-efficient design solutions if smaller and lighter structures with higher complexity can be used instead of heavy, less complex structures such as rocks.

Several recent studies measured the habitat complexity of biogenic reefs formed by polychaete worms, bivalves and corals. These species groups form large-scale biogenic reefs, interact with the sediment (polychaete worms, bivalves) and influence the local hydrodynamics on a scale which is relevant for biodiversity enhancement on scour protection. In each section a brief description is given of the ecology, reef construction and components and fractal dimension.

### 4.4.3 Comparison of biogenic and geogenic reefs

The different biogenic and geogenic reef types differ in various aspects of morphology, structural components, interstitial spaces and fractal dimension, which is summarized in table 4.1. A common aspect of all reefs is the interaction between the reefs and surrounding soft sediments: mobile species can dig burrows in the sediment and acquire a stable cover from the hard substrate. The structural complexity is lowest in encrusting polychaete reefs (e.g., *Sabellaria alveolata*, $1.22 < D < 1.51$) and higher in serpulid reefs which form hemispherical structures (*Serpula narconensis*;; $2.08 < D < 2.29$). The habitat complexity is highest in the irregular and hemispherical Virginia oyster reefs ($2.67 < D < 2.74$) and corymbose and branching corals ($2.3 < D < 2.6$). The reefs with high structural complexity substantially increase turbidity and create wakes, which leads to higher retention of food and larvae. On the other hand, corymbose and branching corals are sensitive for hydrodynamic disturbances.

### 4.4.4 Worms

Polychaete reefs are usually very shallow and encrusting soft sediments in intertidal, subtidal and offshore areas. In soft sediments they achieve stability by constructing tubes of sand and/or shell fragments on small, hard substrates (empty shells, gravel) or next to other tubes of conspecifics. They provide settling substrate for various epibenthic species and small crevices for mobile species. The fractal dimension of a Antarctic serpulid reef was $2.08 < D < 2.29$ (Montes-Herrera, 2023).

### 4.4.5 Bivalves

Mussel reefs are very shallow and are encrusting hard substrates and soft sediments in intertidal and subtidal areas. On soft sediments they achieve stability by connections between mussels with byssal threads and individual mussels can adjust their position during their lifetime. They provide settling substrate for various epibenthic species and small crevices for mobile species. The fractal dimension of mussel beds was 1.03 < *D* <

1.31 in the vertical plane and 1.36 < *D* < 1.86 in the horizontal plane (Commito & Rusignolo, 2000). The fractal dimension of a horse mussel reef was 1.3 (Bertolini et al., 2017).

Oyster reefs consist of bivalves cemented permanently to hard substrates or with conspecifics. They occur on hard substrates and soft sediments in intertidal, subtidal and offshore habitats. They vary from encrusting structures to relatively complex structures with small and large crevices. They can cover substantial areas of rocky coasts, artificial hard substrate and soft sediments. The fractal dimension of a restored Virginia oyster reef was 2.67, the fractal dimension of an undisturbed, reference reef 2.74 (Cannon et al., 2023). Bivalve reefs provide extensive hard substrate for epibenthic species and small and large crevices for mobile species as well.

#### 4.4.6 Corals

Corals display the largest variety in growth forms, which range from encrusting to branching (table 4.1). They occur on hard substrates in tropical and subtropical climate zones in subtidal and offshore habitats. They can cover extensive areas of both rocky coasts and soft sediment areas. The fractal dimension of a reef with mainly encrusting to hemispherical corals was 1.7 < D < 2.3 (George et al., 2021). The highest structural complexity is found in corals with tabular, corymbose or branching morphology (table 4.1). The fractal dimension of these reefs was 2.3 < D < 2.6 (Zawada & Brock, 2009). The fractal dimension of a reef with all growth types was 2.0 < D < 2.6 (Torres-Pulliza et al., 2020). Coral reefs provide hard substrate for epibenthic species, where live polyps at the surface are absent. The small and large crevices provide a habitat for many mobile species. The patches with soft sediment between the corals provide additional habitat for soft sediment species including burrowing mobile species.

*Table 4.1. Comparison of biogenic and geogenic reefs with scientific name, morphology, structural components, fractal dimension and number of interstitial spaces.*

| Reefref | Scientific name | Morphology | Components | Fractal dimension | Interstitial space |
|---|---|---|---|---|---|
| Sabellaria reef | *Sabellaria alveolata* | Encrusting, shallow reef | Connected tubes | 1.22-1.51 | Absent to small crevices |
| Serpulid reef[1] | *Serpula narconensis* | Encrusting, shallow reef | Connected, calcified tubes | 2.08-2,29 | Absent to small crevices |
| Blue mussel[2] | *Mytilus edulis* | Encrusting, shallow reef | individual bivalves connected with byssus threads | 1.03-1.31 1.36-1.86 | Absent to small crevices |
| Horse mussel[3] | *Modiolus modiolus* | Encrusting, shallow reef | individual bivalves connected with byssus threads | 1.3 | Absent to small crevices |
| Native oyster | *Ostrea edulis* | Encrusting to hemispherical | Individual bivalves cemented together | N.A. | Low number of small crevices |
| Virginia oyster[4] | *Crassostrea virginica* | Irregular 3D-structure to hemispherical | Individual bivalves cemented together | 2.67-2.74 | Numerous small and medium sized crevices |
| Corals (examples) | | | | | |
| Siderastreidae[5] | Various species | Encrusting | Clonal colonies | 1.7-2.3 | Absent to small crevices |
| Poritidae | Various species | Hemispherical | Clonal colonies | | Small crevices |
| Acroporidae | Various species | Tabular | Clonal colonies | | Crevices present |
| Acroporidae | Various species | Corymbose | Clonal colonies | | Numerous, small to large |
| Acroporidae[6] | Various species | Branching | Clonal colonies | 2.3-2.6 | Numerous, small to large sized crevices |
| All groups | Various species | All types | Clonal colonies | 2.0-2.6 | Numerous, small to large sized crevices |
| Moorlog | N.A. | Hemispherical | Peat clumps | Unknown | Absent to small |
| Geogenic reef | N.A. | Encrusting to hemispherical | Stones | Unknown | Absent to small |

## 4.5 Field experiments

The construction of scour protection around monopiles and on other offshore infrastructure generally uses a standard armor and filter layer. The material used may consist of rock material of various origins and of uniform dimensions. However, previous sections show that it is precisely the diversity in size that can contribute to an increase in biodiversity. There is also the question of whether the type of material (granite, concrete, marble, etc.) may affect the attachment of different types of organisms. The following paragraphs describe various activities undertaken within the BENSO project to provide insight into the effects of size and material under fiels conditions.

### 4.5.1 Size matters: experiment with different sizes of stones

To investigate the effects of different grades of stone material, an experiment was set up in which, in offshore conditions, the influence on the occurrence of larger (mobile) organisms would be monitored.
In this context, an expedition was organized in September 2021 to Dogger Bank .

- **Expedition goals**

The project focuses on scour protection: boulders that protect the seabed around wind turbine piles against erosion. Scour protection can be designed to benefit certain species such as fish, crabs and lobsters. For the BENSO project, with this expedition the aim is to place various sizes of rocks used in scour protection. We will set up an experiment in which we mainly want to encourage larger mobile species to be attracted, as well as growth and development. In the experiment we are going to place two different gradings (sizes) of hard substrate on the North Sea bed. It is expected that the different in sizes attract other species. The underlying questions are: does the size of hard substrate and scour protection determine the population composition of mobile species? And what effect exists on biodiversity in general? Also, the biodiversity development on rocks will be a good indication of restoration potential of this specific location with stony reefs, and thus goes beyond testing scour protection for windfarm development.

- **Methods**

The main research methods include:

- Preparations of stony reef material
- Exploring the site by visual means, using divers
- Placement of stony reef experiment
- Recording

- **Preparation**

For the deployment of the experiment, 2 different grades of potential scour protection material were selected. In doing so, the trade-off between manageability and applicability within scour protection construction was made. The gradings used are: 45-50 cm (60-300 kg) and 25-30 cm (10-60 kg).
The material used is Grauwacke rock (figure 4.2), sedimentary rock, formed by transformation of sandstone, originating from Germany. This material is not yet widely used in wind turbine construction. In the current experiment however, the dimensions are more important than the material to be used. The advantage of the material used is that the surface is relatively rough and the stones angular, this provides fouling possibilities and good interstices where mobile organisms can settle. From both gradings 3 stacks (1/2 cubic meter each, approximately 1000 kg) were set out, a total of 6 stacks.

*Figure 4.2. Grauwacke rock used for Doggerbank experiment.*

A condition for being allowed to set out the experiment is that it can also decommissioned afterwards. For this reason, a net was developed that was both strong enough to carry the stones and fine-meshed enough to also allow smaller organisms to be brought on board during removal for analysis of the overall biodiversity (figure 4.3 a). The mesh size of the net is 2 cm, the dimension is 2 by 2 meters. The net consists of 2 layers, with the outer layer providing the necessary strength. In total, there are reinforcements at 6 points of the net to prevent "lifting" from the seafloor and to enable the construction to be hoisted. All nets and contents are numbered (see figure 4.3 b).

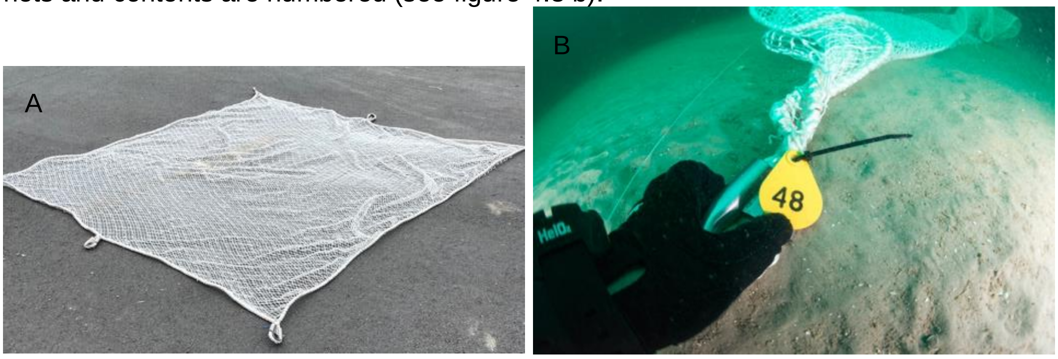



*Figure 4.3. a) net as applied under rock reefs, b) labelling of reefs (photo's by Udo van Dongen).*

Based on existing knowledge, a choice was made from a number of potential wreck locations where the experiment could be carried out. The wreck should be located on the NCP and at a working depth for Waardenburg Ecology's professional diving team (max 30 meters depth). The choice for a wreck location is based on fishing pressure (and possibly damaging fishing gear) reduced to a minimum. The first choice is the wreck of the Jeanette-Kristina. The implementation of the experiment was reported to RWS.

- **Site exploration**

After locating the wreck, divers descended to inspect the site and determine where best to place the stacks of rocks without damaging the wreck in the process. The identified site appeared to be flat and consist of a sandy bottom (figure 4.4). The location was marked with buoy lines so that orientation at the water surface was possible. The marked location was approximately 20 meters from the cabin of the wreck, 240 degrees relative to the roof.

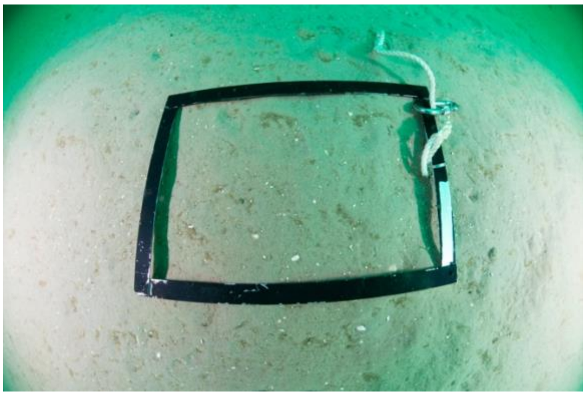


*Figure 4.4. Site exploration (photo by Udo van Dongen).*

- **Installation of stony reef experiment**

Based on the marking (buoys) and the sonar signals, the ship was positioned so that the stones could be hoisted overboard. This required clear coordination between deck and bridge crew. The nets containing the stones were hoisted using a quick release hook. When the stones hit the sea bottom, the hook was successfully opened, and the pile of stones remained on the seabed.

The exact locations of where the vessel was during the descent of the stones was recorded using a GPS handheld field tablet.

- **After installation recording**

After placing the nets with the stacks of stones, divers descended again to assess their condition. The deployment appeared to be successful. The stacks were placed at reasonable intervals. The divers opened the nets and connected them to each other (figure 4.5), so that they can still be easily located in the event of subsidence.

Subsequently the stacks of stones were photographed. With the photos the zero situation has been determined and calculations can be started regarding the size of the created holes and cavities.

*Figure 4.5. Installed stone reef experiment (photo by Udo van Dongen).*

Expedition Sept 2022: visit the experimental site at Dogger bank and look for developments of the stony reefs.

- **Expedition goals**:

In follow up of the deployment of the experimental site, major goal of the expedition is to check on the presence of mobile species and compare with the bare sand surrounding of the piles.

- **Methods**

The main research methods include:

- Exploring the site by visual means, using divers
- Recording of the stony reefs:
  - make pictures for fractal dimension measurements
  - measure the crevice sizes
  - check the stones (6 piles) on presence of (large) mobile species

- **Results**

By September 2022, little remained of the deposited piles of rocks (figure 4.6 a-b). Nets had disappeared or stones were removed or covered with sediment. Population with (larger) mobile organisms was absent. However, some stones the still present above the seabed showed some growth of sessile organisms like sponges and hydrozoa (4.6 b).

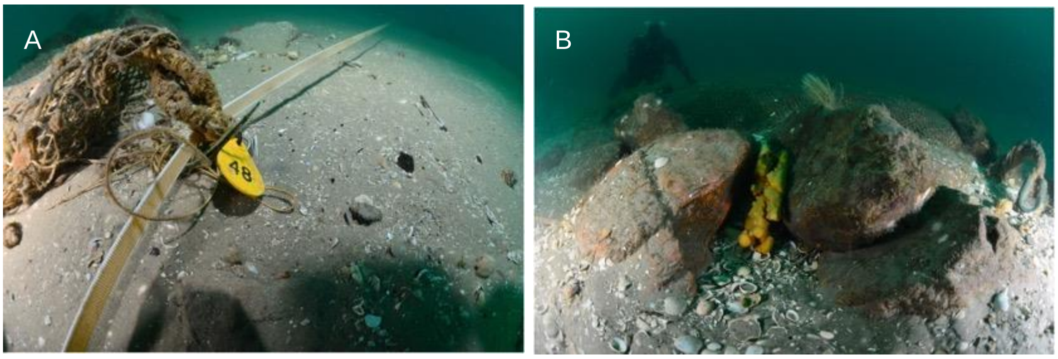



*Figure 4.6. a) remains of rock reefs at Doggerbank, b) growth on the stones at Doggerbank*

<u>Expedition July 2023: visit the site GBS Halfweg</u>.

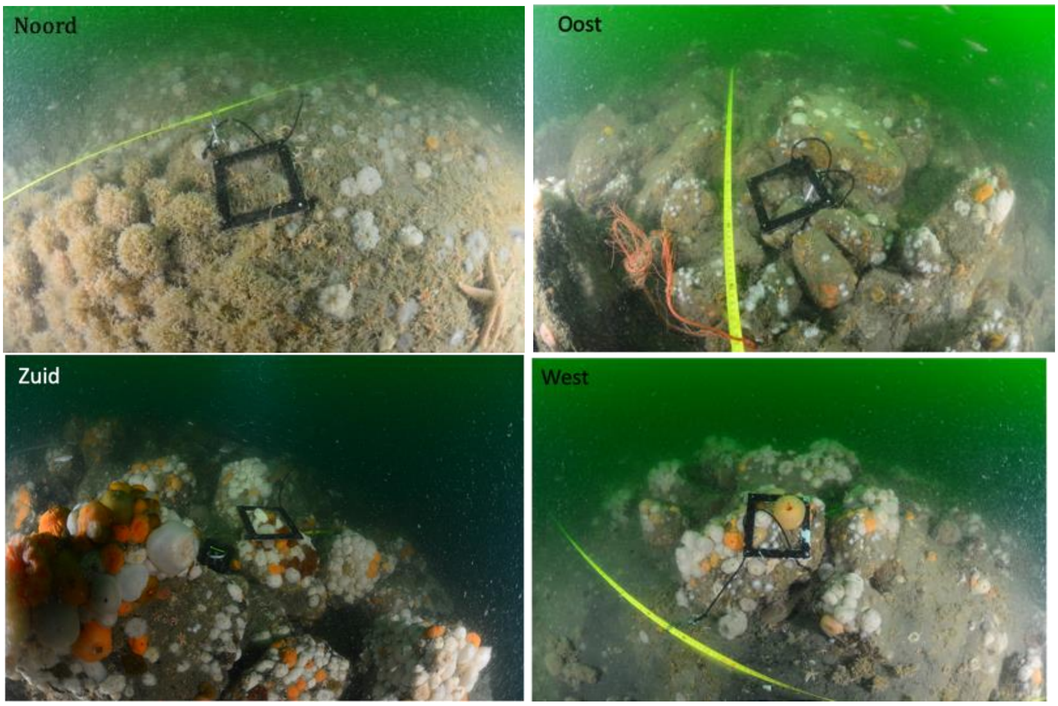
- **Expedition goals**:

As an alternative for Doggerbank experiment we visited the site GBS-Halfweg. At this location scour protection placed around a former gas platform is already present for 25 years. This gives the opportunity to view for long term development on (mobile) species presence.

- **Methods**

The main research methods include:

- Exploring the site by visual means, using divers (figure 4.7)
- Recording of the stony reefs:
    - make pictures for fractal dimension measurements
    - make pictures for analyzing sessile benthos species
    - measure stone sizes (l*h*w)
    - check the area on presence of mobile species along a transect




*Figuur 4.7. Impression of the 4 different sites (cardinal directions) and the difference in stone size composition around the platform.*

- **Results**

Stone sizes were recorded at three sites: East, West and South sides of the GBS platform. The mean surface areas of the stones were calculated according to the method described in Coolen et al. (2020): lenght*width + length*height + height*width. No significant differences were found in the surface areas (figure 4.8 a), whereas stones at the west side of the platform seem smaller than on other sites ($p<0.05$, $R^2=0.04$).

Larger surface areas of the stones may lead to more and more divers growth of sessile species. However, the analyses of the pictures made at the different sites show no significant difference (figure 4.8 b) in number of species present ($p<0.05$, $R^2=0.06$). The south side of the platform seems less species rich, however the number of transects and quadrants (10 per site) is relatively small for significant findings.

A

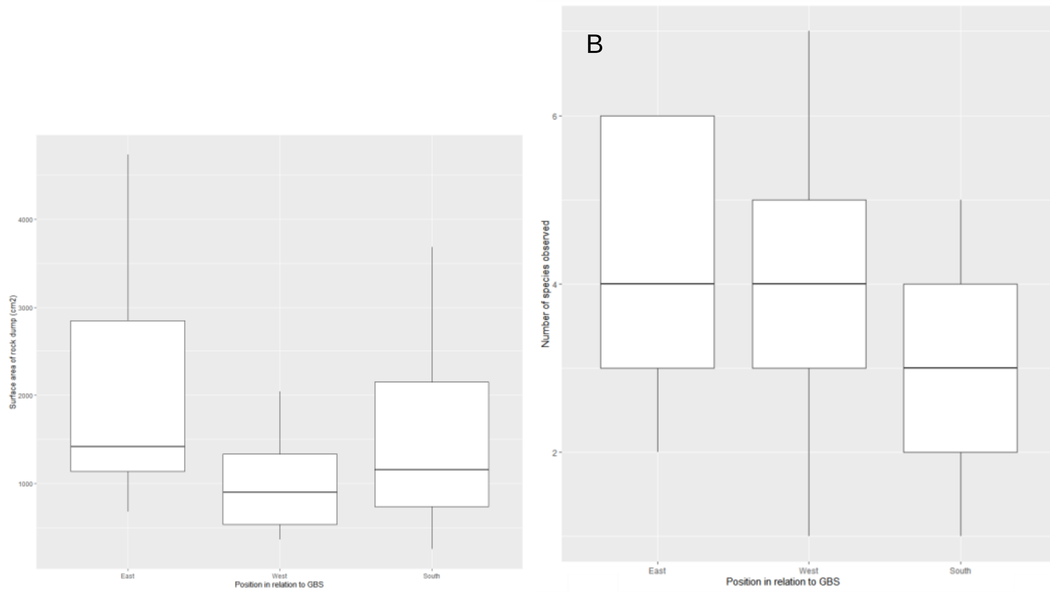



*Figure 4.8. a) Surface areas of the stones at GBS Halfweg, b) mean number of sessile species at the different sites at the location GBS Halfweg.*

In addition to the size of the stones, the number of holes visible between the stones was estimated at the various locations (table 4.2). For this purpose, a number of square meters was assessed in the different wind directions. Especially on the south side of the site, the number of holes were significantly higher. This also results in higher numbers of organisms using those holes. The number of species was limited to the velvet swimming crab, brown crab and tompot blenny. Especially the swimming crabs seem to benefit from the presence of more holes between stone structures (see table 4.2).

*Tabel 4.2. number of holes and present organisms between rock dumps at GBS Halfweg.*

| Site | # holes/m2 | Velvet sw crab | Brown crab | Tompot blenny |
|---|---|---|---|---|
| east | 1,0 | 7 | 2 | 1 |
| west | 0,5 | 12 | 1 | |
| south | 2,7 | 28 | 14 | |
| south | 3,1 | 29 | 5 | 1 |
| north | 0,5 | 12 | 5 | |

### 4.5.2 What stones? Experiment with different materials in OWF Borssele

**Background**

By improving the design of existing and new marine infrastructure, such as offshore windfarms, restoration goals can be achieved at a much larger scale (ter Hofstede et al., 2023a). Aligned with this perspective, this study focuses on enhancing the nature inclusive characteristics of the scour protection in offshore windfarms to optimize the diversity of the epibenthic community. This was done by examining the potential effect of alternating substrate material and substrate grading on the biodiversity at the scour protection. This is one of the first *in situ* studies on the potential to make the scour protection in offshore wind farms more nature inclusive and therefore our results contribute to the understanding on how to tailor the future design of the scour protection in offshore windfarms with regards to the epibenthic biodiversity.

**Results**

This study examined the effect of substrate material and grading of the scour protection on the epibenthic biodiversity *in situ*. Research cages containing crates ($n$ = 15) with different types of substrates (concrete, granite, and marble) were deployed on the scour protection of the two monopiles in the Borssele Offshore Wind Farm Site Lot V (The Netherlands).. A significant ($p < 0.05$) positive relation between available substrate surface (pebble size) and taxonomic richness was found. Furthermore, a biological trait assessment of living habits (Tube dwelling, Burrowing, Free living, Crevice dwelling, *Epi*/endobiotic, and Attached) revealed variations in habit modes across substrate types, with marble and concrete samples showing greatest divergence. Marble samples contained a higher prevalence of tube dwelling organisms, whereas concrete samples contained a relatively higher prevalence of free living, *epi*/endobiotic and crevice dwelling organisms.

**Conclusion**

In conclusion, our study revealed that habit traits vary with different substrate types, suggesting that variation in scour protection substrates could enhance the functional diversity of the epibenthic community. Moreover, we identified a positive correlation between available surface area and taxonomic richness, indicating that expanding the surface area of the scour protection may stimulate the biodiversity. We recommend further research on a larger scale to explore the potential benefits of diversifying rock sizes and shapes, incorporating more calcareous rocks, enhancing surface roughness, and actively introducing specific species (such as the ecosystem engineering species *O. edulis*) to promote biodiversity within the scour protection. By adopting a nature inclusive design for scour protection, we can optimize the coexistence of renewable energy production and a diverse marine benthic fauna.

**Findings** of this part of the BENSO project are published in the Journal of Sea Research:

Kingma Enzo M., Remment ter Hofstede, Edwin Kardinaal, Rebecca Bakker, Oliver Bittner, Babeth van der Weide, Joop W. P. Coolen. Guardians of the seabed: Nature inclusive design of scour protection in offshore windfarms promotes benthic diversity. Journal of Sea Research 199 (2024) 102502: https://doi.org/10.1016/j.seares.2024.102502

## 4.6 Discussion

Work has been done within BESO to test smart design of scour protection with the aim of achieving ecological gains. By definition, introducing hard (artificial) substrate into a soft substrate environment leads to an expansion of biodiversity. Indeed, substrate diversity offers different habitat types and associated species groups. For instance, a dead man's fingers will not grow on a bare sandy bottom, but a Sand mason worm will not be able to establish itself on a bare rock. Therefore, from a theoretical perspective, it follows that the more complex the habitat you provide, the broader the species palette found in such a ‘complex’ location. For the translation to scour protection, this means that offering uniform type of scour protection both in type of substrate (granite, concrete, marble) and in size range also leads to limited enrichment of local biodiversity. As the experiment from this project also shows, it is both the diversity of substrate that leads to more crevises and hollows where organisms can reside. In addition, the availability and accessibility of a lot of (substrate) surface stimulates the diversity of species that occurs. In addition, the type of material appears to select for different groups of organisms (e.g. more tube dwelling organisms on marble and more free-living, epi/endobiotic and crevice dwelling organisms in concrete samples).

Overall, this knowledge argues in favour of designing scour protection as diverse as possible: different types of material combined with different sizes of material. Substrate types that were not considered in the BENSO project but are believed to have an additional impact on species occurrence are wooden structures and/or other fully biodegradable structures such as shell material preferably cloughed together with nature-friendly cement.

# 5 Approach to select smart, nature-inclusive design available to OWF industry

## 5.1 Background

The conventional scour protection of offshore wind turbines resembles an artificial reef habitat. In recent decades, more emphasis has been placed to use sustainable methods and materials in the development of artificial reefs and to integrate these in the natural environment (Figure 5.1). The oldest artificial reefs included materials of opportunity, such as shipwrecks, old tyres and granite and limestone rocks from quarries. In the 2000's, concrete structures became popular because they are cost-effective through mass production. New manufacturing processes made it possible to create and deploy ever more complex structures with high fractal dimensions (Figure 5.1 I,J). Incorporating design features from natural reefs is likely to be effective in enhancing biodiversity (e.g. Matus et al., 2024; Tokeshi & Arakaki, 2012; Torres-Pulliza et al., 2020). In recent years cost-effectiveness and low $CO_2$-footprints have become more important in the application of nature-inclusive design.

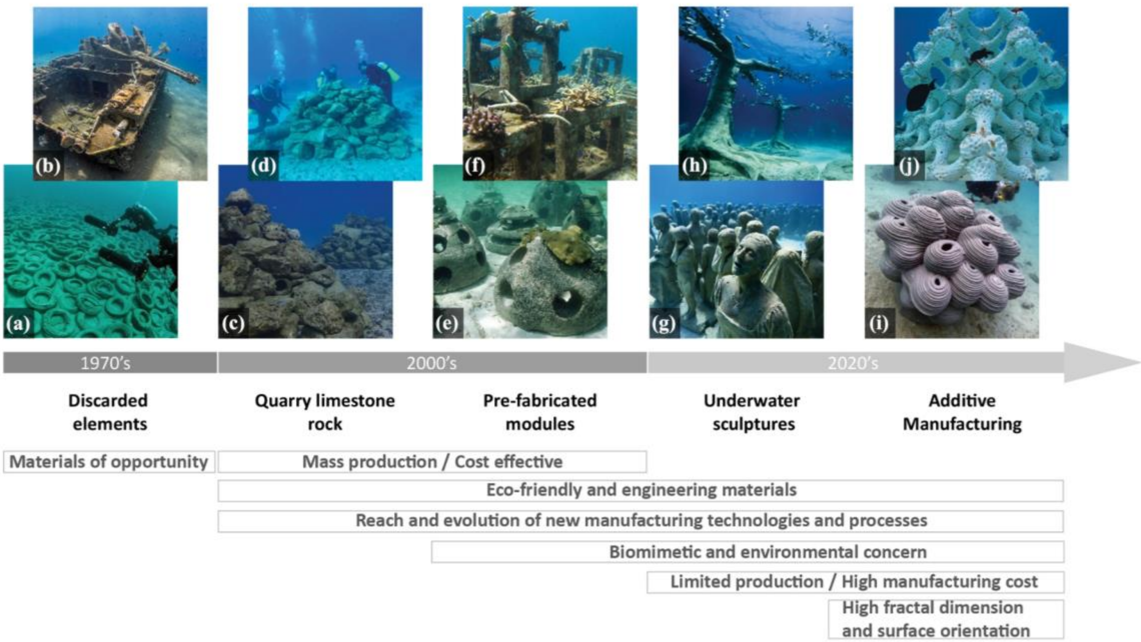



*Figure 5.1. The evolution of artificial reef design from discarded elements - (a) shipwrecks, (b) tyres; rocks – (c), (d) limestone; prefabricated components – (e) reef balls, (f) concrete structures; underwater sculptures – (g), (h, (i), (j)); additive manufacturing by 3D-printing (Matus et al., 2024).*

In recent years several studies presented overviews of nature-inclusive designs for scour protection ranging from changes in rock grading (Groen, 2019; Hermans et al., 2020; Lengkeek et al., 2017) to highly complex add-ons (Hermans et al., 2020; Lengkeek et al., 2017). An increasing number of manufacturers have made nature-inclusive add-ons commercially available combined with claims of biodiversity enhancement often based on own research (Hermans et al., 2020).

Many artificial reefs have been deployed in tropical and subtropical areas with low to mild hydrodynamic systems (Matus et al., 2024). The artificial habitats of an offshore wind turbine with scour protection are very different. They are characterized by a physically harsh environment with challenging conditions for both engineering and biodiversity caused by stochastic disturbances, such as powerful, storm-induced waves, scouring sediments, strong currents in addition to depth related light regimes, turbidity and temperature stratification. Therefore, the hydrodynamic stability of scour protection and add-ons is an essential requirement. In this section we present a new approach, the trait-based industrial design approach, to select nature-inclusive designs for scour protection and add-ons in offshore conditions. This approach combines the analysis of hydrodynamic stability with an array of required ecological requirements. The innovative element in this array is the application of fractal dimension as a measure of habitat complexity, as a proxy for the potential of biodiversity enhancement. This provides the possibility of an objective assessment of the biodiversity enhancement potential in the absence of objective monitoring results.

## 5.2 Aims

a) To make smart ecological design of scour protection (as settling substrate for sessile species and habitat for mobile species) available to the OWF industry
b) Development of an approach to select smart ecological design of scour protection.

## 5.3 Approach to apply a trait-based industrial design to nature-inclusive scour protection

The trait-based industrial design approach is used in engineering and bioinspired design and recently proposed to solve complex ecosystem restoration challenges (Temmink et al., 2023). For the design of scour protection, a large array of possible solutions is available with respect to the design of the protecting layers and the shape, texture and material of the components (e.g., Hermans et al., 2020). The structured approach to deal with an abundance of possible solutions is a morphological analysis, which include the aim, required hydrodynamical and ecological functions and an array of possible solutions.
The approach starts first with an assessment of the hydrodynamical stress level (low, medium or high) and identification of the overall important function (stability). From this follows a five-step design-based approach that (1) identifies biodiversity-related functions; (2) creates multiple solutions for a morphological analysis (figure 5.2); (3) select the best possible solutions with a multi-criteria analysis (MCA); (4) choice of solution and (5) testing in a flume tank and in the field. If the flume tank and field tests show that the chosen solution fails to meet the requirement the process may be iterated from step (2) or repeat step (4) with the new information.

After a thorough ecological analysis of the requirements of species groups dependent on, benefitting from or associated with artificial reef habitats four required functions were selected (table 5.1): hard substrate for attachment, an appropriate settlement cue, low predation pressure and water velocity dissipation. The set of required functions can be adapted or enlarged depending on the focal species group. Constructional requirements are to prevent scour and stability of the scour protection. The chosen solutions include a single layer of components to maximize ecological interaction with the sediments, interlocking components to increase stability, concrete as hard substrate, shell paste as settlement cue, numerous small- and large-sized crevices and a high porosity to slow down water velocity. Three selected solutions, interlocking components, numerous crevices and high porosity are correlated with a high fractal dimension (or space-filling dimension).

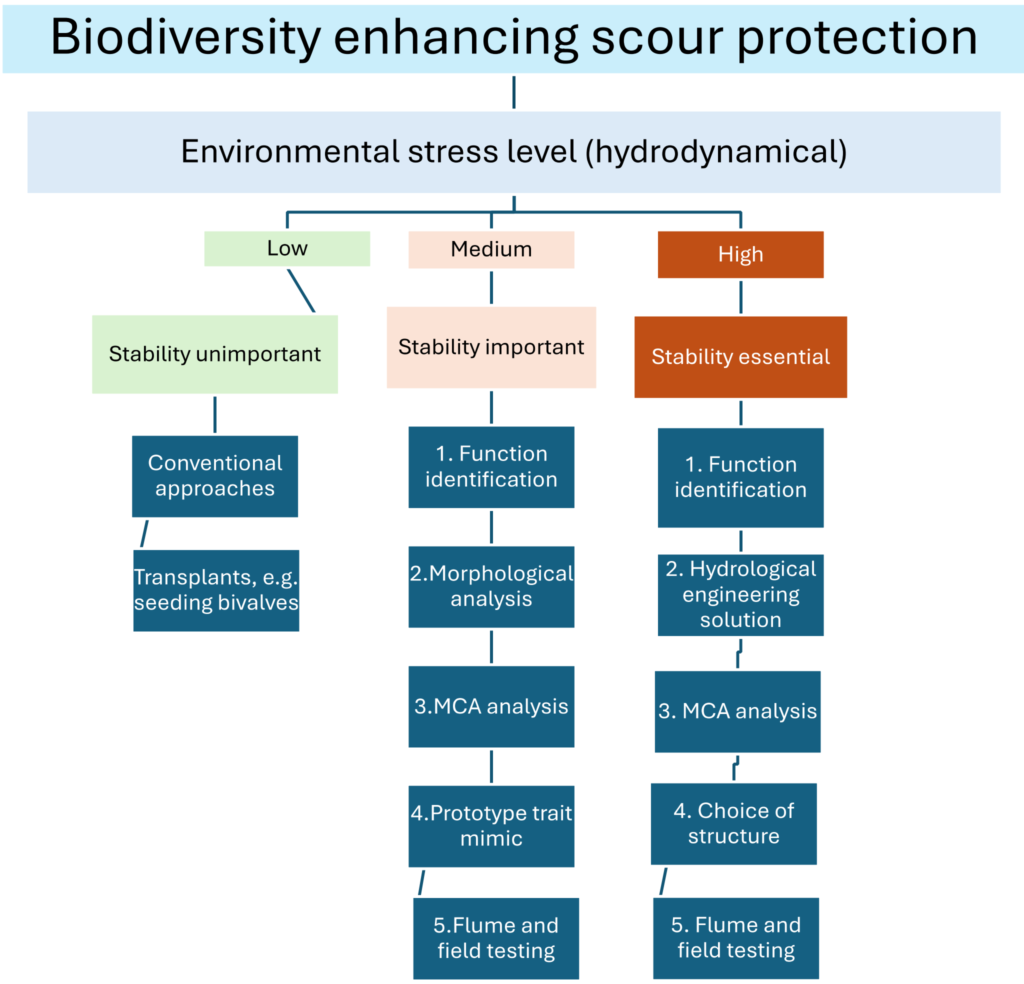



*Figure 5.2. Possibilities and environmental context of trait-based biodiversity enhancement. The flow chart shows routes to enhance biodiversity on scour protection characterized by low, medium or high hydrodynamic stress levels. The dark blue blocks depict the required step to design a trait-based enhancement solution with ecologists, industrial designers and engineers (adapted from Temmink et al., 2023).*

*Table 5.1. Morphological matrix for the analysis of the design of biodiversity enhancing scour protection. The required hydrodynamic functions are to prevent scour and stability, the ecological functions are attachment substrate, settlement cue for epibenthos, low predation pressure, and water velocity dissipation for higher food availability and larval retention (Adapted from Temmink et al., 2023). The options with the highest performance per category are in green. High fractal dimension is linked with interlocking components, high crevice variability and high porosity and highlighted.*

| Aim<br>Biodiversity enhancing scour protection | | | | | |
|---|---|---|---|---|---|
| Required functions | | | | | |
| Prevent scour | Stability | Hard attachment substrate | Settlement cue | Low predation pressure | Water velocity dissipation |
| Filter & armor layer | Large rock size | Granite rocks | Shell paste | No crevices | No porosity |
| No scour protection | Interlocking components | Limestone rocks | Rope | Few crevices | Medium porosity |
| Concrete matress | Cubic concrete blocks | Concrete | Shells | Numerous small- and large-sized crevices | High porosity |
| Single layer | | Wood | Biofilm | | |
| | High fractal dimension (D) | | | High fractal dimension (D) | High fractal dimension (D) |

# 6 Conclusions and recommendations

The BENSO project's objective was to develop and test scour protection guidelines on how to design scour protection that promotes the most positive impact for local biodiversity on and around the scour protection in offshore windfarms and accompanying hardware. Moreover, within the BENSO project a variety of monitoring techniques that can be applied in the offshore wind park settings have been developed and tested.

In the context of which marine organisms can occur on various substrate types, we contributed to the development of an international database. The database contains data from all types of artificial substrates around offshore gas and oil installations, but also on structures such as those being constructed in rapidly developing offshore wind projects. Looking at the data, the picture emerges that the diversity of fouling organisms is related to the surface area and structural complexity of the substrate on which the organisms can settle and attach.

This assumption is further developed along the theoretical framework of habitat complexity and fractal dimension. Based on the complexity and surface roughness of the material used, the enhancement of biodiversity can be worked out in advance. This applies not only to sessile benthic organisms but also to mobile species, such as fish, crabs and lobsters. The more open, space-filling structure can be offered within an artificial structure (such as scour protection) the more places are created for different types of organisms to settle, seek shelter or find food.

Apart from the size of the hard substrates offered, the type of material also seems to select which organisms will settle on the substrate. Based on the study conducted within this BENSO project, differences occur between marble, granite and concrete substrate. Whether this is a result of surface roughness, or the chemical composition of the material remains yet unanswered.

Besides considering optimal ecological benefits for biodiversity, one cannot ignore the reason why scour protection is applied in the first place: to prevent scouring of infrastructure on the seabed in a highly dynamic environment. In order to select the right design of scour protection, we advocate a trait-based industrial design approach. This will create the right balance between (industrial) stability requirements combined with maximum biodiversity yield.

Based on the above, we conclude that the following parameters should be taken into account in the design of scour protection:

- Increase the size ranges of the stones of the armour layer in a conventional scour protection design;
- Make use of various types of material within the armour layer (mix of various rock types, as well as wood and other natural materials);

- Use material that contributes to an optimal balance between lots of surface area for settling and at the same time creates lots of space between the material for foraging and hiding of mobile species;
- Design or select scour protection according to the principle of trait-based industrial design for maximum biodiversity gain within industrial requirements
- Consider omitting filter layers for creating extra space between sediment and hard substrate for infaunal species which contributes to the overall biodiversity.

To track the success of design interventions around scour protection, but also on the soft sediments between the monopiles, techniques are needed that provide good data but are also easy to handle in an offshore wind environment. In that context, within the BENSO project, several techniques have been developed, improved and applied in an offshore environment.

Two visual techniques have been optimised for imaging biodiversity: the drop cam and the baited cam. Both devices were made robust and applicable in offshore environments. The techniques have been successfully applied in offshore conditions for surveying scour protection at cable crossings and around monopiles. Making the techniques widely applicable to non-ecologists is the next challenge in this development. Using the techniques provides a large amount of data ready for analysis. A next step in the development of such visual techniques is the fast and detailed recognition of target organisms, AI techniques will play an important role there in further developments.

The development of the underwater GPS and its uses will also gather the necessary data. Expanding the application in combination with other techniques, such as the visual techniques described above, are going to provide much more accurate insight into where already existing biodiversity hotspots are present. In this way, the design of new initiatives, for the construction of offshore infrastructure, can match and take into account natural values and possibly enhance them. Effects of new initiatives can the

be tracked more accurately using the GPS system because locations can be traced exactly instead of 'approximately'.

To enable the applicability of monitoring techniques without having to undertake complicated (and therefore expensive) logistical initiatives, research facilities have been designed within the BENSO project that can contribute to this. First, a cage was designed that is demonstrably robust in an offshore environment: the Werc dock. The cage has been in service at the offshore test site for several years. So far, the cage has been examined a few times using divers. For the future and to actually test the application for which the cage is intended, the use of a (small) ROV will be required in the future to lift the racks.

The use of an unmanned automated vessel (AUV) has been demonstrably successful. Further extending its range and equipping it with different types of sensors will increase its applicability.

In short, much has been achieved within the BENSO project, which does not eliminate recommendations for future activities:

- AI tools should be designed for the analysis of a lot of (visual) data
- Further roll-out of the techniques for people without an ecological background
- A combination of underwater GPS with visual techniques makes it possible to produce good inventories of existing natural values

- Deploy underwater GPS + visual techniques to track biodiversity developments over time
- Visit the Werc dock with a (small) ROV to demonstrate workability of the cage
- Extend the AUV's range to make the system suitable for missions further out to sea

# 7 Outreach

**Scientific papers and reports**


Dannheim, Jennifer, Paul Kloss, Jan Vanaverbeke, Ninon Mavraki, Mirta Zupan, Vanessa Spielmann, Steven Degraer, Silvana N.R. Birchenough, Urszula Janas, Emma Sheehan, Katharina Teschke, Andrew B. Gill, Zoe Hutchison, Drew A. Carey, Michael Rasser, Jolien Buyse, Babeth van der Weide, Oliver Bittner, Paul Causon, Roland Krone, Marco Faasse, Alexa Wrede, Joop W.P. Coolen (n.d.). Biodiversity Information of benthic Species at ARtificial structures – BISAR (under review).

Didderen, K., Reuchlin-hugenholtz, E., Kardinaal, W. E. A., Bos, O. G., Nijland, R., Bartelink, A. K. M., & Lengkeek, W. (2022). Dogger Bank Expedition 2021: Cruise report: Biodiversity-Nature restoration–Marine science–Film (No. 22-085). Bureau Waardenburg.

Van der Have, T.M., Kardinaal, W.E.A. (under review). Habitat complexity and fractal dimension of biogenic reefs. Developing smart ecological design for scour protection in offshore wind farms. Bureau Waardenburg Rapportnr. 22-191. Waardenburg Ecology, Culemborg

Kingma, E. M., ter Hofstede, R., Kardinaal, E., Bakker, R., Bittner, O., van der Weide, B., & Coolen, J. W. (2024). Guardians of the seabed: Nature-inclusive design of scour protection in offshore wind farms enhances benthic diversity. Journal of Sea Research, 199, 102502. https://doi.org/10.1016/j.seares.2024.102502

Zupan, M., Coolen, J., Mavraki, N., Degraer, S., Moens, T., Kerckhof, F., ... & Vanaverbeke, J. (2024). Life on every stone: Characterizing benthic communities from scour protection layers of offshore wind farms in the southern North Sea. Journal of Sea Research, 102522. https://doi.org/10.1016/j.seares.2024.102522

# References

Bertolini, C., N.R. Geraldi, Montgomery W.I. & O'Connor, N.E. (2017). Substratum type and conspecific density as drivers of mussel patch formation. Journal of Sea Research 121: 24-32.

Bouma, S., & Lengkeek, W. (2013). Benthic communities on hard substrates within the first Dutch offshore wind farm (OWEZ). Nederlandse Faunistische Mededelingen, 41, 59–67.

Cappo, .M, Harvey, E. and Shortis, M. (2007). Counting and measuring fish with baited video techniques - an overview. In: Lyle J.M., Furlani D.M., Buxton C.D. , editors. Cutting-edge technologies in fish and fisheries science, January 2007.

Cannon, D. J., Kibler, K. M., Taye, J., & Medeiros, S. C. (2023). Characterizing canopy complexity of natural and restored intertidal oyster reefs (Crassostrea virginica) with a novel laser-scanning method. Restoration Ecology, 31(7), e13973.

Commito, J. A., & Rusignuolo, B. R. (2000). Structural complexity in mussel beds: the fractal geometry of surface topography. Journal of experimental marine biology and ecology, 255(2), 133-152.

Coolen, J.W.P., Lengkeek, W., van der Have, T.M. & O. Bittner. (2019). Upscaling positive effects of scour protection in offshore wind farms. Wageningen Marine Research Report C008/19, Wageningen (Commissioned by TKI Wind op Zee).

Coolen, J. W. P., Bittner, O., Driessen, F. M. F., van Dongen, U., Siahaya, M. S., de Groot, W., Mavraki, N., Bolam, S. G., & van der Weide, B. (2020). Ecological implications of removing a concrete gas platform in the North Sea. Journal of Sea Research, 166, 101968. https://doi.org/10.1016/j.seares.2020.101968

Coolen, J. W. P., Vanaverbeke, J., Dannheim, J., Garcia, C., Birchenough, S., Krone, R., & Beermann, J. (2022). Generalized changes of benthic communities after construction of wind farms in the southern North Sea. Journal of Environmental Management, 315, 115173.

Dannheim, Jennifer, Paul Kloss, Jan Vanaverbeke, Ninon Mavraki, Mirta Zupan, Vanessa Spielmann, Steven Degraer, Silvana N.R. Birchenough, Urszula Janas, Emma Sheehan, Katharina Teschke, Andrew B. Gill, Zoe Hutchison, Drew A. Carey, Michael Rasser, Jolien Buyse, Babeth van der Weide, Oliver Bittner, Paul Causon, Roland Krone, Marco Faasse, Alexa Wrede, Joop W.P. Coolen (n.d.). Biodiversity Information of benthic Species at ARtificial structures – BISAR (under review).

Dannheim, J., Bergström, L., Birchenough, S. N. R., Brzana, R., Boon, A. R., Coolen, J. W. P., Dauvin, J.-C., de Mesel, I., Derweduwen, J., Gill, A. B., Hutchison, Z. L., Jackson, A. C., Janas, U., Martin, G., Raoux, A., Reubens, J., Rostin, L., Vanaverbeke, J., Wilding, T. A., … Degraer, S. (2020). Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. ICES Journal of Marine Science, 77(3), 1092–1108. https://doi.org/10.1093/icesjms/fsz018

Degraer, S., Carey, D., Coolen, J. W. P., Hutchison, Z., Kerckhof, F., Rumes, B., & Vanaverbeke, J. (2020). Offshore Wind Farm Artificial Reefs Affect Ecosystem Structure and Functioning: A Synthesis. Oceanography, 33(4), 48–57. https://doi.org/10.5670/oceanog.2020.405

George, E. E., Mullinix, J. A., Meng, F.,t Bailey, B. A., Edwards, C., Felts, B., ... &Haas A.F., Hartmann A.C., Mueller B., Roach T.N.F., Salamon P., Silveira C., Vermeij M.J.A., Rohwer F., Luque, A. (2021). Space-filling and benthic competition on coral reefs. PeerJ, 9, :e11213 http://doi.org/10.7717/peerj.11213

Groen, O. D. (2019). Nature-enhancing design of scour protection for monopiles in the North Sea (Doctoral dissertation, MSc thesis]. Delft University of Technology, The Netherlands. http://resolver. tudelft. nl/uuid: f612bc90-785c-4706-90e6-b7116f4b8077).

Gutow, L., Teschke, K., Schmidt, A., Dannheim, J., Krone, R., & Gusky, M. (2014). Rapid increase of benthic structural and functional diversity at the alpha ventus offshore test site. In Ecological Research at the Offshore Windfarm alpha ventus (pp. 67–81). Springer.

Hermans, A., Bos, O. G., & Prusina, I. (2020). Nature-Inclusive Design: a catalogue for offshore wind infrastructure: Technical report (No. 114266/20-004.274). Witteveen+ Bos.

Kovalenko, K.E., S.M. Thomaz & D.M. Warfe, (2012). Habitat complexity: approaches and future directions. Hydrobiologia 685(1): 1-17.

Lengkeek W, Didderen K, Teunis M, Driessen F (2017). Eco-friendly design of scour protection: potential enhancement of ecological functioning in offshore wind farms. Towards an implementation guide and experimental set-up (http://edepot.wur.nl/411374). Bureau Waardenburg. Report 17-001

Leonhard, S. B., & Christensen, J. (2006). Benthic Communities at Horns Rev Before, During and After Construction of Horns Rev Offshore Annual Report 2005. Bio/consult as report.

Li, C., Coolen, J. W. P., Scherer, L., Mogollón, J. M., Braeckman, U., Vanaverbeke, J., Tukker, A., & Steubing, B. (2023). Offshore Wind Energy and Marine Biodiversity in the North Sea: Life Cycle Impact Assessment for Benthic Communities. Environmental Science & Technology, 57(16), 6455–6464. https://doi.org/10.1021/acs.est.2c07797

Matus, I. V., Alves, J. L., Góis, J., Vaz-Pires, P., & da Rocha, A. B. (2024). Artificial reefs through additive manufacturing: a review of their design, purposes and fabrication process for marine restoration and management. *Rapid Prototyping Journal*, *30*(11), 87-122.

Montes-Herrera, J. C., Hill, N., Cummings, V. J., Johnstone, G. J., Stark, J. S., & Lucieer, V. (2024). Remote sensing of Antarctic polychaete reefs (Serpula narconensis): reproducible workflows for quantifying benthic structural complexity with action cameras, remotely operated vehicles and structure-from-motion photogrammetry. Remote Sensing in Ecology and Conservation, 10(1), 72-90.

Spielmann, V., Dannheim, J., Brey, T., & Coolen, J. W. P. (2023). Decommissioning of offshore wind farms and its impact on benthic ecology. Journal of Environmental Management, 347, 119022. https://doi.org/10.1016/J.JENVMAN.2023.119022

Vanagt, T., & Faasse, M. (2014). Development of hard substratum fauna in the Princess Amalia Wind Farm. Monitoring six years after construction. eCOAST report 2013009 (Issue April).

Temmink, R. J., Angelini, C., Verkuijl, M., & van der Heide, T. (2023). Restoration ecology meets design-engineering: Mimicking emergent traits to restore feedback-driven ecosystems. Science of the Total Environment, 166460.

Tokeshi, M., & Arakaki, S. (2012). Habitat complexity in aquatic systems: fractals and beyond. Hydrobiologia, 685, 27-47.

Torres-Pulliza, D., M.A. Dornelas, O. Pizarro, M. Bewley, S.A. Blowes, N. Boutros, V. Brambilla, T.J. Chase, G. Frank & Friedman, A. (2020). A geometric basis for surface habitat complexity and biodiversity. Nature Ecology & Evolution 4(11): 1495-1501.

Zawada, D. G., & Brock, J. C. (2009). A multiscale analysis of coral reef topographic complexity using lidar-derived bathymetry. Journal of Coastal Research, (10053), 6-15.

Zupan, M., Coolen, J., Mavraki, N., Degraer, S., Moens, T., Kerckhof, F., ... & Vanaverbeke, J. (2024). Life on every stone: Characterizing benthic communities from scour protection layers of offshore wind farms in the southern North Sea. Journal of Sea Research, 102522.

Zupan, M., Rumes, B., Vanaverbeke, J., Degraer, S., & Kerckhof, F. (2023). Long-Term Succession on Offshore Wind Farms and the Role of Species Interactions. Diversity, 15(2), 288. https://doi.org/10.3390/d15020288