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Summary

Subsea power cables transport offshore generated energy to shore. Generally buried, they protrude from the seabed when crossing an existing pipeline or cable. Rock is placed on top of the cable to protect it, forming a cable crossing of ~0.2 Ha. This hard substrate in a predominantly sandy environment allows reef formation adding to the biodiversity of an area. TenneT will install another 90 cable crossings before 2032. Optimising the technical design to facilitate reef development could stimulate species biodiversity. In this study, annual field surveys over three years post-installation were conducted to assess the influence of rock size (D90 80 mm 'sprinkle layer' and D90 400 mm 'armour layer') and material (granite and marble) on species biodiversity. These surveys employed dropcam and eDNA methods to monitor differences in macrobenthic and fish abundance and diversity. Our findings indicate that the addition of calcareous marble did not significantly increase the species biodiversity in terms of fish or macrobenthos. Species diversity increased over the three survey years. Lastly, only one invasive species was found on both marble and granite rock. Our findings show that cable crossings can contribute to the species biodiversity, where the addition of marble rock does not result in a higher species count. Larger, more stable rocks should be used as the outer layer of a cable crossing in order to promote reef development. The observed species composition did not suggest that an ecological climax stage was reached at year three. Additional surveys in years 5 and 10 are recommended to determine if these findings remain consistent over longer periods.

Keywords

Subsea power cables; reef development; cable crossings; benthic community; fish community.

1 Introduction

1.1 Cable crossings required for OWF expansion

TenneT is responsible for realizing and operating the Dutch offshore electricity grid and aims to develop this grid as nature-inclusive as reasonably possible, in line with the Development Framework for Offshore Wind Energy [1], and TenneT's Corporate Social Responsibility (CSR) goals [2]. With every installed grid connection, newly installed cables also cross already existing offshore infrastructure. Although generally buried, at crossings sites, cables protrude above the seabed and are especially vulnerable to disruption from anchoring, fishing activities or heavy storms. To mitigate these risks, cable crossings are protected by granite rock berms. The cable crossings are designed according to the Environment and Planning Act, NEN 3656, 2022 which states that the armour layer needs to be fully covered by a sprinkler layer (D90, 80 mm) because cable crossings need to be over-fishable. This legislation and technical requirements have led to a standard design of ~100x20x1m, where the exact footprint is determined by the type of asset being crossed, along with a natural slope ratio of 1:3 to 1:4. TenneT will install more than 90 crossing structures by 2032. These crossing structures will cover almost 20 hectares or 30 football fields of hard substrate.

1.2 Reef development

The upscaling of offshore wind and the expansion of the offshore grid takes place in an environment that is under pressure. The ecological status of many benthic habitats in the North Sea, especially sandy nearshore habitats, is poor [3], [4], [5]. The decline of biogenic reefs in the North Sea is an important contributor to this poor status, with the decline of flat oyster beds (*Ostrea edulis*) being one of the most prominent examples [6]. Flat oyster beds are protected under OSPAR [7] and associated with high species richness, providing habitat, refuge and foraging ground for many invertebrates and vertebrates [8]. In addition, their filter-feeding behaviour enhances water clarity and plays an important role in the exchange of nutrients and organic matter between the water column and the seafloor (benthopelagic coupling) [8]. This way, the oyster is considered a keystone species: when a healthy reef develops and when abiotic and biotic conditions allow, other reef-associated species are expected to thrive too [9], [10], [11].

As such, the general consensus is that if reef-building species like oysters flourish, the (local) ecosystem could benefit. However, as described in literature, due to decades of bottom trawling oyster fisheries followed by disease (the *Bonamia* parasite), the flat oyster reef ecosystem is currently considered 'collapsed' under the IUCN framework [12], [13]. Historically, oyster reefs covered millions of hectares of the European seafloor, but currently there are no known locations where flat oyster reefs are found at the scale of more than 0.1 ha [6], [13], [14]. Measures to conserve and restore this habitat include regulation of fisheries, and the introduction of suitable substrate and broodstock to promote recovery [3]. As such, restoration of oyster reefs has been a focus for Dutch policy for several years now [15], [16], [17]. Cable crossings could provide a suitable habitat for oysters and other hard substrate, and reef-associated species, and possibilities are explored to optimise the cable crossings for these species through nature-inclusive design.

The degree to which restoration efforts have the potential to positively contribute to the condition of North Sea habitats, depends largely on the location and the scale of the measures [10]. In addition, when focusing on providing suitable substrate, research to flat oyster restoration has shown that there are several other key criteria to successful substrate design. For flat oyster larvae to settle and grow successfully, substrate needs to be stable (not rolling or washed away easily), elevated above the seabed (to prevent sedimentation, and increase filter feeding efficiency) and of sufficient size (creating resiliency) [19]. Since offshore cable crossings meet these criteria (Figure 1), they might provide an opportunity to contribute to the restoration of flat oyster beds and benthic hard substrate habitats in general.

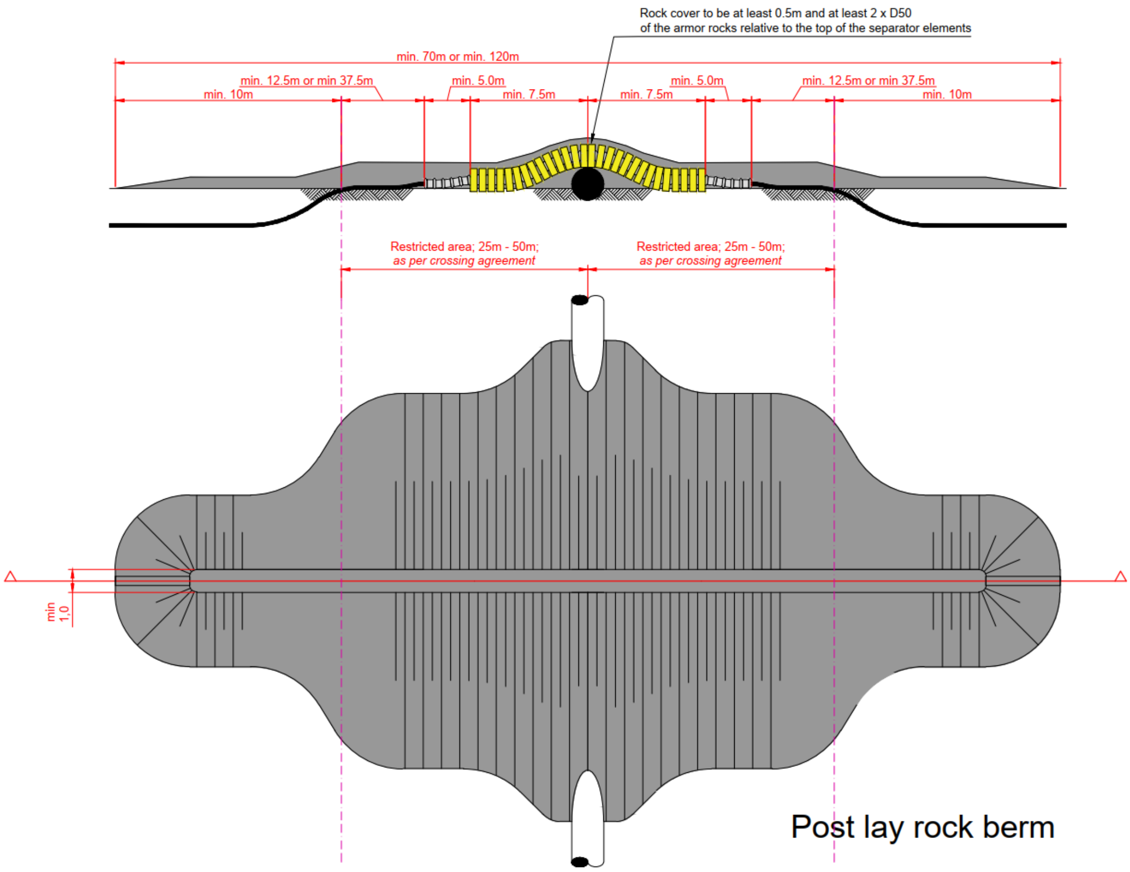


Figure 1 - ***Standard cable crossing design***

Anecdotal evidence already shows cable crossings can provide substrate on which species can successfully settle, while simultaneously providing shelter to crustaceans (Figure 3). Newly created habitats at cable crossings might then become a 'stepping stone' between existing habitats [20]. This concept is based on the idea that species distributions can expand (in two or more generations) if two unconnected areas are connected through suitable intermediate habitats [21]. So, by providing settlement substrate within the larval dispersal range of benthic species (like the flat oyster), this can have a large impact on overall species distributions and with that, on large-scale benthic recovery. There are furthermore indications that substrates can be optimized even further by implementing calcareous substrate types (like limestone and marble), which could aid settlement of bivalves, and particularly the native flat oyster [17], [22].

1.3 Dropcam and eDNA

To research the suitability of (optimized) cable crossings for benthic habitat development, underwater monitoring is required. Several traditional methods are commonly employed, including diver-based surveys, grab or core sampling, remotely operated vehicles (ROVs), and drop cameras [23]. Diver-based techniques, such as quadrat sampling or transect surveys, are not desired in the offshore wind industry due to safety considerations. Grab and core sampling, while effective, are inherently destructive, potentially damaging both sensitive reef habitats and the structural integrity of the cable crossing. ROVs, although capable of high-resolution observations, are cost-intensive and often limited by operational constraints such as wave heights [23], [24], [25].

Drop cameras are frequently employed in biodiversity surveys. Due to their non-invasive nature, ability to capture high-resolution imagery, and ease of deployment, employing drop cameras is a cost-effective imaging method. They can operate across a wide range of depths and minimize the human bias that may arise from the presence of divers in the environment [26], [27]. These attributes make drop cameras a versatile and reliable option for assessing marine biodiversity on cable crossings. There limitation of this technique include that the data quality is dependent on visibility and static perspective.

Recent research has furthermore utilized Environmental DNA (eDNA) monitoring to study the presence and biodiversity of benthic and fish communities, demonstrating increased sensitivity compared to traditional (diving based) methods [28], [29], [30], [31], [29], [30], [31], [32]. This approach shows promise as a cost-effective, non-invasive and safer (no-diving) alternative for surveys in temperate waters and offers potential for scaling up to routine monitoring [37]. This technique complements the drop camara data collection as it reveals species presence that are not readily shown on camara as nocturnal or cryptic species. However, eDNA has limitations, providing only presence-absence data without information on abundance or specific behaviors, and detecting a wide range of species can make data interpretation complex. Despite these challenges, eDNA complements methods like drop cameras by revealing "dark diversity" — species that are present but remain undetected by traditional visual surveys [25].

1.4 Optimalisation cable crossings

In this study, the suitability of cable crossings for reef development and the effect of different materials and rock sizes is investigated. To this end, multiyear survey data was used to compare a sprinkler layer of granite and a sprinkler layer of marble, a calcareous rock believed to provide a more suitable settlement substrate for larvae. Drop camera footage showed the behaviour of the sprinkler layer in the dynamic coastal environment of the Dutch North Sea, the benthic community development and the use of crevices by crustaceans. e-DNA provided insight in fish occurrence and whether the crossings provide habitat for non-native species.

2 Materials and Methods

2.1 Survey data

The study area is located on the 34 km export cable laid from the Tweede Maasvlakte to the offshore wind farm Hollandse Kust Zuid (HK(z)) in the Netherlands (Figure 3). In the center of the offshore wind farm two offshore high voltage stations (OHVS) are located, alpha and beta. From the OHVS, two cables run parallel to shore, resulting in the alpha1, alpha2 (east), beta1, and beta2 (west) export cables. These four cables cross three pipelines: (1) TAQA (P15-D to Maasvlakte) Gas pipeline, (2) TAQA (P15-C to Hoek van Holland) oil pipeline and (3) Neptune (formerly GDF Suez) (Q13a-A to P15-C) Oil pipeline (Table 1).

Of three of the crossings of the alpha2 cable the sprinkler layer of granite was replaced by a sprinkler layer marble. The three crossings of alpha1, located 200m eastward, with a traditional granite sprinkler layer were used as the reference locations (Table 1). Dropcam and eDNA surveys were conducted in 2022 (3-6 July), 2023 (16-18 June) and 2024 (14-16 July) from the Standby Safety Vessel Tender I.

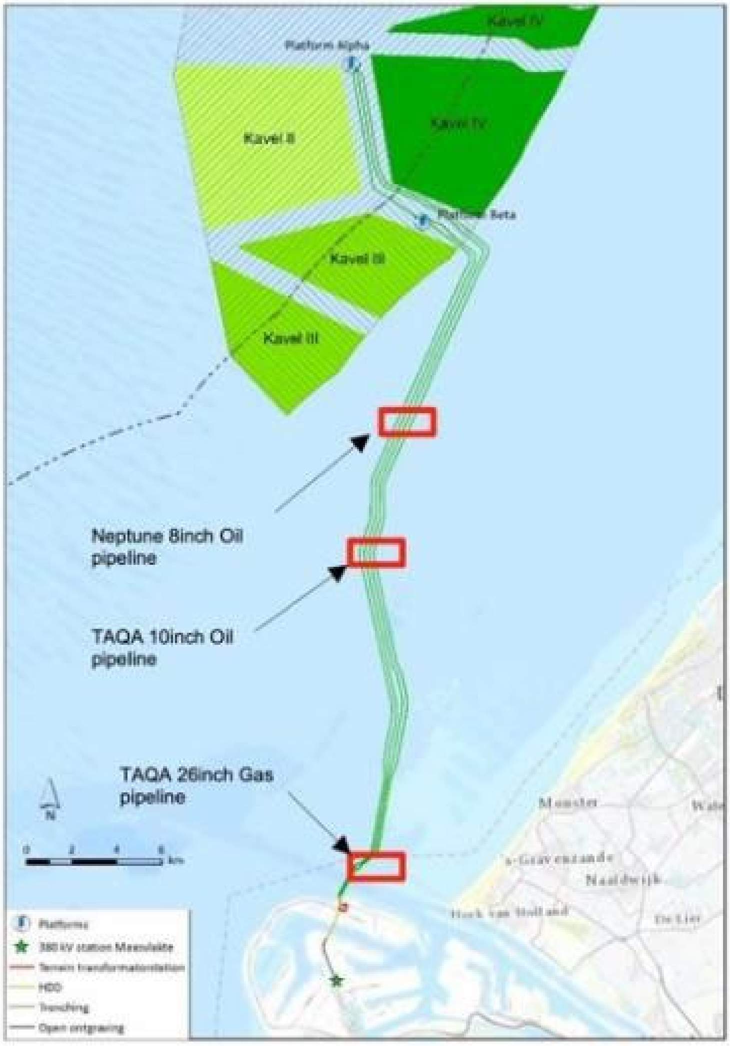


Figure 2 - Overview of the monitoring locations with cable crossings indicated in red triangles.

Table 1 – Pilot setup of the cable crossings. Crossings are listed from south to north

CDS location	Alpha 1 Sea conventional design	Alpha 2 Sea pilot design
TAQA 26-inch Gas P15D to Maasvlakte Pipeline	22-90mm Granite	22-90mm Marble
TAQA 10-inch Oil P15C to Hoek van Holland Pipeline	22-90mm Granite	22-90mm Marble & 22-90mm Granite1
Neptune 8-inch Oil Q13a-A to P15C Pipeline	22-90mm Granite	22-90mm Marble

Benthic sessile species and crustaceans were monitored with a drop cam system (Figure 3). The camera used was a remotely controlled Z-cam E2 4K video camera in a Nauticam NA-E2 underwater housing. The video camera was mounted in an in-house developed camera frame with an integrated in-house developed lighting system (Figure 3D). The specific deployment location was determined by sonar scans, the tidal current, wave action and wind direction. After deployment by the crane, a combination of drifting and wave movement allowed the drop cam system to land regularly on the seabed, 'hopping' in an transect perpendicular over the crossing. For each site several controlled drifts crossings were executed until enough good footage was acquired.

Simultaneous with camera deployment, at each monitoring location 60 L of sea water was collected for eDNA-analysis. A dedicated eDNA filter cartridge (0,45 µm pore size, filter material cellulose nitrate cellulose acetate was attached to the drop-cam frame (Figure 3C). The outlet of the eDNA filter cartridge was connected to a vacuum hose, which was connected to a vacuum pump on deck. The inlet of the filter cartridge was opened directly before deployment and closed when the pump was retrieved. After sampling, the filters with eDNA were on site conserved with a preservation buffer solution and stored. The cable crossings located at TAQA (P15-D to Maasvlakte) Gas pipeline (most south) are within ~35m distance of each other and therefore the two eDNA samples should be considered as a duplicate. Within seven days after collection the eDNA samples were shipped to a specialized lab for eDNA analysis (DATURA).

During acquisition of the video footage and the collection of the eDNA samples the position of the ship was logged with a GPS tracker. All video footage was during the inspections saved on the camera's memory card. At the end of each day all footage was backed up on external SSD hard disks.

***Figure 3** - Overview of cable crossings showing (A) an armour layer rock (D90 400mm) covered with marine growth and (B) different types of sprinkle layer (D90 80mm) with a Edible crab (Cancer pagurus) and a common starfish (Asterias rubens), source: DPM. Monitoring techniques used on the cable crossings showing (C) the dropcam frame with the camera mounted in the center and (D) the pump used to collect water for eDNA analysis.*

2.2 Data processing

For image analysis all videos per substrate per location were selected and loaded in VLC media player (v.3.0.21 Vetinari). Of each landing that provided a stable view a still was extracted and directly stored and sorted out per substrate (granite, marble or sand) (Figure 4). Afterwards the 20 most representative stills per substrate were selected in Adobe Lightroom Classic (v.14.0.1) examples shown in Figure 4. For this selection several parameters like rock size, substrate, abundance/coverage and diversity of life were taken in consideration to obtain the most diverse possible selection of each substrate, to emphasize analysis on diversity rather than abundance. All visible and recognizable species were counted and analyzed to the highest taxonomic level possible and recorded in Excel (Tabel S1).

Fish eDNA analysis was performed by using metabarcoding. DNA was extracted from water samples, minimising inhibition from substances like humic acids. Target DNA was amplified using 12S and 16S primers tagged with unique 7-nucleotide identifiers to distinguish samples. Amplifications were conducted in 12 replicates using TaqMan® Environmental Mastermix 2.0. The replicates were pooled, and amplification success was verified by gel electrophoresis. PCR products were prepared for sequencing by adding Illumina Nextera XT adaptors. Pooled and purified libraries were sequenced on an Illumina Novaseq 6000 platform (150 bp paired-end).

Sequencing reads were processed and analysed using Illumina software and OBITools. Raw reads were processed using RTA3.4.4 and Bcl2fastq v2.20 pipelines, with adapter trimming, PhiX control removal, and quality assessment via FastQC. Forward and reverse reads were merged to create consensus sequences (Illuminapairedend). An NGS filter was used to identify and couple the reads to a specific sample by means of a 7 nucleotide tag. Non-aligned, low-quality, or short sequences (<15 bp) were removed (Obigrep). Identical sequences within samples were merged to reduce dataset complexity (Obiuniq). Sequences were matched to a curated reference database using Ecotag. Sequencing and PCR errors were identified and corrected using Obiclean, applying stepwise stringency thresholds (r=0,05 d=1; r=0,005 d=2 ; r=0,001 d=3 and r=0,0005 d=4). Processed reads were compiled into a taxonomic abundance table for each sample.

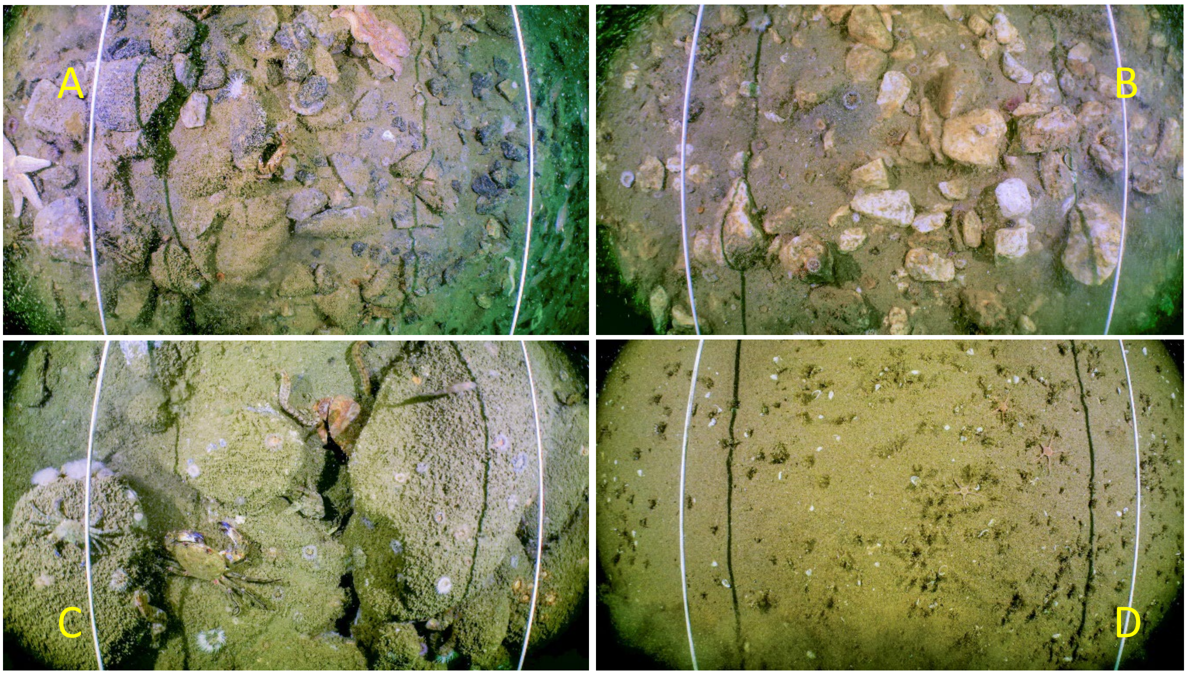


***Figure 4* - Examples of analysed stills. A: Granite sprinkler layer, B: Marble sprinkler layer, C: Armour layer, D: Sand (TAQA 10-inch Oil P15C)**

2.3 Statistical analysis

Data of selected pictures were analysed using R version 4.3.2 [38]. Not for all combinations of substrate (granite: G, marble: M, sand: S), year (2022, 2023, 2024) and location (1, 2, 3) there were 20 suitable stills available. The lowest number was 17, for location 3M 2022. Stills for S were obtained from the G and M transects. To ensure balanced representation, 16 stills were selected for each combination, with 8 stills randomly chosen from each transect per location. This random selection process resulted in a total of n = 432 stills. Since not all species could be reliably counted (e.g., individual identification was not feasible), species diversity was assessed based on species richness.

Bar plots were created to visualize the number of species per still for each location separately and for all locations combined, using the R package *ggplot2* [39]. To test whether the mean number of species per still differed between substrates, a general linear mixed model (GLMM) was done using the *brm* function from the *brms* package [40]. The model included location and year as random effects, with a Poisson distribution family. The maximum tree depth was set to 11, and delta was set to 0.999. Pairwise comparisons were conducted using the *brmsmargins* function from the *brmsmargins* package [41], with random effects included, *k* set to 100L, and the seed set to 1234.

To get a broader perspective on the species richness on the different substrates, point plots were made showing the total number of unique species per substrate per location per year and for locations combined. With that, a dendrogram was made showing the clustering of the substrates at different location for all years combined. Distances were calculated based on the regional dissimilarities of the Hill Numbers, using the *hill_taxa_parti_pairwise* function from the 'hillR' package, with q set to 0 to exclude species abundances [42].

Lastly, the presence of invasive species on the different substrate types was determined based on the invasive species included in the Dutch Species Register [43].

3 Results

3.1 Biodiversity of cables crossings

A total of 90 species were detected across 432 stills during three years of surveying at the cable crossing sites. The number of species per still (covering approximately 0.14 m^2) increased from a median of ~3.5 in 2022 to ~6.5 in 2023 at both hard substrate sites (granite and marble) but declined slightly in 2024 (Figure 5). This trend was consistent across locations, except for 2M, where 2024 showed a higher median than 2023, and location 3, which exhibited a more pronounced increase between 2022 and the subsequent years.

The total number of unique species per substrate increased from 2022 to 2023 for all substrates, with only a small change for coarse sand (S). Between 2023 and 2024, a slight increase was observed for granite (G) and marble (M), while S showed a decrease. In 2023 and 2024, species richness was highest on G, followed by M and S, whereas in 2022, M hosted fewer species than G and S.

When separated by location, location 1 showed stable or declining species numbers across substrates between 2022 and 2023, in contrast to increases at locations 2 and 3. Both locations 2 and 3 exhibited a decline from 2023 to 2024, although species numbers remained higher than in 2022 for G and M. Location 1 displayed a slight increase for G, stability for M, and a decrease for S in 2024. Notably, the overall stability in M species numbers between 2023 and 2024 masks variation across locations, suggesting differences in species assemblages on M substrates in 2024 (Table S1). Overall, species richness patterns appeared consistent across locations.

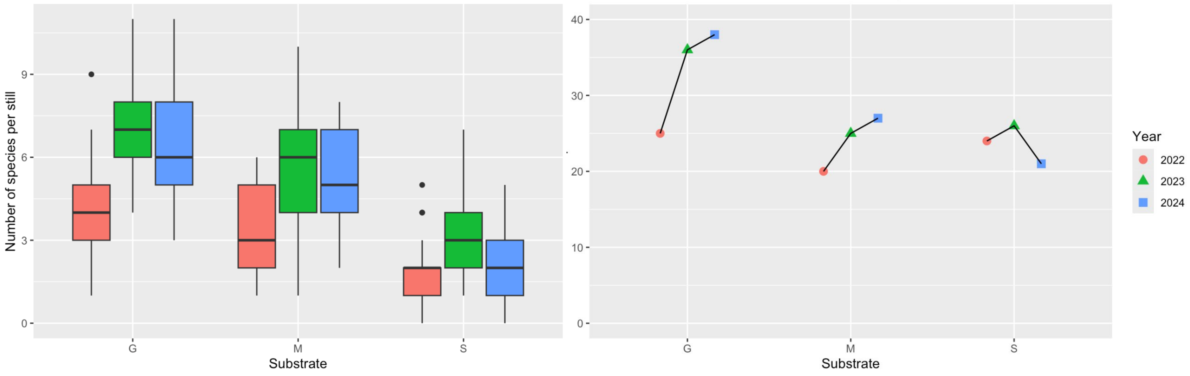


***Figure 5** - (left) Number of different species counted per still, separated for substrate and year. With n = 48 for each substrate in one year. Horizontal line shows median, the box the range of values between Q1 and Q3, the whiskers Q1/Q3 -/+ 1.5 * IQR and the points are outliers, and (right) Total number of different species counted for a substrate, separated per year. With n = 48 for each substrate in one year. Black lines connect the years for the same substrate.*

The similarity among the different substrate-location combinations was analysed using a dendrogram (Figure S2). The results indicate that species diversity for substrates G and M at the same location exhibit the highest similarity. Furthermore, species diversity for substrates G and M from different locations is more similar to each other than to their respective S substrate at the same location. Among locations, locations 2 and 3 show the greatest overall similarity across all substrates.

3.2 Effect substrate type

A significant effect of substrate type on the number of species per still was observed, with both M and S supporting fewer species per still compared to G (GLMM, R-hat = 1.00 for all). The median posterior estimates for the number of species per still were 5.73 (95% CI: 5.35–6.12) for G, 4.86 (95% CI: 4.54–5.27) for M, and 2.48 (95% CI: 2.22–2.72) for S (Table 2). Both hard substrates supported a greater number of species per still than the surrounding soft substrate of coarse sand.

***Table 2** - Pairwise comparison of the number of species per still per substrate, with location and year as random effects in a GLMM. With the median of the differences between the posterior samples and the 95% Confidence Interval.*

	Median of differences posteriors	95% Confidence Interval
Granite – Marble	0.86	0.40 – 1.32
Granite – Sand	3.24	2.85 – 3.64
Marble – Sand	2.39	2.02 – 2.77

3.2.1 eDNA

The most commonly detected species across the three years included Atlantic herring, whiting, Atlantic mackerel, Atlantic horse mackerel, European sprat, and sand goby, with all species recorded in at least one consecutive year at all sites (Table S1). In 2024, rarer DNA fragments were identified, including those of the greater weever, black goby, Atlantic cod, whiting/saithe/pollack, shorthorn sculpin, rock gunnel, and lesser pipefish. The greater weever was detected at site 2G, while the other rare species were found at site 3G, which exhibited the highest species diversity in 2024 based on eDNA presence. In contrast, at site 1M, eDNA fragments of only three common species were detected in 2024. No clear distinction in species composition could be identified between sites with granite or marble as the primary sprinkle layer based on eDNA presence/absence (Table S1).

3.3 Invasive species

In 2024, four individuals of an invasive species known as the common slipper limpet (*Crepidula fornicata*) were observed at three locations; M1, G2 (twice) and G3. The species is associated with hard substrates [44] and has been present (and increasingly common) in Dutch waters since the early 1900's. No other invasive species have been observed during the monitoring period, and also in the eDNA fish monitoring only native species have been observed.

4 Discussion

4.1 Interpretation of the findings

4.1.1 Species

The species found at the cable crossings are species that have been observed elsewhere in the North Sea on and around hard substrates, for instance at rocky reefs and on scour protection around wind turbines and oil and gas platforms [45], [46]. Seeing the size of the observed individuals, the monitored locations do not seem to have been substantially overfished between 2022-2024. In terms of species richness, benthic biodiversity was higher on the hard substrates than on the surrounding coarse sand. This is in line with research to biodiversity around the scour protection of wind turbines in the North Sea [45], [47], [48], [49].

Although not researched in this study, the soft sediments around the cable crossings are also expected to show an increase in species richness compared to soft sediments further away from the crossing [50], [51]. Species typically considered 'hard-substrate species' are known to partially colonize the soft sediments at distances of tens to >200 m away from the hard substrates [50], [51]. As such, the effects of the presence of hard substrate can spread out towards the soft sediments over time [50]. Important to note is that this observation of increased biodiversity on an around hard substrates applies specifically to epifauna: species occurring on the seabed and on the hard substrate. For endobenthos species, which are burrowed in the sediment, this has not specifically been researched (nor monitored in this campaign).

Especially in areas outside wind farms and away from drilling platforms and shipwrecks, cable crossings could provide new substrate that could host species that have not been occurring in those specific locations of the North Sea recently. Cable crossings could also be stepping stones for hard-substrate species which are projected to show northward species shifts (the majority of benthic North Sea species) with increasing water temperatures in the coming decades [52], [53]. It is however not considered likely that cable crossings will play a significant role in the spread of new marine invasive species, as biofouling on vessels and the dispersal through ballast water are still considered the main factors in new species introductions [54]. Also, contrary to the vertical substrates that offshore wind turbines can provide [55], the hard substrate placed at the seabed partially resembles naturally occurring rocky reefs in the North Sea, limiting the chance that species unknown to the North Sea appear. From the species that have been identified to species level, only one invasive species has been observed during the monitoring, the common slipper limpet. This hard-substrate species has been present (and is increasingly common) in Dutch waters since the early 1900's.

The flat oyster has not been observed during the monitoring campaigns. This is as expected, as there is no natural population or flat oyster reef present that could have provided flat oyster larvae to the monitored cable crossings, which would in turn have had the time to develop into flat oysters visible through this type of monitoring.

4.1.2 Substrate type and size

The crossings with a calcareous-rich sprinkler layer showed higher species richness than the surrounding sand, but lower species richness than the crossings with a granite sprinkler layer. Although hypothesised to aid settlement of bivalves, [17], [22], this monitoring thus did not show any positive effects of the presence of calcareous material on settlement of species. These findings are in line with an increasing body of research to the main drivers of successful colonization of hard substrates by bivalves and other invertebrates offshore. As discussed, especially factors like stability [19], [56], [57], scale of available hard substrate [58], and habitat and surface complexity, with areas sheltered from high flow velocities (leesides) [17], are usually considered essential for the development of a biodiverse benthic community. So far, no positive effects of implementing calcareous substrates (e.g. shells) compared to granite have been observed in Dutch marine waters [11], [17].

In addition, the application of the sprinkler layer partially undermines the stability the armour layer could provide for species attempting to settle. Based on experience the small rocks of the sprinkler layer disperse in regular North Sea conditions, and especially in harsh weather and storms. Furthermore, these small, rolling rocks do not provide stable substrate for settlement of species [56], [57], as shown in Figures 3 and 4. In addition, small rocks cause abrasion of the larger rocks of the armour layer, and once dislocated away from the armour layer, suffer high levels of traction and abrasion (by sand) themselves, limiting species settlement [56], [57]. So, neither for the stability of the cable crossing, nor for the development of a biodiverse benthic community, a sprinkler layer (regardless of the specific substrate type) has any benefits.

4.1.3 Limitations pilot location

A limitation of the pilot is that the project is located in an area with dynamic conditions, suboptimal for reef development. Especially for the flat oyster, high sedimentation rates and strong hydrodynamic forces can impede the establishment and growth of reefs [59].

Additionally, high suspended sediment concentrations can lead to excess mortality among oysters, further hindering reef development [60]. However, the design characteristics of the crossings, including their elevation, reduce the most common challenges such as sedimentation and high turbidity near the seabed. A more favourable outcome may however be expected in areas with conditions that are less dynamic. Despite these potential limitations, the pilot provides a valuable indication of biodiversity on cable crossings, offering insights into the effects of substrate type and the potential risk of invasive species.

4.2 Bigger picture

4.2.1 Considerations cable crossing installation and maintenance

Offshore cable crossings in the North Sea create clusters of hard substrates in soft-sediment habitats. If located within the larval dispersion range of hard-substrate species already present in surrounding Natura 2000 areas with rocky reef habitats, or at the wind farms and shipwrecks, these cable crossings could function as ‘stepping stones' between these areas. Potentially, this could link ecologically important areas, or biodiversity hotspots, in the North Sea together, potentially also aiding the recovery of lost (flat oyster) reef habitats. Based on the expected larval dispersal rate of reef-forming and reef-associated species [21], [61], [62], cable crossings with the highest potential to provide suitable habitat within suitable range could be determined. As such, these cable crossings could be optimized and prioritized to enhance the chance of a benthic community developing.

Optimization of cable crossings should firstly focus on stability of the substrates and the creation of areas sheltered from highly dynamic conditions. This can be provided by removing the sprinkler layer, which provides opportunities for the settlement of species, without harming the integrity or stability of the cable crossing and thus without losing their primary function to protect the cable. Furthermore, removing the sprinkler layer reduces costs, shipping fuel and granite source material. Absence of fisheries with seabed-disturbing gear (mobile bottom-contact fisheries) further increases changes of survival of (starting) reefs.

In addition, as long as viable source populations of the flat oyster do not occur in vicinity of these crossings, flat oyster reef restoration at cable crossings requires active intervention. In the last few years, methods have been developed for seeding or outplacing adults and/or oyster larvae at appropriate locations for flat oyster restoration in the North Sea. For instance, in the protected areas Voordelta and Borkum Reef Ground, pilots have been conducted and planned with varying methods, including spat-on-shell and spat-on-rock (hard substrate pre-seeded with flat oyster larvae), and introduction of adult oysters [63], [64], [65], [66]. Opportunities in neighbouring countries, where cable crossings are not required to be over-fishable or where mobile bottom-contact fisheries are even prohibited in Natura 2000 areas (like in Germany) might further contribute to the stepping-stone effect between nature-inclusive crossings and existing reefs.

After installation, maintenance activities at cable crossings, typically occurring at intervals of approximately 10 years, may significantly impact reef development. These operations, particularly rock dumping, are likely to disrupt the established reef structures. Conversely, the natural development of reefs may enhance the stability of the rock layers over time, potentially reducing the need for frequent maintenance [67]. Alternative cable crossing designs, such as mattresses, may offer distinct advantages. Mattresses can be designed with reef-like structures and are inherently linked, enhancing mutual stability compared to unconnected stones [68]. However, in the shallow North Sea, mattresses are prone to displacement during storms, which could damage the assets they are intended to protect. In areas further offshore however, in more low-dynamic conditions, this might be considered.

5 Conclusion

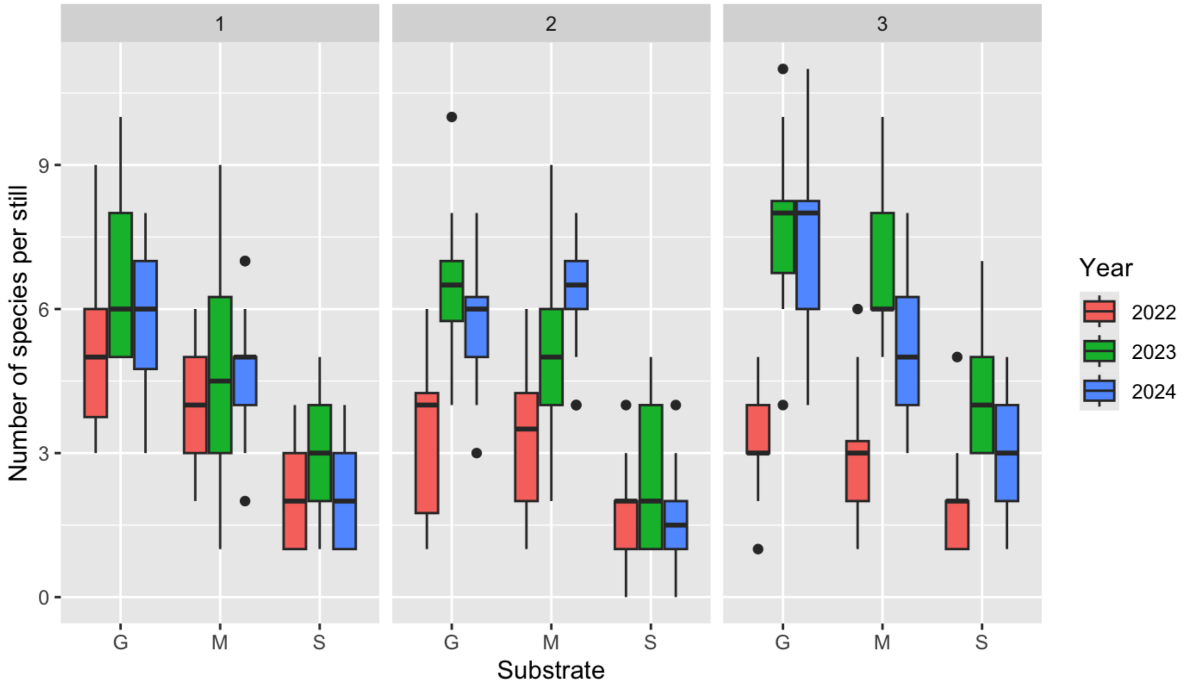
Cable crossings have the potential to be successful biodiversity hotspots due to the stability of the armour layer, elevation above the seabed and substantial size of the crossings. Calcareous rock does not seem to contribute to settlement of hard-substrate species, or biodiversity in general. The risk of invasive species on cable crossings appears minimal. The presence of the sprinkler layer does not contribute to reef development. It is suggested to explore the opportunities for active flat-oyster restoration (spat and/or adults) at cable crossings that are located in favourable abiotic conditions.

Supplementary materials

***Table S1* – Overview of species presence/absence using eDNA**

Scientific name	Common name	Year	Habitat	1M	1G	2M	2G	3M	3G
Pleuronectes platessa	Plaice	2022	benthic	Y		Y	Y	Y	Y
Clupea harengus	Atlantic herring	2022	pelagic	Y		Y	Y	Y	Y
Gasterosteus aculeatus	Three-spined stickleback	2022	pelagic	Y		N	N	N	N
Merlangius merlangus	Whiting	2022	benthic	Y		Y	Y	Y	Y
Platichthys flesus	Flounder	2022	benthic	Y		Y	Y	Y	Y
Pollachius pollachius	Pollock	2022	benthic	Y		Y	Y	Y	Y
Pollachius virens	Coalfish	2022	benthic	Y		Y	Y	Y	Y
Pomatoschistus minutus	Sand goby	2022	benthic	N		Y	N	N	Y
Sardina pilchardus	European pilchard	2022	pelagic	N		Y	N	Y	Y
Scomber scombrus	Atlantic mackerel	2022	pelagic	N		Y	N	N	N
Sprattus sprattus	European sprat	2022	pelagic	Y		Y	Y	Y	Y
Trachurus trachurus	Atlantic horse mackerel	2022	pelagic	Y		Y	Y	Y	Y
Ammodytes spec	Sandeel	2023	benthic	N	N	N	N	N	Y
Clupea harengus	Atlantic herring	2023	pelagic	Y	N	N	N	N	N
Clupea harengus and/or Sprattus sprattus	Herring and/or European sprat	2023	pelagic	N	Y	Y	N	Y	Y
Engraulis encrasicolus	European anchovy	2023	pelagic	N	Y	N	Y	Y	Y
Merlangius merlangus	Whiting	2023	benthic	Y	Y	Y	Y	Y	Y
Merlangius merlangus or Pollachius virens or Pollachius pollachius	Whiting, Saithe and/or Pollack	2023	benthic	N	N	N	N	N	Y
Pomatoschistus minutus	Sand goby	2023	benthic	Y	N	Y	N	Y	N
Scomber scombrus	Atlantic mackerel	2023	pelagic	N	N	N	N	N	Y
Sprattus sprattus	European sprat	2023	pelagic	N	N	N	N	Y	N
Trachurus trachurus	Atlantic horse mackerel	2023	pelagic	Y	Y	Y	Y	Y	Y
Trisopterus luscus	Pouting	2023	benthic	Y	Y	Y	Y	Y	Y
Clupea harengus	Atlantic herring	2024	pelagic	Y	Y	Y	Y	Y	Y
Gadus morhua	Atlantic cod	2024	benthic	N	N	N	N	N	Y
Gobius niger	Black goby	2024	benthic	N	N	N	N	N	Y
Hyperoplus lanceolatus	Great sand eel	2024	benthic	N	N	Y	N	N	Y
Limanda limanda	Common dab	2024	benthic	N	N	Y	N	N	Y
Limanda limanda or Hippoglossoides platessoides	Common dab or American plaice	2024	benthic	N	N	Y	N	N	Y
Merlangius merlangus	Whiting	2024	benthic	Y	Y	Y	N	N	Y
Myoxocephalus scorpius	Shorthorn sculpin	2024	benthic	N	N	N	N	N	Y
Pholis gunnellus	Rock gunnel	2024	benthic	N	N	N	N	N	Y
Platichthys flesus or Pleuronectes platessa	European flounder or European plaice	2024	benthic	N	Y	Y	Y	N	Y
Pleuronectes platessa	European plaice	2024	benthic	N	N	Y	N	N	Y
Pomatoschistus minutus	Sand goby	2024	benthic	N	N	Y	N	N	Y
Scomber scombrus	Atlantic mackerel	2024	pelagic	N	N	Y	N	N	Y
Sprattus sprattus	European sprat	2024	pelagic	Y	Y	Y	Y	Y	Y
Syngnathus rostellatus	Lesser pipefish	2024	benthic	N	N	N	N	N	Y
Trachinus draco	Greater weever	2024	benthic	N	N	N	Y	N	N
Trachurus trachurus	Atlantic horse mackerel	2024	pelagic	N	Y	Y	N	Y	Y

Trisopterus luscus	Pouting	2024	benthic	N	Y	Y	Y	Y	Y
Trisopterus minutus	Poor cod	2024	benthic	N	N	N	N	N	Y



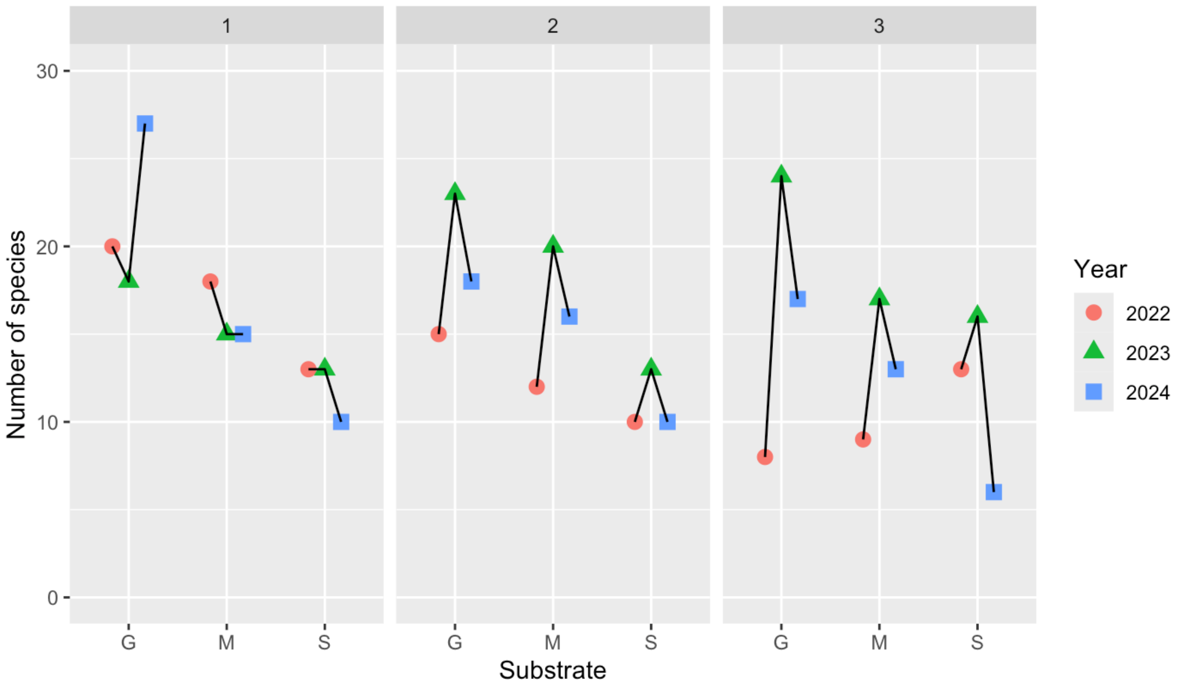


***Figure S1 -** (top) Number of different species counted per still, separated for substrate, location (1, 2, 3) and year. With n = 16 for each substrate at one location in one year. Horizontal line shows median, the box the range of values between Q1 and Q3, the whiskers Q1/Q3 -/+ 1.5 * IQR and the points are outliers, and (bottom) Total number of different species counted for a substrate, separated per location and per year. With n = 16 for each substrate at one location in one year. Black lines connect the years for the same substrate.*

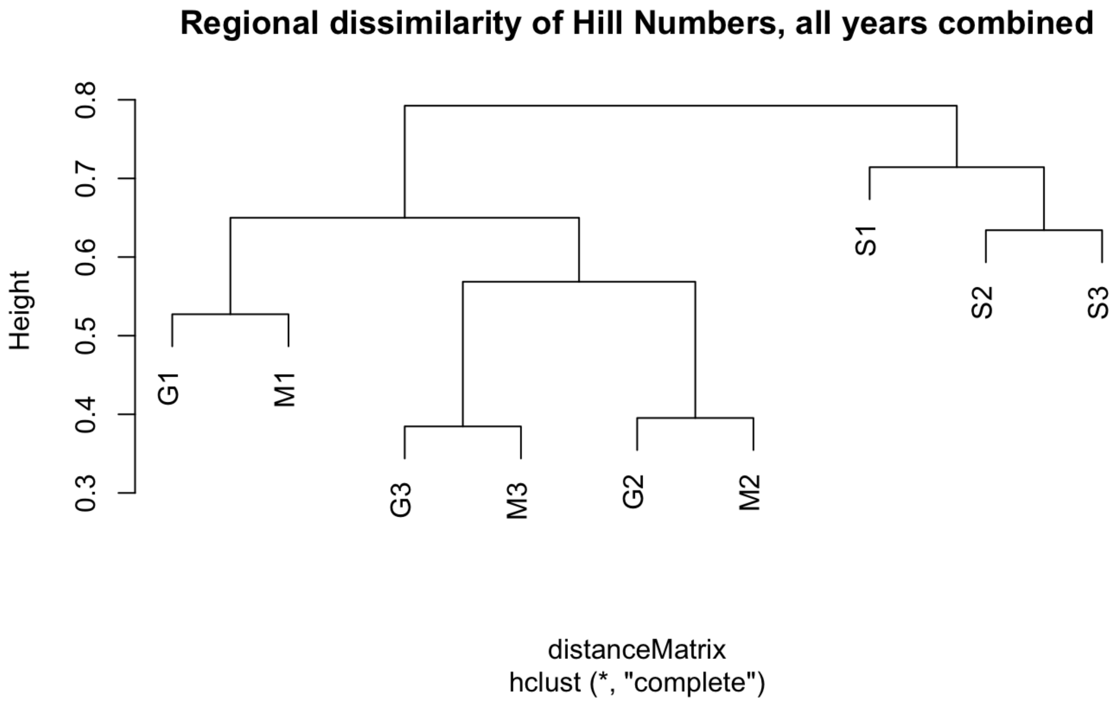


***Figure S2** - Dendrogram where the substrate-location combinations (all years combined) are clustered based on a distance matrix, calculated with the regional similarities of the Hill Numbers. For clustering the method 'complete' was used.*

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