Evaluating nature-inclusive design scour protection in offshore windfarms: Engineered Reef Unit Solutions (ERUS)

SPREE Project WP4 final report

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8. Coastruction
9. Reefy
10. Geowall

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Contents

Glossary

CPS	Cable Protection Systems
ERUS	Engineered Reef Unit Solutions
NID	Nature Inclusive Design
O&G	Oil and Gas
OWF	Offshore Wind Farm
SPL	Scour Protection Layer
TRL	Technology Readiness Level

1 Introduction

1.1 Nature inclusive design in offshore windfarms

Offshore windfarms (OWFs) play an important role in the ongoing energy transition towards more sustainable energy production. They can be located in morphodynamically active settings, which requires scour protection around foundations and assets, including Cable Protection Systems (CPS), subsea cables, and cable crossings, to mitigate seabed erosion. Currently, OWFs are often situated in sandy environments characterized by relatively low biodiversity. The addition of scour protection introduces hard substrate into these habitats, providing surfaces that can serve as habitat, shelter, refuge, and nursery grounds for a variety of marine species (Degraer, et al. 2020; Lengkeek, et al. 2017).

The potential for protection materials to enhance reef ecology is gaining attention among stakeholders and is increasingly reflected in regulatory requirements for new projects and tender procedures in The Netherlands (e.g. Hollandse Kust-West OWF[1], IJmuiden Ver[2]) and in a broader sense internationally as well: see for example *the offshore-wind-energy-roadmap-2030*[3]*, the EU State Aid Guidelines*[4]*, the Net Zero Industry Act promoting non-price criteria*[5]*, as well as the OCEaN's support for ecological criteria in offshore wind farm auctions*[6]*.* In the United States (US), although regulatory requirements do not include the incorporation of features that enhance reef ecology, permits incorporate language that generally requires that project materials introduced to the marine environment be designed not to deter marine growth. In the US, growing interest among stakeholders in Nature-Inclusive Design (NID) in association with offshore wind development is evident through the relatively recent creation of research consortium such as MOCEAN[7], workshops (e.g., Jedele et al. 2023), and white papers (e.g., Nature Conservancy, and Inspire Environmental[8]).

Recent research and NID guidelines substantiate this trend. In the context of offshore wind infrastructure, the term NID refers to "[…] options that can be integrated in or added to the design of an offshore wind infrastructure to create suitable habitat for native species (or communities) whose natural habitat […] been degraded or reduced. […] NID options can be part of […] a scour protection layer or a cable protection measure." (Hermans et al., 2020). To date, scour protection has seen mainly NID 'add-on' artificial reef elements being deployed. These elements are not an integral part of the actual protective infrastructure but rather constitute additional elements (e.g. fish cages or artificial reef blocks) that have been installed on top of or besides the necessary scour protection. To what extent such artificial reef units can function as an integral scour protection and with what ecological benefit, has not been conclusively studied to date. This gap has given rise to a new line of thinking: rather than adding ecological elements to existing designs, could protective infrastructure itself be engineered to deliver ecological value?

[1] Letter to Parliament Ministerial Order granting offshore energy permits sites VI VII Hollandse Kust west Wind Farm Zone.pdf
[2] Conceptregeling vergunningverlening windenergiegebied IJmuiden Ver kavel Alpha_0.pdf
[3] *offshore-wind-energy-roadmap-2030*
[4] *EU State Aid Guidelines*
[5] *the Net Zero Industry Act promoting non-price criteria*
[6] statement-on-ecological-criteria-in-owf.pdf
[7] https://mocean.us/
[8] https://www.nature.org/content/dam/tnc/nature/en/documents/TurbineReefs_Nature-BasedDesignsforOffshoreWind_FinalReport_Nov2021.pdf?hss_channel=fbp-1764596200510985

1.2 Engineered Reef Unit Solutions (ERUS)

Building on the growing interest in NID, it is increasingly recognised that infrastructure in OWFs can evolve into valuable ecological habitats. Conventional scour protection made of rock armour, for instance, has been shown to function as artificial reef, supporting diverse marine communities (Degraer et al., 2023; Lengkeek et al., 2017; Thomassen et al., 2025; Vivier et al., 2021). While this ecological role is largely incidental, it highlights the potential of intentionally integrating reef functions into the design of protective infrastructure.

The JIP-SPREE project (Chapter 1.3) takes this concept further with the development of Engineered Reef Unit Solutions (ERUS), a specialised sub-category of NIDs. ERUS are prefabricated units, typically made from specially designed concrete mixes, that serve a dual purpose: providing scour protection while simultaneously enhancing ecological value. Unlike conventional rock armour or add-on elements, ERUS are conceived as integral parts of the scour protection itself. Their engineered properties, such as porosity, surface roughness, opening sizes, and material composition, can be customised to support colonisation, habitat complexity, and biodiversity gains, while maintaining their role in protecting against physical scour.

Examples of ERUS include modular structures and other purpose-built units designed to balance structural stability with ecological function (Figure 1). Furthermore, the ability to fabricate these units presents an advantage in situations where loose rock is scarce. To support the development of these ecosystem-enhancing solutions, industry stakeholders are keen to explore whether ERUS can serve as effective protection systems for OWFs.

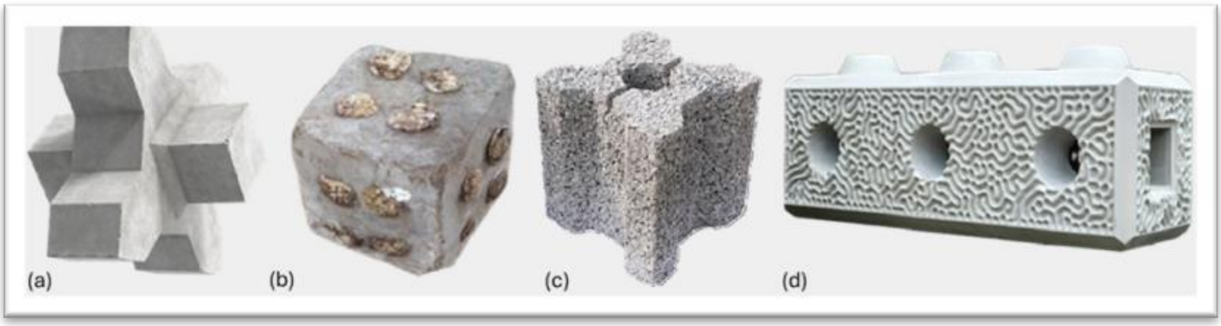


Figure 1. ERUS designs of participating partners from left to right; (a) BAM, (b) Geowall, (c) Holcim, (d) Reefy. The ERUS designs have a dimension ratio of 1H:1V:1L, except Reefy which has a ratio 1H:1V:3L. The ERUS sizes can vary, length (height or width for cubes) may range between 0,2 – 0,5 m. (Source: BAM, Geowall, Holcim, Reefy)

1.3 SPREE project

The **Joint-Industry Project SPREE (Scour Protection for Ecological Enhancement)**[9] is a collaborative research initiative aimed at advancing nature-inclusive design (NID) solutions for offshore wind farm (OWF) infrastructure. The JIP-SPREE ran from March 2024 to October 2025, and brought together a consortium of twelve industry and research partners, including: BAM, Boskalis, Coastruction, Deltares, Geowall, Holcim, INSPIRE Environmental (Venterra Group), Reefy, RWE, TenneT, Vattenfall and Wageningen Marine Research. This was done to investigate the technical and ecological potential of **Engineered Reef Unit Solutions (ERUS)** as alternatives to conventional scour protection methods from armour rock. The project explored how ERUS can serve not only as protective structures for monopile foundations, cable crossings, and cable protection systems (CPS), but also enhance ecosystem functions for marine life. Through lab-based physical testing, a life cycle assessment, and ecological evaluations, JIP-SPREE assessed ERUS' hydraulic stability, installation feasibility, production sustainability and NID performance for case studies in the North Sea and the US East Coast/western North Atlantic. The knowledge generated through this research will contribute to raising the Technology Readiness Level (TRL) of ERUS and provide valuable guidance for innovators, contractors, developers, planners, and regulators[11].

[9] Testing innovations to enhance nature-inclusive design of offshore wind farms | Deltares

The project consists of four work packages:

Work Package 1: The consortium partners conducted a desk assessment of installation feasibility using existing technologies. This process involved largely the evaluation based on industry experts and their knowledge of different vessel types and installation technologies. As a result, installation with fall-pipe vessels was deemed the best at this point in time. The project scope did not include assessment of installation technology developments. In addition, the work package included physical testing of scale model ERUS in the Deltares wave and flow facilities[10] to evaluate their falling behaviour.

Work Package 2: The main focus of this work package was to test the hydraulic stability of ERUS by conducting scale model tests in the Deltares wave and flow facilities. In total three different test campaigns were conducted evaluating the deformation effect of ERUS in comparison with conventional armour rock. The tests were conducted for scour protection, CPS and cable crossings. The hydrodynamic conditions were defined for representative 50- and 100-year return period storm conditions in the North Sea and western North Atlantic. The results of the work show the feasibility of creating armour layers entirely from ERUS. The recommendations in terms of layout extent and complexity of these structures provided the basis for Work Package 3 and Work Package 4.

Work Package 3: An illustrative ERUS unit that defined based on some averaged parameters of tested ERUS units (WP1 & WP2) was defined in order to conduct a life cycle assessment (LCA) of these units in comparison to armour rock. The LCA was conducted for an idealized case studies in the North Sea and western North Atlantic. The method used for the LCA was the Milieukostenindicator (MKI) to assess environmental impact costs of the illustrative ERUS and conventional armour rock. The results provided insights into the drivers of environmental impact as well as highlighting the contextual sensitivities that inform the comparability of LCAs for different scour protection materials.

Work Package 4: A desk review was conducted using the latest scientific literature on artificial reef impacts, alongside key regulatory frameworks for offshore wind infrastructure in the Dutch North Sea and the western North Atlantic. This review informed the development of evaluation criteria used to compare the potential of conventional armour rock and ERUS to contribute to ecosystem enhancement objectives. Using design features recommended in WP2 for ERUS and rock as armour layers, the provision of specific ecosystem services was assessed for target taxonomic groups in both regions. This allowed for evaluation of the ecological effects of specific design elements and the development of additional recommendations for armour layer design from an ecological perspective. Furthermore, the consortium partners organized a stakeholder workshop to identify ecological considerations relevant for policy discussions on decommissioning, including the extent to which different aspects should be evaluated for both ERUS and conventional rock armour. At present, the prevailing approach focuses mostly on full removal of artificial structures (including NIDs/ERUS) once they reach the end of their operational lifetime. However, because these structures can also contribute to biodiversity enhancement and habitat restoration in certain areas, complete removal may reverse ecological gains. Stakeholders emphasized that long-term ecological monitoring is essential to inform future decommissioning decisions and to balance environmental, technical, and policy objectives. Therefore, several potential monitoring strategies are outlined.

1.3.1 This report

This report (Work Package 4) forms part of the JIP-SPREE focusing on the ecological benefits and biodiversity potential of ERUS in comparison with conventional/traditional armour rock solutions. In particular, it examines the capacity of ERUS to support the protection and restoration of marine biodiversity around offshore wind farms, drawing on environmental reference sites in the Dutch North Sea and western North Atlantic along the U.S. East Coast and aligning with existing policy and assessment frameworks.

Through a literature review, NID Requirements for these locations were identified that can both enhance ecosystem functions and mitigate potential ecological risks. On the basis of these requirements, the JIP-SPREE partners developed a qualitative evaluation framework. Applying this framework in consultation with marine

[10] https://www.deltares.nl/en/research-facilities/wave-and-flow-facilities/scheldt-flume

ecology experts, the NID design parameters of conventional armour rock and ERUS were compared in terms of their ecosystem enhancement effects for key taxonomic groups. In collaboration with stakeholders, recommendations were also developed for decommissioning strategies tailored to ERUS. Finally, in response to strong industry interest, the report addresses multiple potential offshore monitoring strategies that can serve as a foundation for future in-field pilot studies deploying ERUS.

The report is structured into five main chapters, followed by a concluding overall chapter containing recommendations about ERUS deployment. After an overview of general methodologies (Chapter 2), each chapter addresses a specific topic related to ERUS with the aim to be able to provide an evaluation of the ecological enhancement potential of ERUS in comparison to conventional armour rock at the selected OWF reference sites.

- Chapter 3: Introduces the reference sites (OWF development sites in the Dutch North Sea and along the U.S. East Coast Atlantic) for this report.
- Chapter 4: Presents a desk study of location-specific NID requirements and ecological objectives, synthesizing the criteria applicable to OWF protection structures for the reference sites.
- Chapter 5: Evaluates the ecological enhancement potential of ERUS versus conventional armour rock.
- Chapter 6: Provides recommendations on decommissioning strategies, addressing ecological and regulatory considerations relevant to ERUS.
- Chapter 7: Elaborates on ecological monitoring approaches for offshore structures that can be used in future ERUS pilots.

1.3.2 Purpose and research questions

The aim of this report is to provide insight in the use of ERUS[11] as a NID option in offshore wind to enhance biodiversity. The research questions are:

- What are environmental and regulatory requirements for ERUS as a nature inclusive design options in offshore wind farms?
- What are the ecological benefits and biodiversity potential of ERUS in comparison with traditional solutions?
- What are the best practices for decommissioning of ERUS?
- Which monitoring methods are available to assess the performance?

[11] ERUS are also known as ecological scour protection, eco-engineered scour protection, nature-inclusive scour protection, eco-adaptive scour protection, eco-scour structures and several other similar terms.

2 Methodologies

2.1 Selection of case study areas

Two case study locations were identified as idealized cases for the JIP-SPREE project: the North Sea (with a focus on the Dutch sector) and the U.S. East Coast Atlantic (with a focus on the southern New England Wind Energy Area). These regions were selected as both are frontrunners in offshore wind energy development, but they differ in their physical settings, development histories, and ecological contexts. Understanding the boundary conditions of these regions is crucial for setting requirements for NID elements and for shaping monitoring and management strategies. Background information on the development of OWF in these regions is provided in Chapter 3.

2.2 Literature review and regulatory requirements on NID

The review in Chapter 4 on 'Regulatory requirements on NIDs' was conducted by searching for relevant scientific publications using Web of Science and Google Scholar, and identifying relevant grey literature items (i.e. reports and theses). The following keywords were used: "armour rock", "scour protection", "offshore construction", "biodiversity", "scour material", and "nature-inclusive design". Moreover, the literature review identified exemplary policy and regulatory documents for specific OWF to identify existing requirements for on-going tenders and OWF developments with regards to their impact on marine ecosystems. Lastly, the review included a search of ecosystem specific target species for the Dutch North Sea and western North Atlantic, as these were the representative locations used as case studies across the JIP-SPREE project.

2.3 Expert interviews on ecological performance

On the basis of the requirements and ecological objectives identified through the literature review in Chapter 4, the JIP-SPREE partners developed a qualitative framework to evaluate the performance of design features in promoting particular ecological functions. Applying this framework in consultation with marine ecology experts, the NID design parameters of conventional armour rock and ERUS were compared in terms of their ecosystem enhancement effects for key taxonomic groups relevant in the Dutch North Sea and the western North Atlantic. To this end interviews were conducted with experts to gather insights into the specific ecosystem functions that essential ERUS and rock armour design parameters contribute towards across various marine taxonomic groups. Further details of the methodology and results are provided in Chapter 5.

2.4 Literature review and workshop on decommissioning

Chapter 6 elaborates on the growing importance of decommissioning as more and more offshore installations in the southern North Sea reach the end of their operational phase. This process involves not only technical and logistical challenges but also broader environmental and societal considerations, shaped by complex policy and legislative frameworks. A desk study was performed to gain an understanding of the different decommissioning strategies that exist (from full removal to reefing and alternative uses) with each carrying different ecological trade-offs. In addition, a workshop was organized to gain input on decommissioning perspectives from different stakeholders within this field. See Chapter 6 for further details on the methodology.

2.5 Literature review and evaluation of offshore monitoring parameters and methodologies

Chapter 7 presents an overview of offshore monitoring parameters and methodologies that could be applied in future pilot projects involving ERUS. The chapter synthesizes relevant indicators and approaches drawn from previous *in situ* ecological monitoring studies conducted in OWFs and assesses their applicability to new research to monitor the ecological performance of ERUS.

3 Case study reference sites

In this chapter two case study OWF locations are introduced where ERUS can be deployed as an ecosystem enhancing solution. The case studies form the basis for this report.

3.1 Offshore wind energy development in Europe: North Sea

3.1.1 Historical development

The commissioning of the world's first OWF in 1991 at Vindeby, Denmark (5 MW)[12] marked the start of a new beginning in renewable energy development. At the time, the idea of generating electricity from wind turbines placed in the open sea was met with skepticism, largely due to concerns about costs, technical feasibility, and exposure to harsh marine conditions. However, the successful operation of Vindeby demonstrated both the reliability and potential of offshore wind power. Its success generated wider interest, particularly across Europe's North Sea region, where a unique combination of shallow continental shelf waters, strong and steady wind resources, and proximity to large energy markets created favorable conditions for large-scale deployment.

3.1.2 Growth and current status

From the early 2000s onwards, North Sea countries such as the United Kingdom, Germany, and the Netherlands rapidly expanded offshore wind capacity, driven by technological improvements, climate commitments, and government incentives. By 2023, the North Sea hosted some of the world's largest wind farms, often exceeding 1 GW in individual capacity. By 2022, Europe had a cumulative offshore wind farm capacity of 30 GW from which a substantial proportion was situated within the North Sea region (Costanzo & Brindley, 2023). This is expected to increase significantly in the coming years. EU targets outlined in the climate neutrality goals in the European Green Deal (2019)[13] set an increase to 450 GW of offshore wind capacity by 2050, with the North Sea accounting for approximately 47% of this figure (Akhtar et al., 2021; Freeman et al., 2019).

[12] https://orsted.com/en/what-we-do/insights/white-papers/making-green-energy-affordable/1991-to-2001-the-first-offshore-wind-farms
[13] https://www.eea.europa.eu/policy-documents/com-2019-640-final

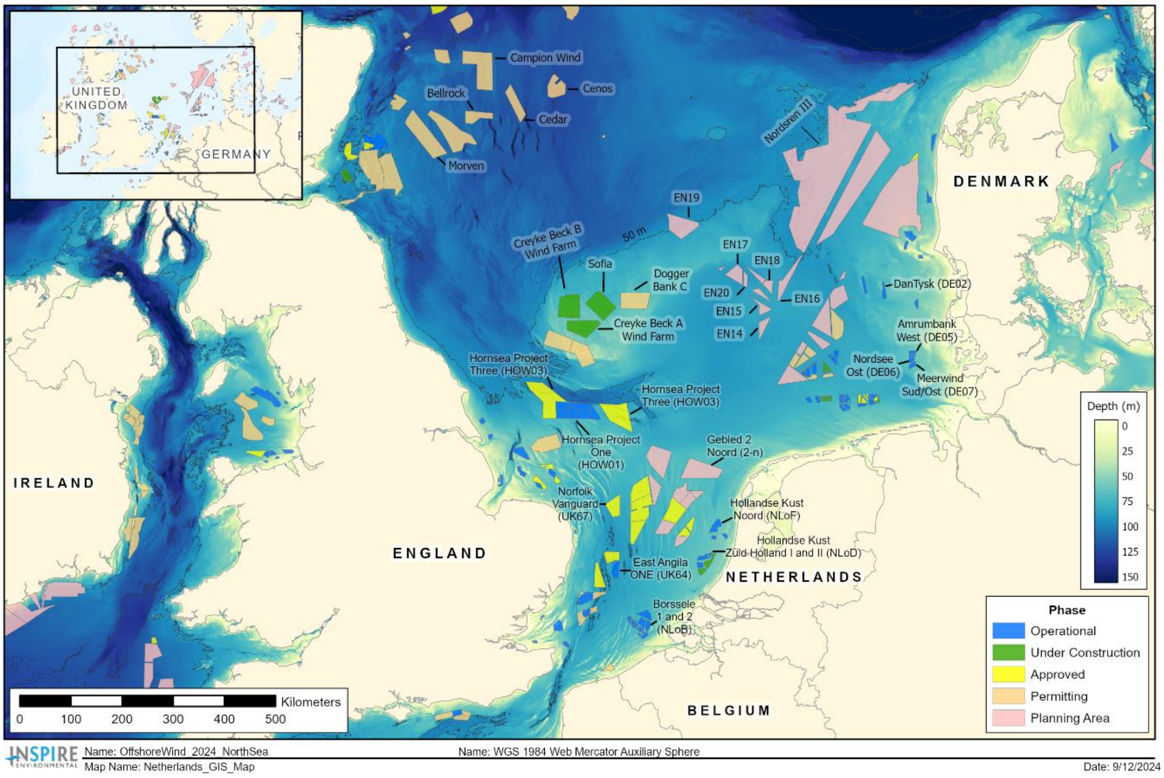


Figure 2. Offshore wind farms within the North Sea (operational, under construction, approved, and undergoing permitting, as well as future planning areas) as of September 2024 (4C Offshore, 2024[14]).

3.1.3 Geology and sediment composition

The seabed characteristics of the North Sea show considerable spatial variation, reflecting its complex geological history and hydrodynamic conditions. In the northern sector, particularly along the Norwegian coast, the seafloor is generally deeper and dominated by rocky substrates, gravel beds, and glacial deposits, which create a heterogeneous benthic landscape. These hard-bottom environments support distinct biological communities and present challenges for turbine installation, often requiring specialized foundation types such as floating platforms or drilled monopiles.

In contrast, the southern and central North Sea, extending toward the coasts of the Netherlands, Germany, and the United Kingdom, is characterized by shallow waters and more uniform sandy and muddy sediments shaped by strong tidal and wave dynamics. This softer seabed has been more suitable for fixed-bottom foundations (e.g., monopiles, jackets, gravity-based structures).

The variation in substrate and depth not only dictates the engineering solutions for offshore wind development but also plays a crucial role in shaping the ecological interactions between turbine infrastructure and benthic ecosystems. As a result, understanding the regional seabed conditions is important for both technical feasibility assessments and environmental impact evaluations.

[14] https://map.4coffshore.com/offshorewind/?_gl=1*pfczjd*_gcl_au*MTY5NDI4MzQyLjE3NjA5ODk2MzY.

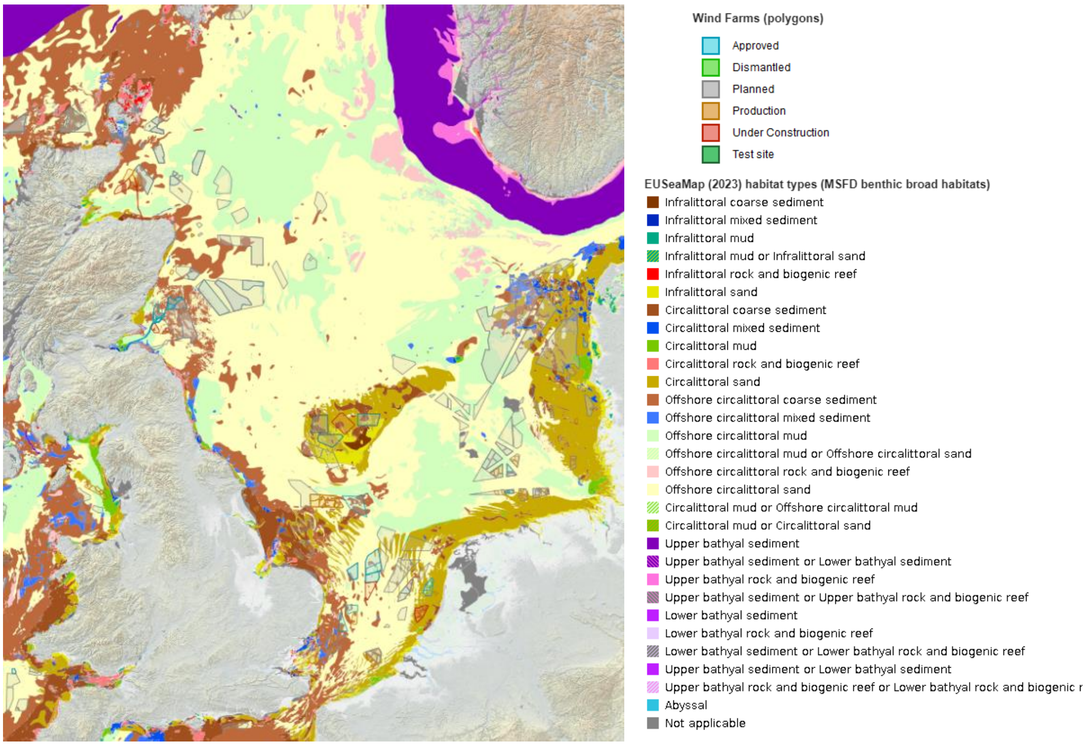


Figure 3. Seabed characteristics and offshore wind farms (approved, dismanteled, planned, production, under construction, test site) within the North Sea basin. (*Source: EMODnet*[15])

3.1.4 The Dutch North Sea

The Dutch sector of the North Sea has emerged as a focal point for offshore wind energy development in Europe. By 2023, ten active windfarms were set in place which accounted for 4,747.5 MW of operational capacity, distributed across several large-scale wind farms (e.g., Hollandse Kust Noord 759 MW, Hollandse Kust Zuid 1,529 MW, and the Borssele cluster) (Table 1)[16].

Under the Climate Agreement, offshore wind capacity is planned to increase significantly in the Dutch North Sea to 21 GW by 2032/2033[17].

Table 1. Overview of operational offshore windfarms in the Dutch North Sea (*Source: RVO*[18]).

Wind farm	Number of wind turbines	Capacity per wind turbine (in MW)	Capacity wind farm (in MW)	In use since
Hollandse Kust Noord	*69*	*11*	*759*	*2023*
Hollandse Kust Zuid	*139*	*11*	*1529*	*2023*
Borssele V (innovation site)	*2*	*9.5*	*19*	*2021*
Borssele I and II	*94*	*8*	*752*	*2020*
Borssele III and IV	*77*	*9.5*	*731.5*	*2020*
Gemini Wind Farm	*150*	*4*	*600*	*2016*
Luchterduinen	*43*	*3*	*129*	*2015*
Prinses Amalia Wind Farm	*60*	*2*	*120*	*2008*
Egmond aan Zee	*36*	*3*	*108*	*2007*

[15] *https://emodnet.ec.europa.eu/geoviewer/*
[16] *https://english.rvo.nl/topics/offshore-wind-energy/operational-wind-farms*
[17] https://noordzeeloket.nl/en/functions-use/offshore-wind-energy/energy-transition-north-sea/
[18] *https://english.rvo.nl/topics/offshore-wind-energy/operational-wind-farms*

3.2 Offshore wind energy development in the United States: East Coast Atlantic

3.2.1 Historical development and planning framework

Offshore wind development in the United States is nascent compared with the industry in Europe. Over the past decade, the US offshore wind industry has grown rapidly since the Block Island Wind Farm[19] was installed in 2016, which was the first commercial-scale project in the United States. Although the Block Island Wind Farm, located in Rhode Island state waters, is relatively small, consisting of five jacket foundations totaling 30 MW of energy, it demonstrated technical feasibility for larger-scale deployment in the Southern New England region.

In federal waters, the Bureau of Ocean Energy Management (BOEM) oversees the OWF development process. Broad Wind Energy Areas (WEAs) are initially designated through stakeholder engagement, environmental review, and spatial modelling. Wind Energy Areas are then organized into individual lease areas[20], which are auctioned to private developers. Leaseholders must conduct detailed site investigation surveys to support the development of permit applications for construction and operations of the individual wind project. This permitting proces[21]s, which typically extends five or more years, includes detailed data collection and impact assessments that balance renewable energy expansion with ecological and community concerns (Guarinello & Carey, 2022).

The U.S. has set ambitious federal goals: 30 GW of offshore wind by 2030 and over 100 GW by 2050 (DOE, 2023). However, challenges in the supply chain, increasing costs for materials, and more recently stalls in federal permitting pipelines resulting from changes in administration priorities have resulted in a low probability of reaching this initial goal. Market assessments in 2024 predicted that up to 14 GW of offshore wind capacity could be deployed by 2030, and expanded to 30 GW and 40 GW by 2033 and 2035 respectively (American Clean Power Association (ACP) 2024[22]). However, recent developments in 2025 by the federal government have led to delays and risks to even the projects that had previously obtained federal permits.

3.2.2 Growth and current status

As of early 2024, the U.S. offshore wind sector spans a growing number of lease areas, auctioned from the Gulf of Maine down to South Carolina (Figure 4). These sites are in various phases of development, from early desktop assessments and environmental surveys to projects that are operational. Several regional clusters are emerging as focal points (Table 2). Together, these clusters illustrate how U.S. offshore wind is transitioning from small pilot projects to an important offshore wind contributor.

Most current and active U.S. offshore wind lease areas are on the Atlantic coast in water depths of 30–60 meters, suitable for monopile and jacket foundations. Block Island Wind Farm showed the use of jackets in shallow, rocky seabeds (Guarinello & Carey, 2022). Coastal Virginia Offshore Wind Research Array (CVOW-r) was completed in 2020 and consists of two monopiles where environmental and engineering research projects are ongoing under the BOEM funded RODEO program[23]. South Fork Wind Farm, the first commercial-scale project completed in federal waters was completed in 2024 and included 12 monopile foundations and is located approximately 16 nautical miles southeast of Block Island in an area with heterogeneous seabed composed of regions of sands, small gravels, and patchy cobbles and boulders (INSPIRE Environmental, 2020).

There are currently four large-scale wind farms actively under construction off the U.S., east coast: Vineyard Wind, Revolution Wind, Sunrise Wind, Empire Wind, and CVOW-c. Vineyard Wind, Revolution Wind, and Sunrise Wind are located in the Southern New England region (RI-MA wind energy area); Empire Wind is located in the NY Bight; and CVOW-c is off the coast of Virginia in the Mid-Atlantic. An additional

19 https://us.orsted.com/renewable-energy-solutions/offshore-wind/block-island-wind-farm
20 https://coastalscience.noaa.gov/science-areas/offshore-wind-energy/spatial-planning/
21 https://www.boem.gov/renewable-energy/regulatory-framework-and-guidelines
22 https://cleanpower.org/resources/market-report-2024/
23 https://www.boem.gov/renewable-energy/studies/rodeo

All other wind farms proposed, permitted, and/or being constructed currently on the U.S. east coast will utilize monopile foundations. Future growth in the U.S. offshore wind industry in regions such as the Gulf of Maine and off the West Coast (Pacific Ocean) will utilize floating foundations, enabling development in these more deeper water regions.

Table 2. Overview of operational OWFs and OWFs currently in construction phase in the Western North Atlantic (US East Coast Offshore Renewable Activities | Bureau of Ocean Energy Management[24]).

Wind farm	# of turbines	Capacity /turbine (in MW)	Capacity OWF (in MW)	In use since/planned for	Notes
Block Island Wind Farm	5	6	30	In use since 2016	Rhode Island Sound: five jacket foundations installed in RI-state waters off the shores of Block Island
South Fork Wind	12	11	132	In use since 2023	Southern New England (RI-MA wind energy area): This area has become the cradle of U.S. offshore wind, hosting flagship projects, which are among the first large-scale developments in federal waters
Vineyard Wind	62	13	806	Expected 2026	Rhode Island, MA: This area has become the cradle of U.S. offshore wind, hosting flagship projects which are among the first large-scale developments in federal waters
Revolution Wind	65	11	704	Expected 2026	
Sunrise Wind	95	11	924	Expected 2027	
Empire Wind (Phase 1)	54	15	810	Expected 2026	New York Bight: east of New York and New Jersey, this area is set to become a major hub with projects serving one of the country's largest electricity markets
CVOW-research	2	6	14.7	In use since 2020	Mid-Atlantic: Pilot-scale research array
Coastal Virginia Offshore Wind (CVOW-commercial)	176	14.7	2,587	Expected 2026	Mid-Atlantic: Lease areas offshore New Jersey, Delaware, and Virginia are advancing planning and permitting for large-scale deployment potential

[24] https://www.boem.gov/renewable-energy/offshore-renewable-activities

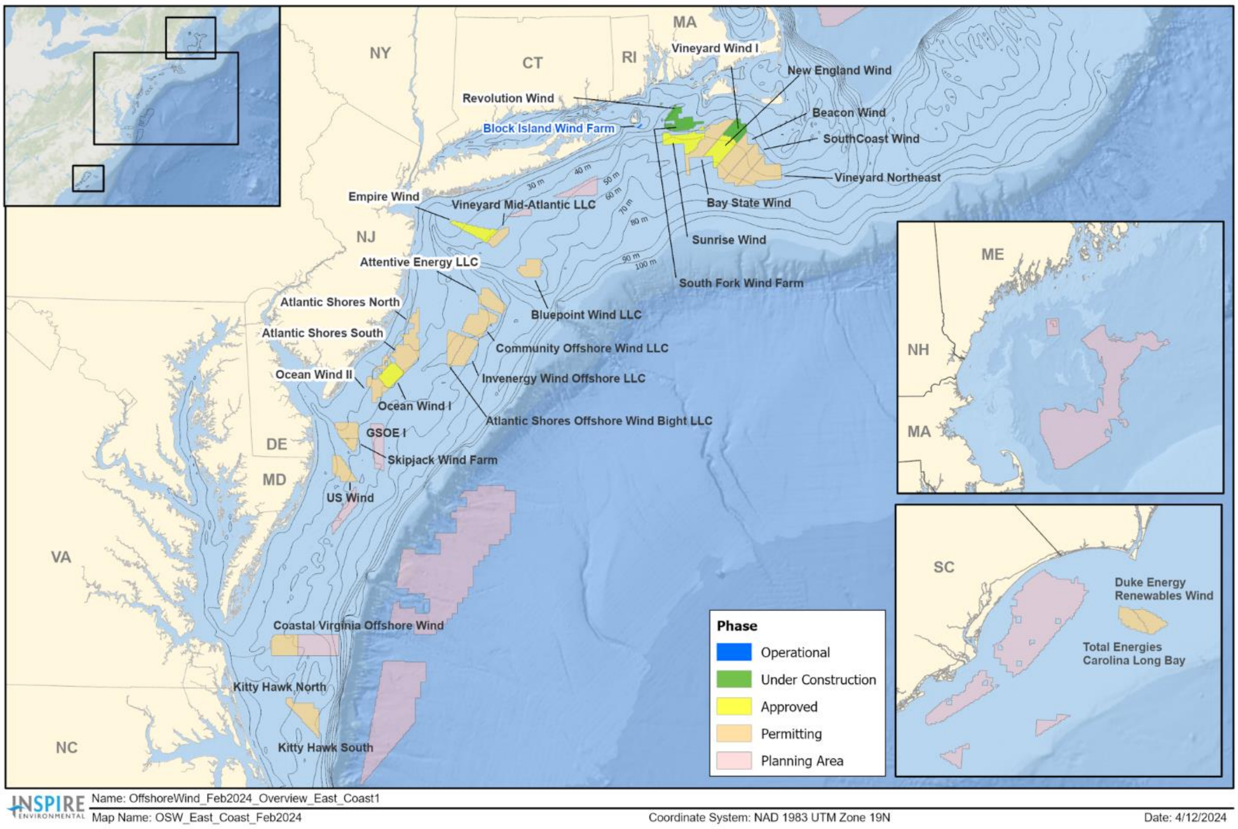


Figure 4. Offshore wind farms along the U.S. East Coast Atlantic (operational, under construction, approved, and permitting) as of April 2024 (4C Offshore, 2024).

3.2.3 Geology and sediment composition

The U.S. East Coast outer continental shelf is generally characterized by sandy seabeds, interspersed with gravelly patches and occasional rocky reefs. The Southern New England leases, within the RI-MA wind energy area, feature a mix of sands and gravels (pebbles to boulders in size), often in areas of ecological and fisheries importance. The New York Bight is dominated by sandy substrates but also includes major features such as the Hudson Canyon, an ecologically valuable submarine canyon avoided during lease siting. Mid-Atlantic areas (NJ/DE/VA) are characterized by broad sand ridges, whose topography influences benthic food availability.

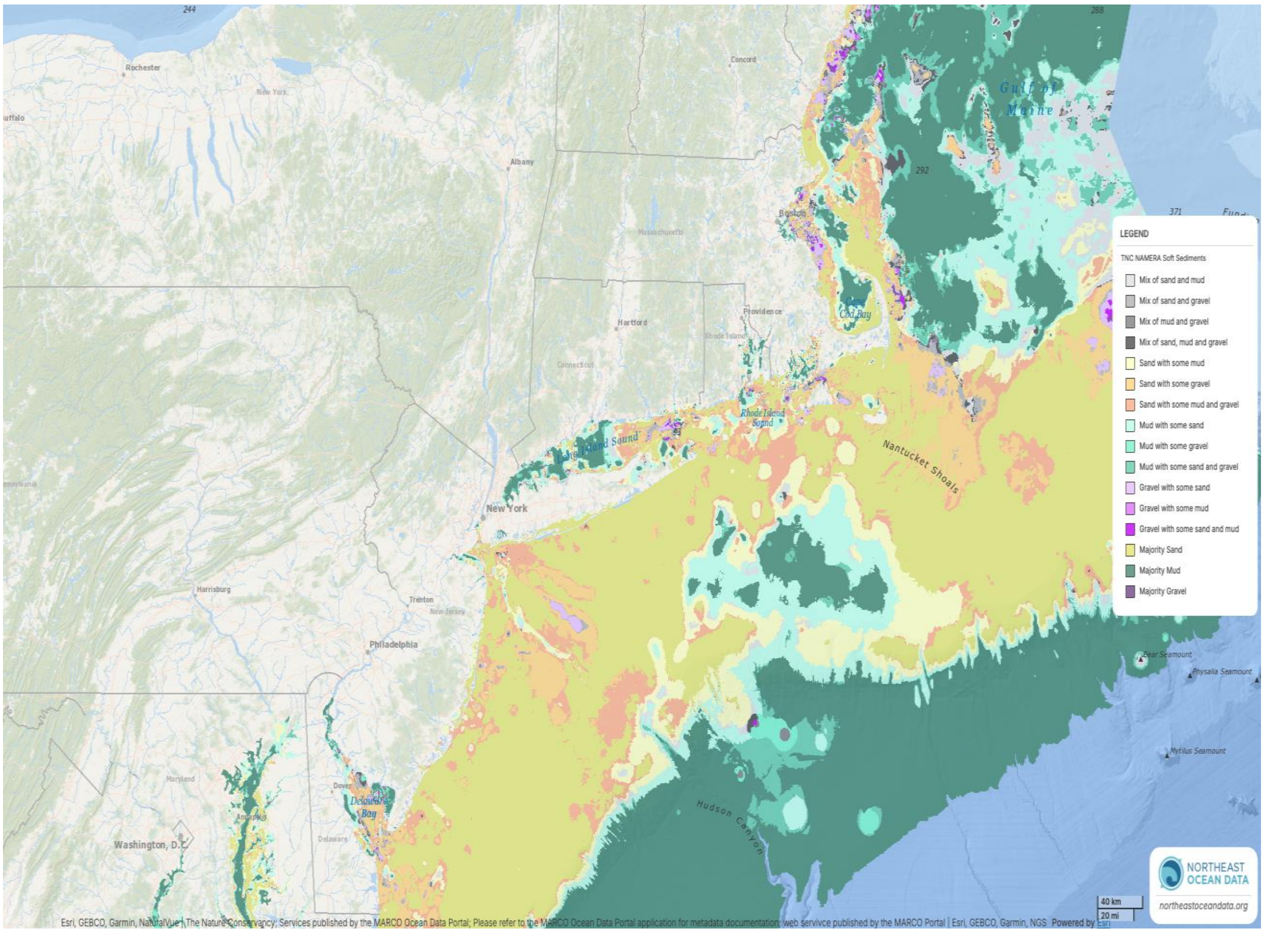


Figure 5. Broad *seabed characteristics off the U.S. northeast coast (TNC 2010*[25]*)*.

3.3 Comparison and relevance for ERUS

Both the North Sea and the U.S. East Coast provide valuable reference contexts for ERUS development. It should be noted however, that for context the U.S. East Coast is much larger compared to the (Dutch) North Sea. The North Sea represents a mature offshore wind region, with large-scale farms, diverse foundation types, and extensive ecological data availability. The U.S. East Coast, while less developed, offers an important comparison as a rapidly growing frontier, with different sedimentary and ecological conditions and a unique planning framework.

For ERUS, these two regions illustrate contrasting but complementary boundary conditions:

- North Sea: shallow waters, mature industry, strong monitoring and regulatory frameworks, sandy and rocky habitats.
- U.S. East Coast: younger industry, broader depth ranges, predominance of sandy substrates, and significant ecological features such as canyons and sand ridges.

Together, they form robust environmental baselines for evaluating how ERUS can enhance biodiversity across different offshore wind contexts.

[25] https://purl.stanford.edu/nn914kj6380

4 NIDs: design possibilities, regulatory requirements and ecological objectives

Because limited information, regulation, and guidance exist on the use of ERUS specifically within scour protection, this chapter outlines the NID requirements and ecological targets relevant to scour protection around monopile foundations and cable crossings. It begins with an inventory of existing knowledge on scour protection layers and their influence on biodiversity, followed by an assessment of regulatory requirements and the objectives of developers and ERUS providers.

4.1 OWF scour protection and their potential to enhance biodiversity

Scour protection involves placing materials, like rock armour, around offshore structures (both offshore platforms and cable crossings) to prevent erosion of the seabed around the structures from hydrodynamic forces. Most commonly, these structures are circular or elliptical rock berms around a foundation (usually a steel monopile or jacket) that includes a filter layer of smaller rocks to prevent soil migration and an armour layer of larger rocks to resist hydrodynamic forces (Figure 5). Based on maximum expected scour depth, the extent of the scour protection is estimated. Based on industry knowledge and experience of project partners it was suggested that the extent usually results somewhere around 1.3 times the diameter of the pile in the North Sea, while in the northwest Atlantic the diameter of scour protection material and monopile is typically up to 3 times the diameter of the foundation alone. They also suggested that the installed rock is graded, i.e. includes different sizes of rock, which is determined based on hydraulic stability for a particular site. In the North Sea rock gradings of 10-60kg is common while in the US the grading would be larger 40-200kg due to the local hydrodynamic conditions.

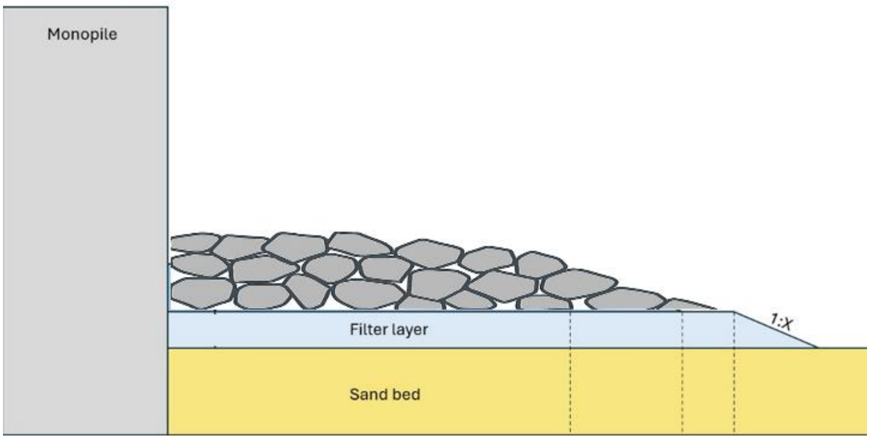


Figure 6. Schematic representation of a conventional scour protection layer for a monopile (MP) foundation.

Scour protection for cable crossings, and specifically the secondary cable protection systems, are required when a newly installed cable crosses an existing cable or pipeline to prevent interface between the assets. At a cable crossing location the cable protrudes out of the seabed and is covered with rock to protect it from damage from e.g. fishing or anchoring activities. Similarly, at a location where target cable burial depth is not possible due to natural hard habitat in the region, secondary cable protection is required. In the North Sea, the crossings are traditionally covered with granite rock, with a rock graded armour layer on top of which a sprinkle layer is added to ensure that the crossing is overfishable (Figure 7). In the US, a combination of loose rock with cable mattress systems are used for secondary cable protection at both cable crossings and naturally rocky habitats where cable burial depth is not achieved (see details in the Construction and Operation Plans for individual projects). Allowing for fishing access, including physically trawling over cable protection areas, is also an important consideration and requirement for U.S. projects.

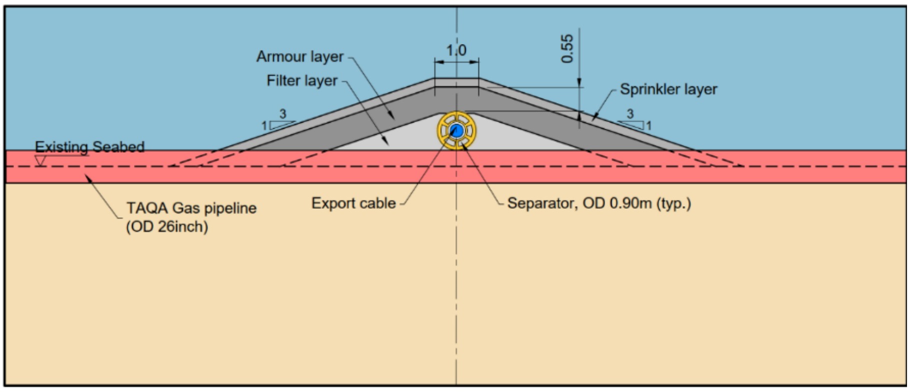


Figure 7. Schematic representation of a traditional pipeline crossing design (Source: TenneT).

Although, initially scour protection material was installed only for technical reasons, it is continuously receiving more attention regarding its apparent ecological value. Scour protection layers (SPLs) can provide both physical refuge for species and food provisioning. SPLs can be enhanced by the bio-deposition products of organisms that are attached to the turbine foundations, and they are a place where a significant amount of organic matter is accumulated (Coates et al. 2014). Because of this and the increased physical complexity of the structures, more organisms are attracted to them, and more food becomes available for mobile and sessile species in comparison to predominantly featureless sand-dominated habitats. Indeed, scour protection layers of offshore wind farms can host complex food webs, where species can exploit a variety of food sources (Mavraki et al., 2020).

Scour protection and other artificial reefs may be designed to incorporate ecological principles and enhance marine life. Research indicates these materials can enhance local biodiversity by providing habitats for various marine species (Coolen et al., 2020; Glarou et al. 2020; Mavraki et al., 2020, Buyse et al., 2022, 2023; Kingma et al., 2024, Zupan et al., 2024) (Figure 8). Furthermore, these structures provide food, and shelter against currents and predators for both sessile and mobile species (Petersen & Malm, 2006; Reubens et al., 2011; Langhamer, 2012; Liversage & Chapman, 2018; Mavraki et al., 2020; ter Hofstede et al., 2022), leading to higher densities of a variety of organisms (Bouma & Lengkeek, 2008; Couperus et al., 2010). The SPLs offer hard substrate that can form biodiversity hotspots in otherwise mostly sandy environments. Therefore, safeguarding the biodiversity of SPLs is of great importance to maintain or enhance the ecosystem functioning. Future designs should be optimized to enhance the benefits that SPLs offer and make them serve as tools for enhancing nature conservation efforts (Kingma et al., 2024; Zupan et al., 2024).
Similarly, secondary cable protection systems at cable crossings and where sufficient burial depth is not achieved provide hard substrate, sufficient size and elevation from the seabed (roughly 100 meters in length and 20 meters width and 1 meter in height) to provide habitat for reef building species (e.g. flat oyster, blue mussel and surrounding the structure possible annelids as ross worm or sand mason worm) and facilitate reef development. In addition, the crevices in the rocks can host crustaceans (European Lobster and North Sea crab) and juvenile fish (Bond et al., 2018).

Figure 8. Example of armour layer rock coverage after 2 years of deployment at cable crossing of Hollandse Kust Zuid export cable (*Source: Dutch Maritime Productions*).

Some projects that aim at testing the effectiveness of artificial reefs in the area of scour protection layers are the following:

- Paimpol-Bréhat tidal test site: Showed increased local diversity due to artificial structures, with ongoing ecological succession even after four years.
- BOEM study (ongoing): Evaluates various materials for cable and scour protection off the coast of Virginia, aiming to enhance marine habitats while monitoring non-native species. Data are not yet available for this study, which is ongoing.
- KOBINE project[26]: installed NID artificial structures within the Dutch offshore wind farms Hollandse Kust Zuid and Borssele were monitored for their effect on biodiversity using for instance ROV images and eDNA. Increased biodiversity on and around the structures have been observed compared to the surrounding sandy environment.
- Reef Enhancement for Scour Protection (RESP)[27]: evaluates the effectiveness of NID reef cubes as integral scour protection through full-scale deployment and monitoring of the ecological impact at Rampion Offshore Windfarm off the UK’s south coast.
- Binational Industrial Research and Development (BIRD) Energy Foundation funded project: deployment of Droplock and rock material off Long Island, NY State in the US conducting 2 years of ecological monitoring.
- NYSERDA study (ongoing): SUNY Stonybrook is conducting scientific evaluation of NID designs in offshore wind infrastructure, and potential benefits for biodiversity at ECOncrete’s[28] Scour Protection installation 12 miles off Long Island.
- South Fork Offshore Wind Farm Benthic Monitoring Program: benthic monitoring program that incorporates visual surveys conducted before, during, and after construction of hard infrastructure introduced to the marine environment habitat (e.g. monopiles, scour protection material, and cable matrasses) and native boulder.

Most of the current ecological knowledge derives from SPLs of offshore wind turbine foundations. However, there is a significant and continuous increase of ERUS installation to enhance/promote local biodiversity. ERUS are specifically designed to enhance the ecological success of these installations by facilitating their capability

[26] https://www.wur.nl/en/research-results/chair-groups/research-funded-by-the-ministry-of-lvvn/soorten-onderzoek/kennisonline/costs-and-biodiversity-of-nature-inclusive-energy-kobine.htm
[27] Reef Enhancement for Scour Protection
[28] https://econcretetech.com/blogcat/offshore-wind-fisheries-biodiversity-research/

of enhancing local biodiversity. Comparing typical scour protections with ERUS can provide us with a reference point on the ecological potential of these units.

4.2 Design possibilities to enhance biodiversity of scour protection

Marine infrastructure modifies the natural marine environment and biodiversity. Its design may also support ecological processes and eventually provide some benefits to marine life (Dafforn et al., 2015; Laboyrie et al., 2018). We acknowledge the negative impacts that marine infrastructure may cause to the marine ecosystem, but if used synergistically, it can provide unique opportunities for nature-enhancement (ter Hofstede et al. 2023a). Apart from continuously adding artificial reef structures, it should be considered to optimize existing ones or novel marine infrastructure (ter Hofstede et al., 2022). Here, we summarize evidence on 5 different design considerations for enhancing biodiversity when introducing scour protection layers.

To boost ecological performances the following techniques could be followed:
- Increase the voids / cavities quantity and their diversity (i.e., incorporating various shapes, sizes, distributions of voids/cavities).
- Increase the thickness of the total structure to provide a larger number of habitats (also protect the core of the inner structure from disturbances).
- Vary material texture and porosity (micro to macro scale) to enhance bioreceptivity and promote epifaunal settlement.
- Increase physical complexity by incorporating different sizes of rocks or ERUS materials to increase niche space for more species to coexist.
- Incorporate intentional biological seeding (e.g. by using oyster spat) and/or surface coatings (e.g. micronutrients) that could attract a specific range of species.

Structural complexity
In general, an increase in structural complexity tends to result in higher biodiversity. There are several ways to intentionally increase structural complexity. Irregular extensions of the scour protection layer in both horizontal and vertical directions will increase the total surface area, it will create heaps and berms and provide leesides for shelter (ter Hofstede et al., 2023a). Combining different rock sizes and/or actively designing structures (for example concrete or marble structures) with various cavities and crevices, will result in an increase in habitat complexity which could lead to a higher biodiversity (ter Hofstede et al., 2023a). Adding an additional layer of rocks within the existing scour protection layers could offer habitat for more species, such as crabs, lobsters and juvenile cod (Hermans et al. 2020). Large holes (30-50 cm diameter) for mobile species (Chapman, 2009) and smaller crevices (10-20 cm) for invertebrates (Mercader et al., 2017; Clifton et al. 2022; Hickling et al., 2023) could enhance the overall biodiversity of such structures. Crevices could also facilitate the succession of flat oyster spat, as the predation rates may get diminished inside these holes.

Material composition
Scour protection layers in the North Sea and along the eastern coast of the U.S. are usually layers of rock material, with one filter base layer consisting of small-sized quarried rocks (mainly granite) and a top or armour layer, which contains larger rocks (ter Hofstede et al., 2022). Occasionally, calcareous rocks are added which are known to attract and increase the settlement of shellfish (Soniat & Burton, 2005). By using different material compositions to design scour protection, biodiversity may be enhanced, meaning that using different substrate types (e.g. marble, concrete, etc.) might attract a diverse array of species (Kingma et al., 2024). For instance, in the Dutch offshore wind farm Hollandse Kust Noord, marble is used as an additional material to the scour protection to investigate whether it stimulates biodiversity (Crosswind, 2023).

Concrete is a material often used to construct artificial reefs, since it can provide micro- and meso-habitat complexity (ter Hofstede et al. 2023b) and by roughening it, it can mimic natural rocks which promote the colonization of encrusting macrofauna (Potet et al. 2021). However, traditional concrete may leach trace metals, while carbon dioxide is emitted during its fabrication process (Hillier et al., 1999; Wilding & Sayer, 2022; Fennell et al., 2021). By using nature-friendly additives such as shells, chalk, wood, etc., concrete toxicity can be reduced. Several studies showed the benefits of incorporating bio-sourced additions in regards to bioreceptivity (i.e. the ability of the material to be colonised by living organisms) enhancement of the structure, such addition may help to reduce the surface pH, increase the surface heterogeneity or act as a food source for different species (Cuadrado-Rica et al., 2016; Bamigboye et al., 2020; Suedel et al., 2022). The addition of products, like oyster shells, is also a way to increase the circularity of the infrastructures by reducing the need in aggregates and replacing a part with industrial wastes, like shells.

Biodegradable materials are also used for artificial reefs creation (e.g. BESE-mesh, wood, or other bio sourced materials) and they will degrade as marine life colonizes the structure (Marin-Diaz et al., 2021; Nauta et al., 2022).

In addition, micro-scale roughness and surface texture are key parameters to consider. Surface texture plays a critical role in facilitating biofilm formation, which serves as a foundational biological layer that supports the development of more complex communities (Hutchinson et al., 2006; Sempere-Valverde et al., 2018; Vivier et al., 2021, 2022).

Habitat suitability
Designing ERUS structures that provide stable complex habitats can be challenging and species-specific. Large-scale biodiversity gains depend on sufficient substrate availability, as biomass and species richness have been shown to increase with surface area and structural complexity (Kingma et al., 2024). Thicker or more intricate designs can offer more microhabitats, which can create species specific niches. Sessile species for instance will benefit from more attachment surface, whereas other species (such as Atlantic cod and lobsters) benefit from more crevices and spaces between elements/rocks. Furthermore, these biodiversity hotspots may also attract higher trophic levels due to the increased food availability present.

4.3 Regulatory requirements for The Netherlands & United States East Coast

The developing knowledge of the reef effects created by foundations and scour protection material have led some regulators to include specific requirements for NID of OWFs in their regulations and tender requirements. Where used these criteria are typically incorporated as part of non-cost indicators into the evaluation process of submitted tender applications, and have been included to varying degrees of specificity and with different objectives in mind. The following provides examples of relevant requirements that have been applied in the recent past to tenders in the Netherlands and the U.S.

The Dutch North Sea
The Site Decision (Kavelbesluit) (i.e. a document where it is identified under which conditions a wind park can be built and/or exploited) outlines specific NID requirements for scour protections, emphasizing stability and habitat complexity. Incorporating eco-friendly scour protection in wind farm design involves one or more of the following key principles: (1) Adding larger structures to create substantial holes and crevices (50 cm or more) to enhance habitat complexity for large mobile species, like the Atlantic cod; (2) Introducing smaller structures to form numerous small-scale holes and crevices, beneficial for juvenile stages and smaller species; (3) Utilizing natural or chemically enriched substrates (e.g., chalk-rich materials) to facilitate species settlement, particularly for species like the European flat oyster; (4) Actively introducing target species to promote population establishment in areas lacking natural recruitment. One example of incorporating these principles in tender processes for OWF is the Hollandse Kust West Wind Farm and the IJmuiden Ver regulations. These documents include requirements such as:

Hollandse Kust West
- Measures to increase the suitable habitat for species native to the North Sea by means of hollows and cracks of various sizes and settlement substrates (Hollandse Kust West[29]):

[29] Vergunningen windparken Hollandse Kust (west) VI en VII | RVO.nl

"

a) *If stones, rocks, or other materials are used to prevent scour around the foundations of the wind turbine piles, then the following measure must be enacted: 20% of the total area of the uppermost level of the scour protection provided for all foundations must consist of contiguous surfaces of materials that include at least two hollows or cracks per square meter of surface area that are at least 10-30 cm in diameter and at least 20-50 cm in depth;*
b) *Provided a surface of the same size is used, the obligation referred to under (a) can also be fulfilled using one of the following alternative methods:*
    - *by embedding - in a radial formation - a minimum of two and a maximum of six concrete pipes per wind turbine into the scour protection structure. Each pipe must be at least 100 cm in length and have an inner diameter of at least 100 cm, one of the ends of each pipe must be accessible at all times and the top side of the pipes must be equipped with a sufficient number of holes (150-300 mm in size) to guarantee water exchange;*
    - *or by embedding a minimum of two and a maximum of six spherical concrete structures per wind turbine pile into the scour protection around each wind turbine pile. These structures must have an inner diameter, of 100-200 cm, each must have 7-15 holes varying between 15-60 cm in diameter and the structures must be installed in a manner that prevents them from sinking into the sea bed or entering sediment;*
    - *or by adding calcium-rich material as a settlement substrate, including a top layer of natural substrate (such as shells) mixed together with rock armour and packaged in wire mesh/gabions;*
    - *or by actively introducing flat oysters in combination with the preceding measure.*
c) *If the permit holder uses stones, rocks, or other materials to prevent scour around the foundations of the wind turbine piles and wishes to employ a method that is not cited under (a) or (b) to increase the volume of suitable habitat for species native to the North Sea by means of hollows and cracks of various sizes and settlement substrate, then the permit holder must formulate a plan of action to this end, including a sufficient and location-specific monitoring program.*
d) *If a, b, or c is applicable, then the permit holder must formulate a plan of action for scour protection and submit this plan of action to the Minister of Economic Affairs and Climate Policy no later than eight weeks prior to the start of construction.*
e) *The work will be carried out in accordance with the plan as referred to in subparagraph d of this Regulation."*

IJmuiden Ver[30]:

Measures to increase suitable habitat for species native to the North Sea (IJmuiden Ver offshore wind farm):

"

a) If stones, rocks or other materials are used to prevent scour around the foundations of the wind turbines, then for at least 20% of the wind turbines, the entire uppermost level of the scour protection must be designed in such a way that no movement of the materials will occur in storm conditions with a likely return period of one year.
b) The uppermost level of the scour protection referred to in subparagraph a must contain at least two slits or cavities per square meter of surface area that are 10-30 cm in diameter and 20-50 cm deep. The design of the scour protection must minimise sedimentation in the cavities.
c) Without prejudice to the provisions in subparagraph a, the obligation referred to in subparagraph b can be fulfilled by installing six artificial structures per wind turbine onto or into the uppermost level of the scour protection referred to in subparagraph

> *a. These structures must be placed on top of the scour protection in a stable manner or be partly or fully embedded in the scour protection and be located outside the area of turbulence created by the wind turbine pile in the dominant direction of the current. The design of the scour protection must minimise sedimentation in the cavities.*

d) With regard to the artificial structures referred to in subparagraph c, the following structures or combinations of structures are permitted: - pipes that are either entirely cylindrical or have a hexagonal exterior with a cylindrical interior and have both a length and diameter more than 100 cm. In addition, one of the ends of the pipe must be accessible at all times and the top side of one of the pipes must be equipped with a minimum of four holes measuring a minimum of 15 cm and a maximum of 30 cm per meter to guarantee water exchange; spherical or cubic structures with an interior diameter of at least 100 cm and accessible via a minimum of 6

[30] Wind-Farm-Site-Decision-IJmuiden-Ver-Alpha.pdf

and a maximum of 15 openings with a diameter varying between 15 and 50 cm; other structures that must include a minimum of 6 separate cavities with the following dimensions: a 10-30 cm diameter and 20-50 cm depth.
e) Without prejudice to the provisions of subparagraphs a and c, other artificial structures or combinations of structures not included in subparagraph d may also be installed. The dimensions of cavities and openings and the numbers of openings in these structures must be such that the structures offer habitats for the intended species in a similar manner as the structures specified in subparagraph d. Furthermore, the permit holder must also organize a location-specific monitoring program to examine the effects of the measures. f) The permit holder must draw up an action plan for the necessary measures, to be submitted to the Minister for Climate and Energy Policy no later than eight weeks before the planned commencement of construction. g) The work must be performed in accordance with the plan referred to in subparagraph."

Other OWFs in the Dutch North Sea focus on some species of ecological or financial interest, like the European flat oyster. They take opportunities to co-design their scour protection layers to enhance oyster bed restoration efforts (Kamermans et al., 2018). This may stimulate the re-introduction of populations that have been significantly declining in the last decades. In this way, scour protections may act as stepping-stones for the dispersal and movement of important species throughout the North Sea (Kingma et al., 2024).

United States (Atlantic Coast)
In the United States there is no universal regulation that requires offshore wind developers to utilize or integrate NID elements into the infrastructure of offshore wind projects being constructed within US federal waters. Instead, potential requirements related to NID elements are made on a project-by-project basis over the course of the permitting phase, where different regulatory entities provide consultation and input on the potential impacts, means to avoid or minimize these impacts, and mitigation strategies. This phase culminates in the record of decision. This is when the proposed offshore wind project receives “consent”, referred to in the US as approval of the project’s Construction and Operations Plan and a permit to construct and operate the proposed wind farm. Within this approval/permit are a project-specific list of conditions that the offshore wind developer must follow to maintain compliance. It is within these project-specific conditions that potential requirements to incorporate NID elements, or, more commonly, language regarding facilitating or allowing biological growth on the structures introduced into the marine environment may be included.
As the offshore wind permitting phase continues to evolve in the US, the specific conditions related to engineering with nature for projects that have received permits have changed over time. Most of the relevant permit conditions occur within the requirements to develop a Scour and Cable Protection Plan. For example, a US offshore wind project that recently received a positive record of decision (a permit to build), Revolution Wind, had the following specific language included within their permit requirements[31]: *“The Lessee must avoid the use of engineered stone or concrete mattresses in complex habitat, as technically and/or economically practical or feasible. The Lessee must ensure that all materials used for scour and cable project measures consist of natural or engineered stone that does not inhibit epibenthic growth and provides three-dimensional complexity in height and in interstitial spaces, as technically and/or economically practical or feasible. The Lessee must minimize the use of scour protection to the minimum amount necessary to accomplish the purpose.”* Further, Empire Wind, another US offshore wind farm that was recently approved by federal agencies had the same permit condition listed above for Revolution Wind with the addition of[32]: *“If concrete mattresses are necessary, bioactive concrete (i.e., with bio-enhancing admixtures) must be used as practicable as the primary scour protection (e.g., concrete mattresses) or veneer to support biotic growth.”*

4.4 Ecological objectives as defined by ERUS producers

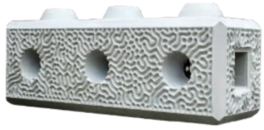
Among the SPREE-project partners, several parties contributed innovations through specific ERUS designs (Figure 1), production technologies or both. Holcim, Reefy, Boskalis, Geowall, and Coastruction have each defined their visions and goals for the development of ERUS as follows:

- BAM: Provide substrate and/or provide shelter for marine life to restore the original habitat and species/increase biodiversity. Disturbance of an ecosystem by a project can be compensated/the ecology can be rebuilt by installing artificial reefs.

[31] https://www.boem.gov/sites/default/files/documents/renewable-energy/state-activities/Rev%20Wind%20Cond%20of%20COP.pdf
[32] https://www.boem.gov/sites/default/files/documents/renewable-energy/state-activities/MASTER%205547_App%20A_Emp%20WindTCs_SV.pdf

- Holcim: The ecological goal should be defined by the global benefit associated with the installation of the structure in regards with various indicators such as biodiversity enhancement or other targeted ecological services. ERUS ecological value should be defined as the benefits in terms of biodiversity in comparison with a classic structure (commonly used, industry standard material).

- Reefy: The challenge in designing artificial units for general biodiversity is to come up with a design that benefits most species without stimulating non-native species. Locally targeted species will differ in a way that makes it impossible to design one solution that fits all. From existing literature, we can use some principles that increase biodiversity overall, like increased complexity and surface area. Specifically for the North Sea but also US East coast, natural stable hard substrates are scarce. These 3 principles should be targeted by artificial reefs in comparison to traditional solutions: (a) higher complexity, (b) more surface area, and (c) stable hard substrate. Flexibility of solutions to accommodate different target species is another goal but can only be validated against current target species of areas of interest.



- GEOWALL: ERUS is a purpose-designed, modular or monolithic construction made from durable and marine-safe materials, intended to be placed on the seafloor to mimic natural reef functions. The ecological value should be to provide physical habitat, shelter, and substrate for the settlement, growth, and reproduction of marine organisms, while also potentially serving additional functions such as shoreline protection, biodiversity enhancement, or wave energy dissipation. While various materials can be used to achieve this, we believe the ideal approach is to design these structures to be as natural as possible, with minimal CO_2 impact.

- Coastruction: The ecological goal should focus on developing marine structures that significantly enhance biodiversity and contribute to the restoration of natural habitats. ERUS should aim to provide benefits similar to those of natural reefs, such as offering stable substrates, creating complex environments, and providing shelter and breeding grounds for native marine species. The design should prioritize ecological functions that support biodiversity while preventing the proliferation of non-native/non-desirable species. Achieving these goals will involve integrating adaptability to different marine environments and aligning with sustainable development principles to ensure long-term ecological resilience. Additionally, the use of local and compatible materials is crucial for fostering biodiversity growth, as it ensures that the artificial habitats are in harmony with the surrounding ecosystem. Key factors such as complexity, porosity, roughness, and material selection are essential aspects that influence biodiversity growth and should be carefully considered in the design of ERUS.

4.5 Ecologically relevant species for ERUS and armour rock

Defining ecological goals for specific cases should be guided by the global benefit associated with the installation of the structure regarding various indicators, such as biodiversity enhancement or realization of targeted ecological services. The ecological value of the ERUS should be defined as the benefits in terms of biodiversity in comparison with a classic structure (commonly used). The SPREE project focused on the Dutch North Sea as well as the western North Atlantic (Chapter 3) as case study areas and identified relevant species of interest as well as ecosystem functions.

4.5.1 Species of interest for the North Sea and western North Atlantic

There are many species of ecological (or financial) interest that may benefit from the presence of artificial reefs like scour protection layers and others that do not take advantage of these installations at all. Most information comes from research conducted on scour protection layers of offshore wind farms, while recently more knowledge has become available from single artificial reefs. This section discusses how different species of interest (either ecologically and/or economically valuable) interact with scour protection layers of offshore wind farms in the North Sea.

Atlantic cod (*Gadus morhua*) and whiting pout (*Trisopterus luscus*) are attracted to scour protection layers (Wilhelmsson et al. 2006, Lindeboom et al. 2011, Bergström et al. 2013), while they are exploiting the scour protection layers of the offshore wind turbines in the southern North Sea for food (Reubens et al., 2011; Mavraki et al., 2021). They also seem to stay there for a long period of time to feed, as it has been confirmed by feeding behaviour studies (Mavraki et al., 2021). Juvenile cod individuals are present in these areas and show high site-fidelity (Reubens et al., 2013). It has been speculated that these two species could also increase their local production around scour protection layers, however, this is yet to be investigated (Mavraki, 2020).

With respect to the US, similar to the North Sea, there are several ecologically and commercially valuable species that are generally structure-associated species that may benefit from added infrastructure associated with offshore wind development. As in the North Sea, the Atlantic Cod (*Gadus morhua*) as well as other gadids and demersal finfish such as Haddock (*Melanogrammus aeglefinus*), Red Hake (*Urophycis chuss*), and Scup (*Stenotomus chrysops*) are attracted to physical structure and benthic habitats that are more complex. Additionally, recreational fishermen in the US east coast, in particular south of Cape Cod, target Black Sea Bass (*Centropritis striata*), that are also structure-associated fish that benefit from the introduction of offshore wind infrastructure. A seven-year demersal trawl research study at Block Island Wind Farm (five jacket foundation turbines in Rhode Island State waters, within 3 nautical miles of the shoreline) revealed abundances of structure-oriented species, such as black sea bass and Atlantic cod increased following turbine installation (Wilber et al., 2022). Recent results from South Fork Wind Farm monitoring indicate high abundances and diversity of these structure-associated fish species utilizing the wind farm infrastructure (foundations, scour protection layer, and cable mattresses) as habitat (INSPIRE Environmental, 2025).

There are several species of structure-associated decapods that are also commercially and culturally valuable, particularly in US New England waters. These include the American Lobster (*Homarus americanus*), Jonah crab (*Cancer borealis*) and Atlantic Rock Crab (*Cancer irroratus*). Jonah Crab and Rock Crab are beginning to replace the lobster as a target species by many fishermen in southern New England as waters continue to warm leading to increased prevalence of lobster shell disease and the overall poleward and offshore movement of the species into cooler waters[33]. A monitoring study at Block Island Wind Farm using ventless traps reflected regional trends in declining southern New England lobster catches both near the wind farm and at the reference location, with no detrimental effects of wind farm construction and operation on lobster abundances (Wilber et al., 2024).

The European plaice (*Pleuronectes platessa*) shows high site fidelity towards offshore wind farms and is attracted to the scour protection layers to get food, while it leaves the wind farm areas in the winter to move to its spawning grounds (Buyse et al., 2023). In the US, several flatfish species are commercially valuable including winter flounder (*Pseudopleuronectes americanus*) and summer flounder (*Paralichthys oblongus*). Wilber et al. 2018 found no change in abundance of any flatfish species, including seven different species observed over a seven-year trawl survey, at Block Island Wind Farm.

On the contrary, pelagic fish, like Atlantic mackerel (*Scomber scombrus*) are not attracted to scour protection layers (Mavraki et al., 2021). This is probably related to their biology. Pelagic fish are not directly associated with the benthic environment, and they are highly mobile.

European flat oysters (*Ostrea edulis*) were highly present in the North Sea, and their beds were considered an important habitat about a century ago (Kamermans et al., 2018). However, their populations have now almost disappeared from the North Sea, mainly due to intensive fisheries in the area (Kamermans et al., 2018). Oysters are a highly important species both for economic and ecological purposes, but they need hard substrates for recruitment and attachment. Offshore wind farms in the North Sea can provide this habitat. Oysters have been found on shipwrecks, buoys and wind farms in the North Sea and they seem to be able to survive and reproduce in the area (Kerckhof et al., 2018). Some Dutch offshore wind farms are considered

[33] https://www.capeandislands.org/science-environment/2018-11-14/as-lobsters-decline-fishermen-switch-to-jonah-crab

suitable locations for flat oysters, and they could potentially promote the creation of oyster beds (Kamermans et al. 2018).

Bivalves on the outer continental shelf off the US east coast include the commercially valuable Atlantic Sea Scallop (*Placopecten magellanicus*) and blue mussel (*Mytilus edulis*). Because sea scallops are not limited by substrate and grow in a range of sediment types in this region from mud to gravels, it is not likely that the introduction of hard structure through offshore wind development will directly affect sea scallop recruitment. However, it is possible that potential physical shifts in flow patterns due to the turbine foundations may change larval distribution patterns of sea scallop populations (Chen et al., 2024). Blue mussels attach to hard substrate and are expected to benefit from the conversion of soft sediments to hard habitats following the installation of foundations and scour protection. Rapid colonization by blue mussels on monopiles is commonly observed including at Block Island Wind Farm, the Coastal Virginia Offshore Wind research turbines, and South Fork Wind Farm (Fonseca et al., 2024; INSPIRE Environmental, 2025).

Sabellaria spinulosa, a biogenic reef builder, was once abundant in the North Sea, but its population is suffering a significant decline due to seabed disturbing fishing activities. The presence of Sabellaria reefs within offshore wind farm areas in the North Sea seems to be increased compared to sediment habitats farther away (Pearce et al., 2014). This might be caused due to fisheries limitations and/or due to changes in sediment flow that promote the presence of Sabellaria. Sabellaria has also been found colonising hard substrates around offshore wind turbine foundations at depths of 23m (Causon et al., 2022). Even though this could indicate a potential increase of the population because of the presence of artificial hard substrates, their colonisation might be considered of lower ecological significance than their natural aggregations in the soft sediment (Causon et al., 2022). This is because when they occupy parts of the turbine foundation, their ability to build reefs and stabilize the sediment is decreased (Causon et al., 2022).

4.6 Conclusions

The review underlines the pertinence of evaluating the suitability of ERUS as unique elements to use for scour protection. The findings of the review informed the definition of the method for a comparative qualitative evaluation between rock armour and ERUS in terms of their ecosystem enhancement potential.

From a regulatory perspective, tender requirements and sectoral recommendations for the Dutch context as well as internationally, suggest that artificial reefs will be considered for testing as ecological innovations and are acceptable measures to fulfil non-cost-criteria.

Existing knowledge and guidelines on artificial reefs emphasize the potential to adjust design parameters of cast elements such as ERUS. Key parameters include increasing voids and cavities, optimizing the volume of protective structures to extend habitat, and adapting material properties, surface texture, and porosity (from micro- to macro-scale) to enhance bioreceptivity. Layout complexity is also an important factor that can be engineered to achieve specific ecological objectives.

Lastly, key species have been identified that are relevant explicitly for the two geographic areas under consideration in the SPREE project, namely the Dutch North Sea and the western North Atlantic. These species have been listed on the basis of their ecosystem functions, their commercial value as well as based on their vulnerability.

In combination these aspects informed the methodology for comparative evaluation between conventional armour rock and ERUS which is elaborated upon in the following Chapter 5.

5 Ecological performance of rock armour and ERUS in scour protection

Building on the literature review of NID knowledge, regulatory frameworks, and best practices presented in Chapter 4, this chapter compares how conventional armour rock and ERUS perform in promoting ecological enhancement when applied in the armour layer of a scour pad (a layer installed to prevent seabed erosion) at the reference sites. To this end, experts were asked to make inferences about the ecological performance of armour rock compared to ERUS for different taxonomic groups. As the base cases for the evaluation, the two case study locations (Chapter 1: IJmuiden Ver in the North Sea and Revolution wind farm in the western North Atlantic) were used and design specifications applied that are representative of these locations.

5.1 Methodology

5.1.1 Evaluation framework

To evaluate the ecological potential of conventional armour rock and ERUS, this study developed and applied a qualitative assessment framework. The analysis incorporated design characteristics of armour rock and ERUS together with two site-specific parameters: water depth and the presence of sandy seabed habitats for the offshore windfarm reference sites IJmuiden Ver and Revolution (Chapter 3). Experts were interviewed and asked to assess how the design features of different scour elements contribute to ecological functions for specific taxa.

In this interview a representative ERUS design was presented based upon three ERUS designs tested in WP2 of the SPREE project, namely the units from BAM, Holcim and Reefy (Figure 1) and also described in Saxoni et al. (2025). These units represent different shapes, sizes and weights. The representative ERUS unit was based on the average unit porosity over the three baseline solutions, the units volume of concrete (solids) equal to the average volume of concrete and the bulk porosity averaged over three baseline solutions. For more information on properties of different ERUS see WP1 report of the TKI JIP SPREE project. It is important to emphasize that the representative design is not representative of any existing or implemented solution and was developed solely for analytical purposes of the JIP-SPREE analyses. The representative ERUS is assumed to be a porous cube with the following characteristic Table 3.

Table 3. Characteristics of representative ERUS design based on three ERUS designs tested in WP2 of the SPREE project (units from BAM, Holcim and Reefy).

Indicator	**Value**
Cube dimension[34]	0.43 m
Average unit porosity[35]	0.42 (42% air/full cube)
Average unit volume	0.0795 m3
Average volume of concrete per unit	0.0461 m^3
Average concrete density	2350 kg/m^3
Average unit weight	108.3 kg
Average bulk porosity	0.55 (55% air/bulk heap volume)

[34] (Vconcrete/(1-unit porosity))^(1/3)
[35] The definition of unit porosity used is: n% = %air/full cube without gaps

Before the interviews were conducted, experts were informed on the key design differences between conventional armour rock and the representative ERUS as armour layer in a scour pad for the reference sites (Table 4 & Figure 8). The characteristics of bulk porosity, relief, material and standard unit size were obtained through tests and measurements during the SPREE project as well as industry standards for rock. The surface area and volume were defined based on the extents of the armour layer and required volume for the case study locations of IJmuiden Ver and Revolution OWF, together with industry standards and test results in the SPREE project from other WPs.

ERUS feature higher rugosity, larger total volume, and greater bulk porosity (55% versus 40%), creating more internal void space and potentially richer habitat compared to conventional armour rock. ERUS are made from concrete (e.g. using CEM III), while conventional armour rock is purely granite, and element sizes are slightly larger and more uniform in ERUS (0.3–0.4 m versus 0.18–0.56 m). Surface pH also differs, with ERUS reaching 9–9.5 after submersion compared to 7–8.5 for conventional rock. In both cases, however, the filter layer is expected to be similar. This overview provided the necessary context for experts to assess how these structural features could influence ecological functions during the interviews.

Table 4. Conventional amour rock scour pad and representative ERUS scour pad design specifications based on calculations from work package 2 and a 10m diameter monopile for Ijmuiden Ver and Revolution OWF.

Characteristics	Armour rock	ERUS
Bulk porosity (% air)	40%	55%
Relief (ratio between a straight line versus a line over the relief of the surface of a scour protection layer)	1,071 – 1,078	1,123 – 1,248
Surface of armour layer in m^2 (based on average relief ratio) (IJmuiden Ver North Sea)	882	1,180
Surface of armour layer in m^2 (based on average relief ratio) (Revolution OWF, U.S.)	1,000	1,249
Volume of armour layer in m^3 (IJmuiden Ver North Sea)	557	1,159
Volume of armour layer in m^3 (Revolution OWF, U.S.)	907	1,366
Material	Granite rock Surface pH 7- 8.5 Texture: vesicular, i.e. porous	CEM III - Blastfurnace cement (Portland cement clinker and granulated blast furnace slag[36]), some ERUS include additional materials e.g. fly ash, shell powder, biochar, crushed coral or limestone etc.) Surface pH (beginning) 12-13.8 reducing to ~9-9.5 upon submersion
Individual unit size	Grading 10-60kg: D50 -> ~0.26 - 0.31m, range grading curve (D10 - D90) -> 0.18 - 0.4m Grading 40-200kg: D50 -> ~0.4 - 0.46m, range grading curve (D10 - D90) -> 0.3 - 0.56m	In the order of 30-40 cm cube (large elements could be 1-2 meters)

[36] "[…] by-product in the production of metallic iron, is granulated, rapidly cooled, and therefore predominantly glassy, basic slag. The slag contains the same oxides (SiO_2, Al_2O_3, CaO) that make up Portland cement but in different proportions. According to the European cements standard EN 197-1, at least two-thirds of the slag by mass must be glass and the mass ratio (CaO + MgO)/SiO_2 must also be greater than 1.0" (Source: Osmanovic et al., 2018)

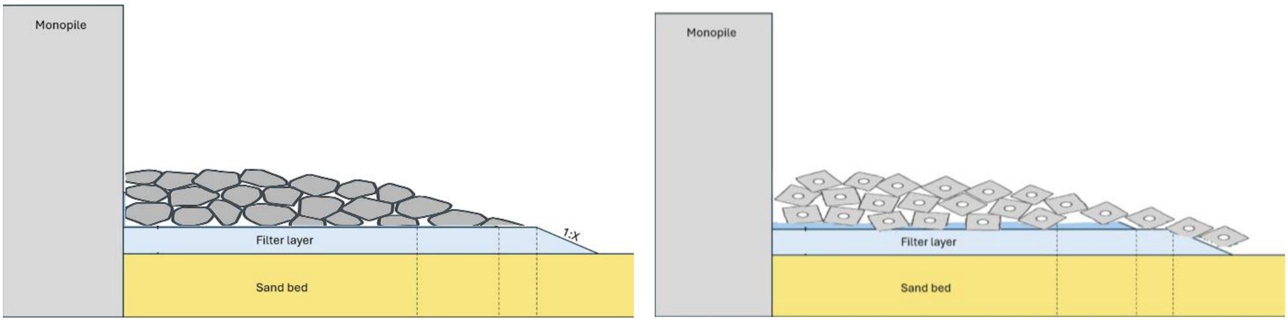


Figure 8: Schematic visualization of armour layer using rock (left) and ERUS (right) (souce: Deltares, ERUS image was AI generated)

After informing on the design characteristics, an interview approach was conducted with expert across multiple marine taxonomic groups. Experts were asked to assess how the design features of different scour elements contribute to ecological functions for specific taxa, using the categories outlined below:

1. Design features: the design features assessed included surface area, volume, porosity, relief, and material composition (Table 5).
2. Ecosystem functions: the ecosystem functions identified as relevant for the evaluation included placement for settlement, provisioning of shelter, facilitating feeding (or provisioning of food), facilitating reproduction, and facilitating distribution of exotic species (stepping-stone function).
3. Taxonomic groups: the following broad taxonomic groups were identified as most relevant for the two locations (Table 6).

Table 5. Design characteristics defined for scour pad elements.

Characteristics	Definition
Rugosity	The rugosity created on the surface of the scour pad compared to a solid sphere's flat plane
Relief	Height difference between the lowest and highest point of the scour protection
Bulk porosity	Compared to a solid sphere, describing the % of water filled gaps between individual rocks or ERUS
Total volume	The total volume created when applying the relevant layer thickness (2.5 and 3 layers)
Material	Specifications of the type of rock conventionally used and material specifications for a representative ERUS
Individual element size	Referring to suitable rock grading for both case studies and ERUS size suitable for the two case studies.

Table 6. Taxonomic groups used in the ecological performance of armour rock and ERUS.

Taxonomic Group	Example Species	North Sea	Northwest Atlantic
Sessile bivalves	Pacific oyster (*Maggalana gigas* (syn. *Crassostrea gigas*))	x	
	European flat oysters (*Ostrea edulis*)	x	
	Sea Scallop *(Placopecten magellanicus*)		x
	Blue mussel (*Mytilus edulis*)	x	x
Polychaete	Ross worm (*Sabellaria spinulosa*)	x	
	Serpulids (like Pomatoceros or Hydroides)		x
Benthic small and large crustaceans	American Lobster (*Homarus americanus*)		x
	Jonah crab (*Cancer borealis*)		x
	Atlantic Rock Crab (*Cancer irroratus*)		x
	European Lobster (*Hommarus gammarus*)	x	
	North Sea crab (*Maja squinado* and *Cancer pagurus*)	x	
	Amphipods	X	x
	Malacostraca	x	x
Flat fish	European plaice (*Pleuronectes platessa*)	x	
	Winter flounder (*Pseudopleuronectes americanus*)	x	x
	Summer flounder (*Paralichthys oblongus*)		x
Benthopelagic/ Demersal fish	Atlantic cod (*Gadus morhua*)	x	x
	Whiting Pout (*Trisopterus luscus*)	x	
	Haddock (*Melanogrammus aeglefinus*)	x	x
	Red Hake (*Urophycis chuss*)		x
	Black Sea Bass (*Centropritis striata*)		x
	Scup (*Stenotomus chrysops*)		x

Experts were then asked to make inferences about the performance of conventional armour rock compared to ERUS for each function and taxonomic group using the following categorization listed in Table 7.

Experts were initially made aware of the two case studies (IJmuiden Ver and Revolution) that were being assessed. In cases where experts suggested that significant differences of the ecosystem or design evaluation would have to be captured, the evaluation was depicted in separate tables. Otherwise, one table for both case study locations was used.

It should be noted that this qualitative approach leaves room for interpretation and can only be understood as providing an indication. Not only were non-design factors excluded from the consideration but also the evaluation categories could have been interpretated in different ways (e.g. capturing an effect that is not fulfilled for a specific design factor and taxonomic group versus indicating that it is not relevant). Therefore, inconsistencies arise in the evaluation criteria use. However, the narrative explanations for each evaluation provides the necessary context for consideration.

Table 7. Evaluation categorization for relation between design functions and taxonomic groups.

Visualization	Definition
Red	Does not fulfil/offer this function for the indicated taxonomic group at all
Yellow	May fulfil/offer this function for the indicated taxonomic group, dependent on […]
green	Will fulfil this function for the indicated taxonomic group
+	Indicates if either elements will fulfil this function better compared to the other
x	Not relevant/applicable
?	Unknown, insufficient data available

5.2 Comparative evaluation results

5.2.1 Taxonomic group: Sessile bivalves

An interview was conducted with Arjan Gittenberger (PhD) from GiMaRIS who is involved in ecological monitoring, particularly of exotic species. Arjan shared insights from ongoing research into fouling communities on vessel hulls and artificial structures across the North Sea, Ireland, and neighbouring regions.

Table 8. Comparative evaluation results (armour rock and ERUS) for sessile bivalves.

Taxonomic group	**Sessile bivalves**							
Location	**North Sea**							
Element	**Armour Rock**				**ERUS**			
Design feature/ Function	Surface Area/ Volume	Rugosity, Relief	Porosity, geometry, orientation	Material Composition	Surface Area/ volume	Rugosity, Relief	Porosity, Geometry, Orientation	Material Composition
Settlement	green	green	green	x	green +	green +	green +	x
Shelter	green	green	green	x	green +	green +	green +	x
Feeding	x	x	x	x	x	x	x	x
Reproduction	x	x	x	x	x	x	x	x
Stepping stone for exotic species	x	x*	x	x	x	x*	x	x
Comments	*For this function, both could be stepping stones (especially the outer areas), but this will be highly dependent on the location.							

A difference highlighted by Arjan was how the Netherlands approaches invasive species compared to other countries. While many nations deliberately select ERUS that minimize the risk of invasive species colonization, this consideration receives relatively little attention in the Netherlands.

It was emphasized that, in terms of habitat design for sessile bivalves, research has shown that factors such as heterogeneity, geometry, stability, and elevation are important factors of the structures - when species need to settle, they can also do this on moderately suitable materials and could survive this, if the other boundary conditions are met. In addition, colour was mentioned as an aspect that plays a role since darker materials tend to attract a more species than lighter ones.

The importance of placing ERUS in sheltered locations (or creating sheltered locations by placing ERUS in the right place) was stressed to maximize their ecological effectiveness. As such, an optimal design might involve an outer ring or extensions of armour rock to create a more sheltered area where ERUS can be even more effective. In high-energy environments, such as areas with increased flow velocity that occurs on the outer edges of armour rock or ERUS installations, species composition will likely be similar on ERUS and armour rock. The key differences between armour rock and ERUS installations emerge in the inner areas, where conditions are more stable and sheltered due to a decrease in hydraulic slope with depth.

To accurately assess ecological value, surface area and volume should be considered in two distinct categories: the outer or surface areas of the scour pad versus the inner or interior areas of the scour pad. The inner surface area includes both the spaces between ERUS or armour rock units and the internal cavities within ERUS features that are not present in traditional armour rock. This internal complexity gives ERUS a distinct advantage, particularly for native species that prefer crevices and sheltered microhabitats, such as flat oysters and larger crustaceans (see section on Taxonomic Group: Large Crustaceans).

Ultimately, the goal should not be to maximize overall biodiversity, but rather to support and to restore the native biodiversity e.g. flat oyster, lobster, North Sea crab. ERUS, with their enhanced structural complexity and capacity to create protected inner habitats, could be particularly well-suited to this objective.

Another expert judgement was obtained by interviewing Boze Hancock (PhD) from The Nature Conservancy. His research focuses on flat oyster restoration more specifically.

Table 9. Comparative evaluation results (Armour rock and ERUS) for sessile bivalves: flat oysters.

Taxonomic Group	**Sessile Bivalves: Flat Oyster**							
Location	**North Sea**							
Element	**Armour Rock**				**ERUS**			
Design feature/ Function	Surface Area/ volume	Rugosity, Relief	Porosity, geometry, orientation	Material Composition	Surface Area/ volume	Rugosity, Relief	Porosity, Geometry, Orientation	Material Composition
Settlement				*		+	+	*
Shelter						+		
Feeding	?	?	?	?	?	?	?	?
Reproduction	x	x	x	x	x	x	x	x
Steppingstone for exotic species	?	?	?	?	?	?	?	?
Comments	* Material composition is only relevant if multiple options are available (i.e., hard structures are not limiting), otherwise larvae will settle on different materials as long as they are generally suitable.							

The recommendation provided was to prioritize the restoration of biogenic habitats (e.g., habitats formed by oyster shells and more generally by living, growing organisms that are self-recruiting. The filtration function of bivalves and some other filter feeders adds biodeposits (food packages) to the structure enhancing biodiversity and biomass) which form the foundation of the food web. The study by Thurstan et al. (2024) provides substantial information on historical flat oyster habitats and their benefits in the European context. In the US Atlantic coast different oysters (Crassostrea) occur which do not occupy full salinity deep waters that occur around OWFs and hence are not relevant for this assessment. Blue mussels may be relevant but their population dynamics in relation to restoration are not well known.

In general there are two main approaches to flat oyster restoration:

1. Providing a suitable substrate and relying on natural larval settlement. In the North Sea, the average maximum larval dispersion is estimated to be around 10 kilometres. However, this method is not considered the most effective because larval supply is limited in the North Sea, and successful settlement depends on chance (other species may settle first).
2. Remote setting, where larvae are cultivated and allowed to settle on materials in tanks; then the materials with settled oyster spat are introduced to the site. This approach is viewed as more promising and successful, and pilot projects have already been conducted in the Netherlands.

Although much research has been done on how material type affects settlement success, in practice, oyster larvae will settle on any available surface as long as the environmental conditions are suitable for them. Material preference only becomes relevant when larvae have multiple suitable options. Both rock armour and ERUS can support settlement, provided the pH is stable and slightly alkaline, and there is no harmful chemical leaching. The ability of oyster larvae to settle on different materials also suggests that further exploration of the use of repurposed materials is possible, as this approach could contribute to reduced costs and environmental impact (e.g. carbon dioxide emissions).
It is also important to note that in natural environments, recruitment surfaces are quickly colonized by other organisms. Even a thin layer of fouling growth will deter oyster larvae from settling. This further supports the suggestion to utilize the remote setting restoration strategy. Living oysters are continuously growing and will provide clean substrate to settle on for new larvae.
Of the two restoration routes, ERUS is particularly well-suited for the second (remote setting). Currently, pilot projects involve allowing flat oyster spat to settle on rock armour, which is then installed using a fall pipe vessel. The mortality rate during installation is still unknown and will be subject of further investigation. If ERUS can also be installed using fall pipe vessels, they would offer greater structural complexity-relief, crevices, porosity - and therefore settlement and shelter functions, which could enhance spat survival.

5.2.2 Taxonomic group: Benthic polychaetes

An interview was conducted with Drew Carey, PhD from the Venterra Group. The evaluation focused on attached (epifaunal) polychaetes (e.g., Serpulids) since biogenic reef building species, such as *Sabellaria,* are present in the North Sea but absent in the Northwest Atlantic. While tube-building polychaetes and amphipods are present in the Northwest Atlantic, they do not exhibit the reef building effect of *Sabellaria*.

Table 10. Comparative evaluation results (Armour rock and ERUS) for benthic polychaetes.

Taxonomic group	**Benthic polychaetes**							
Location	**Northwest Atlantic**							
Element	**Armour Rock**				**ERUS**			
Design feature/ Function	Surface Area/ volume	Rugosity, Relief	Porosity, geometry, orientation	Material Composition	Surface Area/ volume	Rugosity, Relief	Porosity, Geometry, Orientation	Material Composition
Settlement					+	+	+	+
Shelter	?		?	?	?	+	?	?
Feeding		?		?		?		?
Reproduction	?	?	?	?	?	?	?	?
Steppingstone for exotic species				?	+	+	+	?

Another difference between the two case studies lies in the naturally occurring mostly granite rocks of varying sizes which have smooth surfaces shaped by glacial activity that characterize the marine habitat in the area of Revolution OWF. This natural reef is unique to this specific OWF location and differs from other sandy-bottom areas dedicated for OWF development in the western North Atlantic which is similar to the Dutch North Sea. Another important difference between the US context and the Dutch context is that trawling is banned within wind farms in the Netherlands, whereas it is permitted in the U.S.

For polychaetes, which are small organism, both rock and ERUS offer viable settlement opportunities. If elements provide a very small-scale relief it will improve their settlement (the sub-cm scale relief is most meaningful for this taxa). Smooth surfaces, such as found at existing boulders at the US Revolution OWF could be less suitable than ERUS if their sub-cm porosity it higher. The ability to create more sub-cm relief through ERUS will also facilitate shelter provision while for rock this will depend on the type of rock and individual elements' properties.

Some species will settle directly on the armour rock or ERUS while others will settle on the lee side. Therefore, different species will be found in the different parts (inner and outer areas) of the scour pad, irrespective of whether it is rock or ERUS. Increased surface areas provided by ERUS will also support settlement.

Polychaetes that settle on scour protection are adapted to hard substrate, as they create their own protection in the form of calcareous tubes. These are predominantly filter feeders. Therefore, settlement will be determined also by the surrounding food availability, though this is not considered in this assessment.

Following this first wave of settlement, predatory species (e.g. anemones, sea stars) will take advantage of the built structures and the shelter created. One of the cues for settlement for many species is the presence of conspecifics, i.e. individuals or organisms belonging to the same species.

For polychaetes, reproduction is very much linked to the settlement function as these organisms do not move more than a few centimetres following their larval stage. To enhance their reproduction, proximity is key (i.e. substrate needs to be near to the source population), though it is unknown what a critical distance would be for polychaetes. Therefore, in a case like the Revolution OWF, placing rocks in close proximity to naturally occurring rock could contribute to enhancing the settlement of polychaetes. Their characteristics should be as similar as possible to the naturally occurring rocks (e.g. rounded in the case of the US).

There is potential for creating a stepping stone effect by introducing either ERUS or rock. It is uncertain but could potentially accelerate the presence of invasive, but also native species. In the same logic that there is increased surface area and porosity, this effect might be higher through ERUS than through rock. There is a limited surface area; but polychaetes do not smother areas like some other species (sponges, tunicates, mussels) can. The stepping stone effect of exotic species is not or less relevant for this taxonomic group.

The presence of large amounts of filter feeders on artificial structures, like bivalves (e.g. mussels), creates a downwards "carbon pump". They feed off of particles of organic matter from the water column and excrete waste product that is rich in organic carbon that sinks to the bottom floor. In turn these excrements change the sandy sediment to finer sediments. This can benefit settlement of deposit feeders like several polychaetes: habitat and food sources are created for deposit feeders in the surrounding natural benthic habitat. This effect can extend far away from the scour protection, to the seabed. As such, effects of settling species can have secondary impacts that reach beyond the scour protection.

5.2.3 Taxonomic group: Encrusting invertebrates (Hydrozoans and Bryozoans)

An interview was conducted with Joop Coolen (PhD) from Wageningen Marine Research who is a scientist specializing in the ecology of reefs in the North Sea.

Table 11. Comparative evaluation results (Armour rock and ERUS) for hydrozoans and bryozoans.

Taxonomic Group	**Hydrozoans and Bryozoans**							
Location	**North Sea & Northwest Atlantic**							
Element	**Armour Rock**				**ERUS**			
Design feature/ Function	Surface Area/ volume	Rugosity/ Relief	Porosity, Geometry, Orientation	Material Composition	Surface Area/ volume	Rugosity/ Relief	Porosity, Geometry, Orientation	Material Composition
Settlement					+	+	+ (porosity)	+
Shelter	x	x	x	x	x	x	x	x
Feeding						+		
Reproduction	?	?	?	?	?	?	?	?
Steppingstone for exotic species	?	?	?	?	?	?	?	?

In general, what is relevant to consider is that hydrozoans and bryozoans should be treated as separate groups due to their distinct characteristics, even though limited information is available for both. For example, some species are initially considered encrusting but at a later stage form bushes or change orientation such as *Electra pilosa*. For the purpose of this evaluation though, the differences would not result in different outcomes, which is why they were kept together in one table here.

What will amplify the ecological effects achievable with ERUS is a focus on increasing the variability among individual elements. The current ERUS elements are relatively uniform; however, incorporating elements of different dimensions, sizes, and materials would be important to maximize the ecological effects.

Similarly, increasing the diameter of the scour protection and creating a gradient between the scour protection and surrounding soft sediment would enhance ecological functionality. In other words, at the edge of the scour protection layer, creating a gradual decrease of the ratio of hard (i.e., ERUS, armoured rock) to soft (i.e., existing sand) substrate moving away from the scour pad would benefit many species.

The evaluation is undertaken under ‘idealized’ characteristics to compare rocks with ERUS. However, it should be noted that site-specific factors will influence ecological patterns. For instance, higher sedimentation levels in areas such as the Wadden Sea, compared to other locations, will impact the species composition. The frequency of sedimentation and resuspension will influence community structure since attached species can only withstand so much burial. Structures with higher relief (height above the seabed) will support the survival of attached species in areas with high sediment mobility it allows them to settle higher up in the water column and not near the mobile sediments.

In comparison it can be said that ERUS may enhance the ecological functions of settlement and feeding for hydrozoans and bryozoans, compared to rock. This advantage primarily stems from the increased surface area of ERUS, which is essentially achieved through greater relief and porosity of ERUS relative to rock. Consequently there is more surface for attachment. However, increased surface area may also influence the presence of predators which can lead to an alternate effect. A higher surface porosity will lead to more internal surface which can equally create opportunities for attachment.

This taxonomic group encompasses many different species so that material of scour protection will likely have an effect on settlement. A combination of different materials could be beneficial, which would also give ERUS an advantage over rock amour.

While the effect of sedimentation due to element orientation for these groups is uncertain. Yet, there are many different species and this it is likely to create specific niches that will attract other species.

The increased porosity and relief allow for greater water infiltration, which is crucial for feeding, as most or perhaps all of these invertebrates are filter feeders. Lastly, the material composition of ERUS can positively affect settlement, as a mix of materials could be beneficial for this taxonomic group.

It also needs to be noted that the introduction of both rock or ERUS will have a stepping stone effect with more material possibly resulting in an increased stepping stone effect for exotic species. However, too little information is available to evaluate the differences between ERUS and armour rock at this stage (hence the N/A classification in the table.

5.2.4 Taxonomic group: Small crustaceans

An interview was conducted with Jan Beermann (PhD) from the Alfred Wegener Institute who is an expert in benthic ecology.

Table 12. Comparative evaluation results (Armour rock and ERUS) for small crustaceans: Amphipods.

Taxonomic group	**Small crustaceans (Amphipods)**							
Location	**North Sea & Northwest Atlantic**							
Element	**Armour Rock**				**ERUS**			
Design feature/ Function	Surface Area/ volume	Rugosity, Relief	Porosity, geometry, orientation	Material Composition	Surface Area/ volume	Rugosity, Relief	Porosity, Geometry, Orientation	Material Composition
Settlement					+	+		+
Shelter				x	+	+		x
Feeding	x			x	x			x
Reproduction	x			x	x			x
Steppingstone for exotic species	x			x	x			x

For this taxonomic group water depth is a critical factor to consider. In a shallow area, available algae will attract small crustaceans that take advantage of the presence of other inhabitants. It is anticipated that small crustaceans will be abundant in the early phase after installation. However, in the aphotic zone (i.e. areas of scour protection layers that receive little to no light) and with the arrival and settlement of increasingly more species, the use of the area by small crustaceans becomes more complicated and context-dependent. For example, at a 30m depth in the Netherlands and the U.S., algae will not occur due to the aphotic conditions providing limited feeding ground opportunities.

Surface area and volume will not directly influence ecosystem functionality for small crustaceans, but increased availability of settlement habitats and shelter space is beneficial for them. In that sense, ERUS would provide an advantage, although the orientation and creation of stacked units might be more important in achieving these advantages e.g. creating shelter for young individuals, and providing habitat for settlement.

It should also be highlighted that predation pressure within these structures is expected to be high, as multiple fish species that feed on small crustaceans are also attracted to them.

Scour design factors do not affect feeding, as small crustaceans (mainly amphipods) are filter feeders. Similarly, reproduction will not be directly affected as they are brooding and do not have larvae. However, greater surface area and volume that provide shelter can enhance recruitment and improve juvenile survival rates.

The relief is not likely to play a significant role for the initial colonization, though some decapod crustaceans (e.g. *Pisidia sp*.) might utilize the space later being attracted to the crevices. If ERUS lack specific relief features, the holes created by their porosity will be useful. Overall, the difference in design characteristics between ERUS and armour rock is not expected to create any advantages.

In terms of material composition, coarser material tend to be colonised more quickly (e.g. by hydrozoans and bryozoans), which in turn may lead to earlier occurrence of small crustaceans as well. However, in the mid-to long-term, no significant difference between armour rock or ERUS is expected. Otherwise, this design aspect does not play a major role for small crustaceans.

It is to be anticipated that ERUS would increase habitat heterogeneity and thus increase stepping stone effects, including that for exotic species. To attract a more diverse range of species, combining different ERUS would be beneficial.

5.2.5 Taxonomic group: Large crustaceans

The interview was conducted with Marcel Rozemeijer (PhD) from Wageningen Marine Research, who has worked on multi-use for OWFs, including tagging of lobsters at artificial reefs.

Since there are significant differences within this taxonomic group, representative species, namely European lobster and brown crab, were used to assess the effects. While there are different species in the North Sea compared to the Northwest Atlantic, the evaluation is relevant to both locations, as the effects would be largely the same.

Table 13. Comparative evaluation results (Armour rock and ERUS) for large crustaceans: European and American lobster.

Taxonomic group	**Large crustaceans (European and American Lobster)**							
Location	**North Sea & Northwest Atlantic**							
Element	**Armour Rock**				**ERUS**			
Design feature/ Function	Surface Area/ volume	Rugosity, Relief	Porosity, geometry, orientation	Material Composition	Surface Area/ volume	Rugosity, Relief	Porosity, Geometry, Orientation	Material Composition
Settlement								
Shelter	?			?	?	+		?
Feeding			?			+	?	(leakage)
Reproduction	?		?	?	?		?	?
Steppingstone for exotic species	?		?	?	?	+	?	?

Table 14. Comparative evaluation results (Armour rock and ERUS) for large crustaceans: Brown crab.

Taxonomic group	**Large crustaceans (Brown crab)**							
Location	**North Sea & Northwest Atlantic**							
Element	**Armour Rock**				**ERUS**			
Design feature/ Function	Surface Area/ volume	Rugosity, Relief	Porosity, geometry, orientation	Material Composition	Surface Area/ volume	Rugosity, Relief	Porosity, Geometry, Orientation	Material Composition
Settlement								
Shelter	?			?	?	+		?
Feeding			?			+	?	(leakage)
Reproduction	?		?	?	?	+	?	?
Steppingstone for exotic species	?		?	?	?	+	?	?

Settlement: Neither armour rock nor ERUS directly facilitate larval settlement. The most critical component for this function is the filter layer, which is assumed to be composed of rock in both cases. Settlement is only likely if the rock grading is sufficiently small. However, the presence of adult individuals within the armour layer can enhance larval settlement, leading to a higher overall settlement rate across a wind farm. Additionally, a "communicating" system is necessary, one that allows for adequate gene flow and mixing of populations. In the United States, for example, there is a strong coastal larval flow, with larvae arriving from locations up to two weeks upstream.

Shelter: Juvenile European and American lobsters are likely to use ERUS for shelter. However, the overall setup assuming the representative ERUS of a cube measuring 0.4m only, is too small to accommodate adult lobsters. Both the rock grading and ERUS structures can only support a limited range of juvenile sizes. A broader range of crevice and hole sizes is needed to support lobster growth effectively. Larger structural designs would be required to provide meaningful shelter benefits for lobsters, as the holes and crevices of the ERUS and armour rock are not likely to be used by adult. Nevertheless, by increasing the biomass of smaller species, both armour rock and ERUS can enhance food availability, which indirectly benefits lobsters. ERUS is expected to perform slightly better in this regard due to its higher porosity.

For crabs, the shelter function is more effective. Due to their smaller size and greater flexibility, crabs are expected to benefit more from both armour rock and ERUS scour pads. They can easily find suitable shelter in both types of structures.

Feeding: Food availability is crucial for lobsters. Greater surface area increases the likelihood of encountering sufficient food, which is especially important for lobsters. Their tails function as food storage, allowing them to feed in pulses when food is available. A 30 cm lobster, for instance, requires a substantial amount of food and could potentially consume all suitable prey on a single scour pad. While lobsters typically remain near their home pad, they will migrate between scour pads if food is scarce. The average transit distance is up to 2 km, though some individuals may travel farther.

Crabs, on the other hand, are more flexible in their diet and do not need to go as long between feeding events. The structure of both armour rock and ERUS will benefit smaller crabs and other small species, which in turn may attract larger crabs such as brown crabs that prey on them.

Reproduction: Neither ERUS nor armour rock is suitable for lobster reproduction. Lobsters begin reproducing at sizes of 25 cm or more and require larger crevices that can accommodate both a male and a female. Some of the larger artificial reef units may be more appropriate for reproductive purposes.

In contrast, the available spaces in both armour rock and ERUS are suitable for crab reproduction, with ERUS having a slight advantage due to its greater porosity.

Stepping stones: Increased porosity in structures like ERUS may facilitate the movement of invasive or climate-driven migrating species. As such, ERUS could serve as a more effective stepping stone. Whether this is beneficial or harmful depends on the species involved. For example, the introduction of American lobsters into the North Sea could be detrimental due to the risk of interbreeding and the creation of hybrids.

Both lobsters and crown crabs are known to migrate seasonally over distances, over hundreds of kilometres even. Scour pads can serve as stepping stones (not related to non-indigenous species colonization) during these migrations, with the ecological impact again depending on the species involved.

Community development and species behaviour: A newly installed ERUS scour pad will not immediately become a relevant habitat. It typically takes 4–5 years for the community to fully establish and become attractive to lobsters. Some lobsters on the North Sea bed are transient, having been displaced by currents. These individuals will only remain in an area if food availability is sufficient. Female lobsters tend to stay within their home range, while males are more likely to travel. American lobsters can inhabit very deep waters, whereas European lobsters are generally found at depths of 30–40 meters.

5.2.6 Taxonomic group: Flatfish

The interview was conducted with Jolien Buyse (PhD) from ILVO who is studying the ecological effects of anthropogenic activities on the marine environment with a focus on OWF, especially on demersal fish.

Table 15. Comparative evaluation results (Armour rock and ERUS) for flatfish.

Taxonomic group	**Flatfish**							
Location	**North Sea**							
Element	**Armour Rock**				**ERUS**			
Design feature/ Function	Surface Area/ volume	Rugosity, Relief	Porosity, geometry, orientation	Material Composition	Surface Area/ volume	Rugosity, Relief	Porosity, Geometry, Orientation	Material Composition
Settlement								
Shelter	x	x	x	x	x	x	x	x
Feeding								
Reproduction	x	x	x	x	x	x	x	x
Steppingstone for exotic species	x	x	x	x	x	x	x	x

Flatfish and other demersal fish species are often attracted to scour protection structures around offshore wind turbines primarily due to the presence of feeding hotspots on hard substrate and soft sediments nestled between the rocks of the armour layer which provide habitat. Observations show a progression of species starting with mussels, shells, and *Asterias rubens* near the monopile, followed by pouting fish (*Trisopterus luscus*) in the inner armour layer, and eventually flatfish as sediment accumulates. This effect is due to microhabitats providing accessible food sources, such as benthic invertebrates, which are easier for these fish to exploit compared to surrounding seabed areas and reduce their need for extensive foraging.

The degree of attraction to scour protection varies depending on the design and environmental conditions of each wind farm. For example, the Egmond aan Zee OWF has a scour protection pad that resembles a closed rock field, which lacks soft sediment that is interspersed among rocks. Consequently, this scour pad type does not attract flatfish significantly. Meanwhile, the Belwind OWF features substantial sedimentation on the scour protection, creating more suitable habitats for flatfish. The absence of an armour layer near the monopile has led to higher densities of demersal fish. Thus, increasing the surface area of scour protection can enhance biofouling and prey abundance, but it should not compromise the availability of soft sediment in order to achieve an attraction effect.

To enhance the ecological value of scour protection for flatfish, a heterogeneous design is recommended, incorporating a mix of small and large elements and varying hole sizes to increase habitat complexity. The design should ensure that sand patches occur within the elements to support soft sediment benthic species, which serve as prey for fish. Where possible, a gradual transition from hard substrate areas to surrounding soft sediments should be implemented to mimic natural habitats, i.e. gradual decrease in rock density rather than an abrupt change between hard and soft substrate. While the material type of scour protection may influence the composition of biofouling communities, and thus prey availability, there is limited research on its direct impact on flatfish feeding behaviour.

Meanwhile, scour protection does not appear to influence fish reproduction, which is more dependent on environmental factors like currents and tides that transport eggs to nursery areas. Additionally, there is no evidence that demersal fish use scour protection for shelter. Similarly, the presence of exotic species is generally unaffected by scour protection, although certain native species, such as lemon sole, may be more attracted to gravel-like substrates.

5.2.7 Taxonomic group: Benthopelagic/Demersal fish

The interview was conducted with Jan Reubens (PhD) from the Flanders Marine Institute (VLIZ) where he is a postdoctoral research fellow and lectures on fisheries in the EMBC+ master programme.

Table 16. Comparative evaluation results (Armour rock and ERUS) for benthopelagic/demersal fish.

Taxonomic group	**Benthopelagic/Demersal fish**							
Location	**North Sea & Western North Atlantic**							
Element	**Armour Rock**				**ERUS**			
Design feature/ Function	Surface Area/ volume	Rugosity, Relief	Porosity, geometry, orientation	Material Composition	Surface Area/ volume	Rugosity, Relief	Porosity, Geometry, Orientation	Material Composition
Settlement								
Shelter								
Feeding								
Reproduction								
Steppingstone for exotic species								

It can be expected that many of the ecological dynamics observed in the North Sea may also be present in the US Atlantic. Species composition and attraction patterns are likely to be similar, although differences may arise due to species-specific traits. Importantly, fish exhibit individual behaviours, meaning that observed patterns may not always be representative of the entire species. Therefore, inter-specific differences are anticipated, but cannot be confirmed without targeted research and replication.

The effectiveness of ecological restoration using elements such as ERUS depends heavily on the specific project objective. While ERUS offers a wide range of possibilities, the design must be tailored to the target species and local environmental conditions.

Settlement is not universally relevant for all benthopelagic fish. For example, herring require hard substrates for egg deposition. However, the organisms that settle on rocks may attract fish to those areas.

Egg deposition is influenced by several factors, including pH levels. ERUS structures tend to have a higher pH than traditional armour rock, which could influence the potential for settlement.

The relationship between settlement and surface area also varies by species, as some use these areas specifically for egg deposition.

Shelter is significantly influenced by habitat heterogeneity. By combining rocks or units of different sizes, a wider range of organisms can find suitable shelter. In this context, the material composition is less critical than the structural complexity. Features such as interconnected holes increase both heterogeneity and surface area, enhancing the habitat's suitability. However, attracting one species may inadvertently deter others. The size and shape of holes can influence which species are attracted, and the initial attraction of one species can affect subsequent colonization by others. A positive association was found between reef holes and cavities (i.e. void spaces) and hole size with the body sizes of fishes found sheltering in them (Hixon & Beets, 1993; Beets & Hixon, 1994; Friedlander & Parrish, 1998). Smaller reef fishes had higher survival rates on reefs with smaller hole sizes compared to similar sized fish on reefs with larger holes (Hixon & Beets, 1993; Pondella & Claisse, 2022).

Feeding behaviour varies and is influenced differently by structural features. Demersal fish, often day feeders, tend to remain near a single turbine during daylight hours. Their diet includes *Jassa herdmani* mats, small mussels (*Mytilus edulis*), Brittle Stars. Grazers, which feed on organisms growing on the structures, are not affected by heterogeneity, material, or orientation. They will feed on whatever is available. While a larger surface area can support more grazers, it does not change their fundamental feeding behaviour. In contrast, ambush predators benefit from structural complexity, using holes to hide and attack passing prey. Additionally, if structures are positioned too high in the water column, they may primarily benefit pelagic species. The geometry and orientation of the structures thus influence which species groups can utilize them. For example, an abundance of crustaceans may attract more predators that feed on them.

Although eggs and settlement were discussed, they are not the primary focus in this context. Some small species may use crevices for egg deposition, but this is not a central consideration for the current analysis.

The stepping-stone effect, which facilitates the spread of exotic species, is not a major concern in this scenario. For highly mobile species, the design of the structures plays a minimal role in this effect, which is primarily influenced by broader ecological factors.

5.3 Conclusion

This evaluation highlights the comparative ecological potential of traditional armour rock and ERUS in enhancing marine biodiversity and ecosystem functioning at OFW sites. While many of the patterns observed are based on expert knowledge of the North Sea, they are expected to be broadly applicable to the western North Atlantic as well. Similarly, species-specific behaviours and ecological functions must be considered, as generalizations as they may not hold across or even within a specific taxonomic group.

Drawing on expert assessments across multiple taxonomic groups and ecological functions, the analysis reveals that ERUS present opportunities to be engineered in a way to further enhance ecological functioning compared to armour rock in some areas to target specific requirements or preferences of chosen groups.

ERUS show advantages in terms of surface area, porosity, and habitat heterogeneity, which are features that are important for supporting settlement, shelter, and feeding functions across a wide range of marine organisms. These advantages are particularly pronounced for sessile bivalves, polychaetes, hydrozoans, bryozoans, and small crustaceans, which benefit from the increased microhabitat complexity and internal cavities provided by ERUS. For larger crustaceans and demersal fish, ERUS offer modest improvements, particularly in shelter and food availability. Meanwhile there are limited effects in supporting adult reproductive behaviours due to size constraints.

The findings also highlight the importance of tailoring scour protection design to specific ecological goals and local environmental conditions. Factors such as pH levels, material composition, and the spatial arrangement of elements can influence ecological outcomes. Design uniformity in traditional armour rock limits ecological potential. Moreover, the potential for ERUS to act as stepping stones for both native and invasive species warrants careful consideration in future deployments.

To maximize ecological benefits, experts recommended to diversify ERUS designs, by e.g. incorporating a mix of materials and different element sizes in one scour protection heap, as well as designing as much as possible for a gradual transition between hard and soft substrates.

While ERUS present a promising tool for ecological enhancement, further research is needed to assess long-term impacts, and cost-effectiveness in various marine settings. Table 17 was created based on the above expert judgement evaluation to visualize the comparative findings across the taxonomic groups and different functions. As stated in the methods section of this chapter though, the colour coded evaluation is to be understood as indicative only and needs to be understood in the narrative context of each taxonomic group, as the method leaves room for different interpretation of the categories.

Table 17. Summary overview of expert judgement ecological evaluation on armour rock and ERUS.

Element Design feature/ Function	**Armour Rock**				**ERUS**			
	Surface Area/Vol	Rugosity, Relief	Porosity, geometry, orientation	Material Composition	Surface Area/Vol	Rugosity, Relief	Porosity, geometry, orientation	Material Composition
Sessile Bivalves	settlement shelter	settlement shelter	settlement shelter		settlement shelter	settlement shelter	settlement shelter	
Sessile Bivalves - flat oyster		Settlement Shelter	Settlement Shelter	Settlement		Settlement Shelter	Settlement Shelter	Settlement
sessile polychaetes	Settlement Feeding Stepping Stone	Settlement Shelter Stepping Stone	Settlement Feeding Stepping Stone	Settlement	settlement Feeding Stepping Stone	settlement Shelter Stepping Stone	settlement Feeding Stepping Stone	settlement
Hydrozoans & Bryozoans	Settlement Feeding	Settlement Feeding	Settlement	Settlement Feeding	settlement	settlement feeding	settlement Feeding	Settlement
small crustaceans	settlement shelter	Settlement Shelter Feeding Reproduction Stepping Stone	Settlement Shelter Feeding Reproduction Stepping Stone	Settlement	Settlement Shelter	Settlement Shelter Feeding Reproduction Stepping Stone	Settlement Shelter Feeding Reproduction Stepping Stone	settlement
large crustaceans	Settlement Feeding	Settlement Reproduction Shelter Stepping Stone Feeding	Shelter	Settlement Feeding	Feeding	Settlement Reproduction Shelter Stepping Stone Feeding	Settlement Shelter	Feeding
Flat Fish	Settlement Feeding	Settlement Feeding	Settlement Feeding	Settlement Feeding	Settlement Feeding	Settlement Feeding	Settlement Feeding	Settlement Feeding
Benthopelagic Fish	Shelter	Shelter Settlement Feeding	Shelter Feeding	Shelter	Shelter Reproduction	Shelter Settlement Feeding	Shelter	Shelter

In general, natural reef ecosystems should not be compared directly with artificial ones, irrespective of their material base (rock, concrete or other). A natural reef system is by nature stable since it is very old; ecological communities and succession are therefore developed. An artificial reef based on concrete or rock will not have the same level of ecological maturity.

Rocks of SPLs have been proven to attract biodiversity and enhance the ecosystem functioning on a local scale (see chapter 1). A typical SPL consists of natural rocks that could resemble gravel beds (although much more concentrated in one location) or natural rocky reefs in e.g. the southern North Sea. Even though they resemble these habitats, they do not host the same biodiversity, since they are affected by the presence of hard-substrate species on the turbine foundations and their deposits. Furthermore, they are not as scattered, and therefore, they might not allow for the presence of deposit feeding organisms, and on the opposite side attract more suspension feeders. Thus, the communities on typical scour protection layers cannot be compared to those of natural rocky reefs.

Artificial reefs made of concrete attract again a different composition of species. Concrete reefs can be designed to attract a specific species of interest or boost biodiversity in general. Concrete has the following advantages: adjustment of the surface condition (roughness, texture, etc.), adjustment of the porosity and regulation of the pH of the material to promote the creation of habitat.

The simultaneous immersion of rocks and concrete has indicated that biodiversity can be enhanced by this mixture due to the attraction of a larger array of species (Kingma et al. 2024). Therefore, the combination of rocks and concrete structures with crevices and habitat heterogeneity could potentially increase biodiversity, but further research is needed on a large scale to prove whether this can actually happen.

6 Ecological dimensions of offshore decommissioning

This chapter elaborates on the growing importance of decommissioning as more and more offshore installations in the southern North Sea reach the end of their operational phase. This process involves not only technical and logistical challenges but also broader environmental and societal considerations, shaped by complex policy and legislative frameworks. A desk study was performed to gain an understanding in the different decommissioning strategies that exists (from full removal to reefing and alternative uses) with each carrying different ecological trade-offs. In addition, a workshop was organized to gain input on decommission perspectives from different stakeholders within this field.

6.1 Introduction

6.1.1 Offshore artificial structures and their lifespan

The construction of offshore anthropogenic structures in the North Sea initiated in the early 1960s, when the first offshore gas platform was installed. Since then, many more platforms and offshore wind turbines have been deployed. Over 2,500 turbine foundations have been installed, with life spans of around 20-35 years (Chirosca et al., 2022). After this duration, offshore wind turbine foundations need to be decommissioned. The decommissioning of the first offshore wind farm in the world (Vindeby Offshore Wind Farm, Denmark) has already been completed in 2017, after 25 years of operations (Lempriere, 2017). The decommissioning of other offshore wind farms in the southern North Sea is already on the table (e.g. Egmond aan Zee in the Netherlands, C-Power in Belgium) (Offshore Energy Association 2025).

Decommissioning aims to retire facilities or processes in a manner that ensures the safety of public health and the environment. Recent studies have emphasized the need to consider alternative decommissioning approaches beyond complete removal. A key aspect of this discussion involves weighing the energy costs and CO_2 emissions associated with removing structures against the benefits of leaving steel resources *in situ* that could be repurposed or recycled (Knights et al., 2024a). Possible options include complete removal, abandonment *in situ*, partial removal, partial or complete relocation, and repurposing structures as artificial reefs (for more details see section 6.1.3).

In this chapter, we are specifically discussing the effects of decommissioning of OWFs, specifically of monopile foundations and associated scour protection infrastructure that may also function as artificial reefs. The work focused on the marine environmental and ecological effects, while also taking into consideration existing knowledge from other offshore structures, such as O&G platforms.

6.1.2 Current policies and legislations regarding decommissioning of offshore structures

Current legislation is complex and operates at multiple levels. There is no legal basis for (full) decommissioning in the Dutch Environment and Planning Act nor in the Water Act. Globally, the United Nations Convention on the Law of the Sea (UNCLOS, 1982) mandates that unused structures shall be removed to ensure safety of navigation (Art. 60(3)). Article 60(3) does however not impose an obligation to remove offshore installations entirely, as it further states: '*Such removal shall also have due regard to fishing, the protection of the marine environment and the rights and duties of other States. Appropriate publicity shall be given to the depth, position and dimensions of any installations or structures not entirely removed*'. In addition, the International Maritime Organization (IMO) Resolution A.672(16) adopted on 19th of October 1989 provides guidelines and standards for the removal of offshore installations and structures on the continental Shelf and in the Exclusive Economic zone, which may give more concrete guidance.

The OSPAR Convention, however, provides additional guidance through its decision which are legally binding for the contracting parties of the OSPAR convention. Under OSPAR Decision 98/3, the practice of leaving rigs as reefs is prohibited. However, exceptions to complete removal (known as derogations) can be granted by regulators in exceptional cases where significant concerns exist regarding safety, environmental or societal impacts, costs, or technical feasibility. Out of the 170 structures decommissioned in the northeast Atlantic to date, only 10 have been granted derogations. In these instances, the concrete foundations of the platforms were left in place, while the upper sections of the substructures were removed (Knights et al., 2024b).

A more nuanced, case-by-case approach may better serve environmental and societal interests (Sommer et al., 2019). With many marine and offshore structures (MAS) nearing the end of their operational lifespan, there is an urgent need for decommissioning decisions. Unfortunately, the scientific evidence base required for making informed, comprehensive decisions about decommissioning options remains incomplete and insufficient (Lemasson et al., 2022, 2023).

6.1.3 Existing methods of decommissioning

There are currently different proposed (and in some cases executed) methods of decommissioning offshore artificial structures. These differ not only per structure type but also per area. There are multiple approaches to decommissioning infrastructure of offshore wind farms and O&G platforms, including the foundations, erosion protection layers, and cables. Foundations may be fully or partially removed, or left intact, while erosion protection layers and cables can either be removed or left in place (Figure 9).

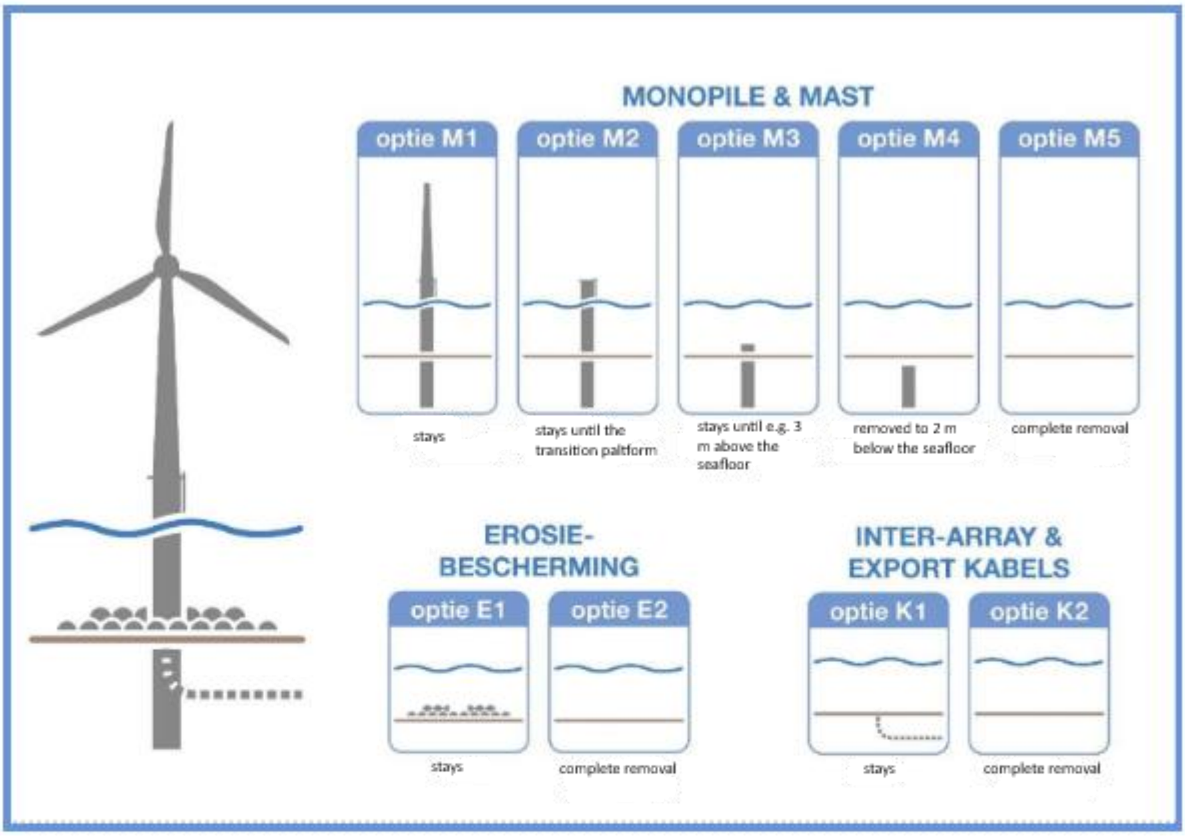


Figure 9. Options for decommissioning monopile foundations (*Source: Van Maele et al. 2023*).

Apart from the complete or partial removal, foundations could be horizontally placed as reefs in place or reefed elsewhere (Figure 10). Furthermore, these structures could also be alternatively used for multiple purposes, such as tourism, recreation, mariculture, energy generation, carbon capture storage, ocean instrumentation and research (Sommer et al., 2019). The potential for alternative use is influenced by various factors, including location (e.g. distance from the shore), water depth, structural type and condition, local environmental conditions, oceanographic characteristics, as well as technical and financial feasibility (Sommer et al., 2019).

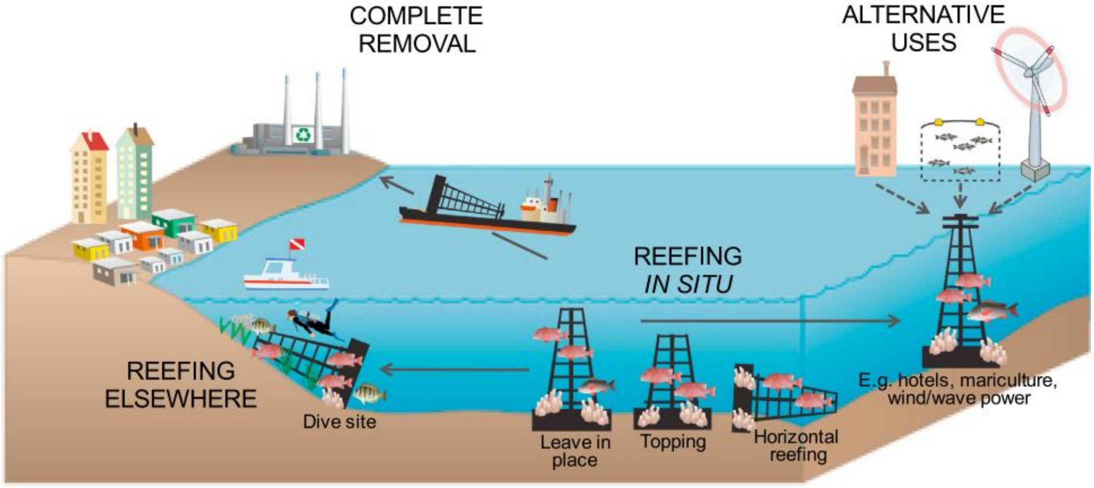


Figure 10. Decommissioning options for jacket foundations including complete and partial (topping) removal, reefing in place, reefing elsewhere and alternative uses (*Source: Sommer et al. 2019*).

In the case of artificial reefs, the decommissioning options are similar to those mentioned above, as they could either be completely removed or left in place, re-located or re-used. In this chapter, we will specifically focus on ERUS, which are designed to enhance the ecological success of installations, such as scour protection layers, by facilitating their capability of enhancing local biodiversity. We aim to identify ecological advantages and disadvantages of decommissioning artificial structures (both partially and completely), evaluating current decommissioning programs and providing recommendations on the potential decommissioning options of ERUS.

6.2 Methodology

The work of the consortium on the topic of decommissioning included a literature review, comprising OWF related information as well as oil and gas platform. The review contributed to identifying existing decommissioning methods (both used in practice and theoretically proposed) as well as known and anticipated environmental impacts.

Subsequently, the information was used in order to design a stakeholder engagement survey to gain insights into different sea user perspectives on the topic of decommissioning from an ecological view. This survey was shared with a broad range of stakeholders online and was open to anyone interested in responding. The survey was disseminated through the professional network of the consortium partners with a focus on North Sea and U.S. North Atlantic stakeholders.

The findings from the survey were analysed and informed the agenda for a smaller stakeholder engagement workshop held online. During the workshop, T.M. van Maele (Institute of Natural Sciences Belgium) presented her recent research on decommissioning OWFs in the Belgian sector and the results of the survey were presented to the participants. Three different discussion groups were hosted to discuss advantages and disadvantages of decommissioning from an ecological perspective as well as required monitoring to inform this decision-making process.

6.3 Environmental impacts of decommissioning

Given the global rates of habitat loss, fragmentation, and degradation (Reddin et al., 2022), the maintenance or creation of "novel" habitats associated with marine and offshore structures could contribute to biodiversity conservation efforts (Ben-Hamadou et al., 2023; van Elden et al., 2022). Regulatory requirements, tender criteria and guidelines encourage developers to implement not only mitigation measures but also compensation strategies, such as (re)creating or restoring habitats, which can potentially restore lost ecological structures and functions. However, these structures can also act as stepping-stones for spread of non-native species (Adams et al., 2014; Bulleri et al., 2006), introduce pollution (Breuer et al., 2008), and disrupt sonar systems (Todd et al., 2009), potentially causing harm to certain environments (Byrnes et al., 2007). As a result, some pressures associated with these structures may be seen as ecologically beneficial, while others are detrimental.

Consequently, decommissioning decisions often require a case-by-case approach (Fowler et al., 2018). In some scenarios, leaving offshore artificial structures in place is undesirable due to negative effects such as the facilitated spread of invasive species (Adams et al., 2014). However, in other contexts, some pressure-effects have been deemed advantageous, such as those enhancing trophic linkages, supporting tourism, providing habitat, increasing population sizes, or promoting stability in population dynamics (e.g., Fayram and De Risi, 2007; Friedlander et al., 2014; Bishop et al., 2017; Meyer-Gutbrod et al., 2020; McLean et al., 2022). Decision-making must, therefore, account for these trade-offs, balancing desirable and undesirable ecological effects (Knights et al., 2024a) while aligning with environmental strategic targets (Knights et al., 2014). In this section, we summarized some of the most mentioned positive and negative effects following full or partial decommissioning.

6.3.1 Negative effects of decommissioning

6.3.1.1 Destruction of established marine habitats

Decommissioning options have varying impacts on biodiversity, particularly when comparing partial and complete removal. Complete removal of all artificial structures results in the almost total loss of associated reef biota (Claisse et al., 2015; Pondella et al., 2015). Offshore structures can enhance both taxonomic and functional diversity by introducing hard substrates into predominantly soft-bottom environments, e.g. the southern North Sea. Consequently, complete removal in these regions is expected to lead to localized biodiversity declines as only the soft-bottom habitats are available for organisms to live in and on (Sommer et al., 2019). The location where the artificial structures are placed also plays a very significant role. If the artificial structures (especially in the form of scour protection layers) are placed in areas where natural hard substrate habitats occur, then the removal of these artificial reefs might have significant negative effects on the biodiversity occupying these structures. This is because it is expected that these artificial structures will be colonized by species that naturally occur in that area (Van Maele et al., 2023). But if they are placed in areas where natural hard substrates do not occur (or very scarcely occur), then the complete removal of the artificial habitats will lead to a decrease of the hard-substrate-related fauna, but the environment will eventually turn back to the previous conditions, where only soft-sediment-related fauna was present.

The effects of partial removal, however, are more complex and depend on the structure’s characteristics and the composition of its associated biological communities (Ajemian et al., 2015; Simonsen, 2013). If only the platform/turbine foundation is removed and the scour protection layer stays in place, a significant part of the biodiversity is lost, as the foundation-related fauna will be removed. The foundation-related fauna produces faeces and pseudofaeces, which are heavy materials that sink to the seafloor surrounding the turbine foundations and may serve as food sources for multiple invertebrates and vertebrates (Degraer et al., 2019). Thus, with the removal of the foundations, there will be no further accumulation of faeces or pseudofaeces on the scour protection layer, decreasing the presence of food sources. Subsequently, this might lead to a decrease in the presence of some species that are attracted towards the scour protection layers because of the increased feeding efficiency, e.g. cod. If part of the foundation is removed, then some influence from the fauna attached to the foundation will be present. However, this will also be different compared to the situation where the entire foundations remain in place, as a lot of mussels fall on the scour protection layers (Krone et al., 2013), but the main mussel zone (ca. 5 m depth) will very likely be removed. Therefore, the composition of materials falling on the scour protection will be different and that will have an effect on biodiversity. However, these effects have not been investigated on real decommissioning projects.

6.3.1.2 Release of contaminants

Chemical pollution from decommissioning operations is a more significant concern for the offshore O&G industry than for the OWF sector, Given that O&G access underground reservoirs, when these structures are being decommissioned the risk hydrocarbon contamination and other residues occurring in the production water (or produced water during operations) and accidental spills into the water column (Fortune & Paterson, 2020). This can be caused by the decommissioning activities that might disturb drill cuttings that have accumulated on the seafloor (especially in the case of O&G structures) (Breuer et al., 2004; Cordes et al., 2016).

For the OWF and artificial reef sector, contamination can be addressed differently. Decommissioning methods that leave components in place (partial removal), contaminant release can result from the degradation of infrastructure materials, such as sloughing fibers, flaking anti-fouling paint, polymer coatings, and corroded steel (Picken et al., 1997; Watson et al., 2023). Therefore, even during partial decommissioning, a lot of contaminants can be released into the marine environment. The effects of contaminants on marine life remain an active research focus, with recent studies exploring the mechanisms, as well as the spatial and temporal scope of their impacts (Main et al., 2015; Henry et al., 2017).

Decommissioning activities of offshore renewables and artificial reefs might further cause air pollution. This can arise from the release of gases during operations, including CO_2, NO_x, and fine particulates (Fortune & Paterson, 2020). Additionally, the discharge of grey water and ground food waste may potentially alter the local ecological balance through artificial nutrient inputs (Fortune & Paterson, 2020). However, these effects are expected to cease after decommissioning. Decommissioning methods that leave components in place can also contribute to localized contamination as materials degrade over time, such as anode materials commonly used to protect structures from corrosion in marine environments (Picken et al., 1997). The effects of contaminants on marine life remain an active research focus, with recent studies exploring the mechanisms, as well as the spatial and temporal scope of their impacts (Main et al., 2015; Henry et al., 2017). Once operations end, disturbances from noise, drilling and organic enrichment would also stop, while the response of the (marine) ecosystem to these changes remains largely unknown (Fujii, 2015).

Leaving structures in place will also harm the marine ecosystem and biodiversity. Over time, various pollutants, such as copper, other metals, zinc anodes, flaking paint, plastics and concrete (including grouting) will leach into the environment (Van Maele et al., 2023). Therefore, by removing the structures, the chances of pollutant removal can be eliminated.

6.3.1.3 Stepping-stone effect for invasive or non-indigenous species

Offshore marine renewable energy devices have been found to function as stepping-stones for non-indigenous species across biogeographical boundaries (Adams et al., 2014). The prolonged presence of offshore structures affects ecological diversity, productivity, and connectivity by influencing movement and dispersal (Henry et al., 2017; Sommer et al., 2019; McLean et al., 2022). This impact on species movement can be detrimental, such as by promoting the spread of non-indigenous species across a region (Sammarco et al., 2012; Anderson et al., 2017). Therefore, leaving artificial structures intact or partially removing them might further promote the spread of invasive and/or non-indigenous species. Especially leaving the entire turbine foundations, including the transition piece in the intertidal zones, might further promote the expansion of non-indigenous species, as these areas accommodate the greatest numbers of non-indigenous species compared to the subtidal parts of offshore wind turbine foundations (Kerckhof et al., 2011). Meanwhile, the removal of foundations or scour protection layers might lead to the unintended spread of non-indigenous species as the decommissioned infrastructure needs to be transported from the offshore site to shore and onwards to e.g. recycling plants. Without adequate handling, this process risks increasing the spatial distribution of non-indigenous species (Sommer et al., 2019).

6.3.1.4 Obstacles for other sea-users

In the case that (part of) the foundations remain intact, issues might occur regarding other sea users. For instance, any remaining structures can pose obstacles to shipping or fisheries and may present hazards to other maritime users (Van Maele et al., 2023). Therefore, it is essential to minimize safety risks as much as possible.

6.3.2 Positive effects of decommissioning

6.3.2.1 Biodiversity

Even though offshore artificial structures have been found to increase local biodiversity, this biodiversity is in most cases considered as "new nature", which is directly or indirectly connected to the artificial habitats (Van Maele et al., 2023). The species that colonize the artificial structures or are attracted to them are either absent from these locations or occur in much smaller abundances in these areas, since most of the offshore artificial structures in the North Sea are placed in mainly naturally soft-bottom habitats. Therefore, a distinction must be drawn between the biodiversity characteristics of the original habitats (which in the case of the southern North Sea often include dynamic sandbanks) and the new biodiversity that emerges on hard substrates introduced artificially (Van Maele et al., 2023).

Van Maele et al. (2023) suggests that the complete removal of structures supporting this new biodiversity is not problematic in areas that had different habitats prior to OWF installation. This is primarily because the new biodiversity is not deemed significant enough to warrant preservation in naturally dynamic sedimentary environments such as southern North Sea offshore wind farms, and because the natural biodiversity in these environments can withstand temporary disturbance caused by the decommissioning activities relatively well (Van Maele et al., 2023). Therefore, complete removal will not disturb the natural biodiversity, and may even allow it to recover.

On the other hand, the presence of O&G platforms and offshore wind turbine foundations in marine ecosystems has been found to enhance foraging opportunities for mobile species, such as cod and pouting (Mavraki et al., 2021), seals (Arnould et al., 2015) and harbour porpoises (Todd et al., 2022). Additionally, the concentration of offshore infrastructure may support regional fisheries by serving as an important source of population (Watson et al. 2023). The removal of these structures, particularly when multiple installations have been in place for decades, could significantly impact species movement patterns by eliminating key factors that initially attracted them, such as habitat availability and foraging resources (Watson et al., 2023).

Finally, leaving the scour protection layer in place might have positive impacts on (new) biodiversity, which can provide opportunities for other human activities (Van Maele et al., 2023). This could also apply for the ERUS units; however, their impact on biodiversity needs to be monitored to substantiate these assumptions.

6.3.2.2 Restoration of natural seabed conditions

When artificial hard structures are removed, natural biodiversity will slowly recover to its previous state. In the southern North Sea, this means that the biodiversity will again be dominated by soft-sediment species, most of which are adapted to living in or on permeable, medium- to coarse-grained sediments structured by sand dunes (Van Hoey et al., 2004, Breine et al., 2018). When removing the structures, the area might be repurposed for (previously conducted) activities, meaning that some harmful activities, such as bottom fishing, sand extraction, etc. If (part of) the offshore wind infrastructure is left intact, it might prevent such repurposing of these areas. If these activities do not occur, soft-sediment habitats and communities are automatically preserved, protected, and restored (Van Maele et al., 2023).

6.3.2.3 Elimination of navigational hazards

If all the artificial structures are removed, no navigational hazards will be present. Navigation risks must be minimized as much as possible for both large and small vessels. This includes preventing collisions (especially when large ships drift during severe storms) and ensuring safe anchoring. Every additional structure in the sea, particularly those that serve no purpose, increases these risks. Over time, cables and abandoned sections of monopile foundations can become exposed if left unattended or unmonitored. Therefore, beyond economic considerations, fully removing foundations and transition pieces is essential to ensure navigational safety (Van Maele et al., 2023). Similarly, fully removing scour protection layers could eliminate risks related to fisheries activities that could initiate in OWF areas after the decommissioning of the foundations.

6.4 Case studies of artificial reef effects

6.4.1 Examples of decommissioning projects and their outcomes

The Rigs-to-Reefs program is one of the most famous programs for reefing O&G platforms in the Gulf of Mexico. In this program, there are three primary methods for removing and reefing a decommissioned structure: (a) Tow-and-place, the structure is severed from the seafloor using either explosive or mechanical cutting techniques and then towed to a designated reef site for deployment; (b) Topple-in-place, the structure is detached from the seabed and toppled onto its side, remaining in its original location; and (c) Partial removal, this method (typically avoiding the use of explosives) involves severing the upper portion of the structure at an approved navigational depth, usually around 85 feet, and placing it on the seafloor next to the remaining base. Even though this program is considered a success for reefing O&G platforms, using explosives is very harmful for the marine environment and the communities that have been established at the base of the platforms. Furthermore, the methods applied in this program are not suitable for all types of foundations. The conversion of a platform into a permanent artificial reef must adhere to engineering and environmental standards. Key factors in assessing its reefing include platform size, structural complexity, integrity and location. Platforms that are complex, stable, durable and free of contaminants are generally suitable candidates for reefing, whereas those that have toppled due to structural failure are not[37]. Apart from this program, several smaller and individual reefing activities take place in different areas in the world. For example, a platform in Malaysia was re-purposed as a fish hotel and dive resort (Sommer et al., 2019) and in New York, artificial reefs are constructed using recycled materials, such as cars, to promote fishing opportunities (Annie Murphey personal communication).

6.4.2 Potential reefing in the North Sea

Potential alternatives to the full removal of offshore installations in the North Sea, such as the Rigs-to-Reefs program, have generally been discussed at a broad level. Discussions often focus on partial versus complete removal (Smyth et al., 2015) or explore the technical approaches available for implementing a small number of genuine alternatives, i.e. realistic, feasible and potentially viable options of stay-in-place structures (Kerkvliet & Polatidis, 2016). Smyth et al. (2015) also proposed that a 'renewables-to-reefs' program could offer a viable decommissioning strategy for offshore wind turbines in the North Sea. Fowler et al. (2018) identified nine possible alternatives to full removal of offshore installations in the North Sea, with expert assessments suggesting that many of these options could deliver environmental outcomes comparable to, or even better than, those achieved through complete removal. The same authors provide the following recommendations as to how to guide the revision of decommissioning policy and practices in the North Sea: (1) implementing a temporary suspension of mandatory removal requirements to enable research on the environmental impacts and ecological considerations, coupled with post-removal environmental monitoring; (2) formally permitting partial removal based on environmental considerations, coupled with post-removal environmental monitoring; (3) expanding the range of environmental assessments to account for the ecosystem services provided by offshore structures; (4) creating a comparative assessment framework designed to optimize decommissioning decisions by focusing on net environmental benefit; and (5) where feasible, extending the scope of assessments to evaluate ecological connectivity between groups of structures and surrounding ecosystems, rather than assessing structures in isolation (Fowler et al., 2018).

6.4.3 Lessons learned from past experiences in keeping artificial reefs

Comparative studies of biological communities across natural reefs, operational foundations, and reefed structures have demonstrated that factors such as depth, vertical relief, and the physical characteristics of installations significantly influence associated fish fauna (Ajemian et al., 2015, Claisse et al., 2015). These studies suggest that reefing is likely to alter community composition. For instance, research in the Gulf of Mexico found that fish assemblages differed markedly between operational and horizontally reefed platforms, whereas no significant differences were observed between operational and topped structures, indicating that topping may have a lesser impact on fish communities (Ajemian et al., 2015). In contrast, studies on fouling and benthic communities are more limited; however, no significant differences were detected in coral density

[37] https://www.bsee.gov/what-we-do/environmental-compliance/environmental-programs/rigs-to-reefs

(Sammarco et al., 2014) or in benthic community composition at distances of both less than 0.25 km and greater than 1.5 km from platforms in the Gulf of Mexico (Daigle, 2011). Therefore, the orientation of the structures could play a role in the community composition of some taxa. However, the location of the reefs will certainly play the most important role in the community composition of the entire fauna.

6.5 Decommissioning survey & workshop

On the 19th of November 2024, the partners of the SPREE project organized a workshop to discuss whether ERUS used for scour and cable protection should be decommissioned or not considering the potential ecological impacts of such programs.

Prior to the workshop, a survey was shared with a broad range of stakeholders, including ERUS producers, project developers, researchers, sea users, licensing bodies, etc. The survey was mainly answered by researchers, followed by innovators and project developers (Figure 11).

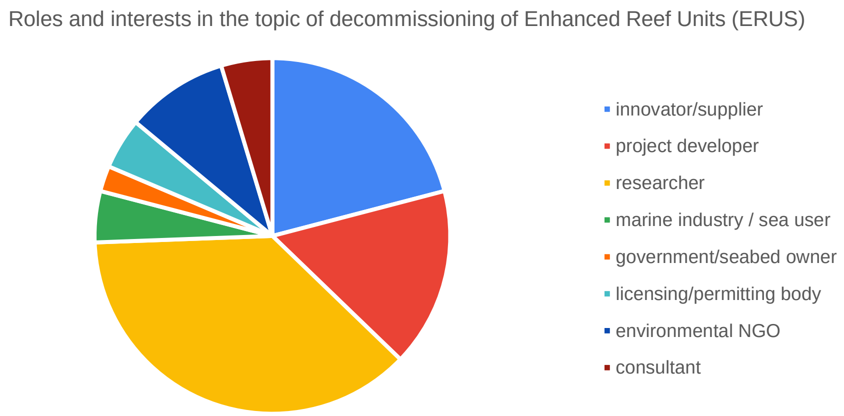


Figure 11. Stakeholder participation decommissioning survey.

6.5.1 Survey outcomes

The online survey provided insights into themes and perspectives that participants deemed relevant with regards to decommissioning of ERUS.

The survey indicated that high priority should be given to the ecological impacts of decommissioning when taking decisions regarding permitting, designing and/or using ERUS units (Figure 12).

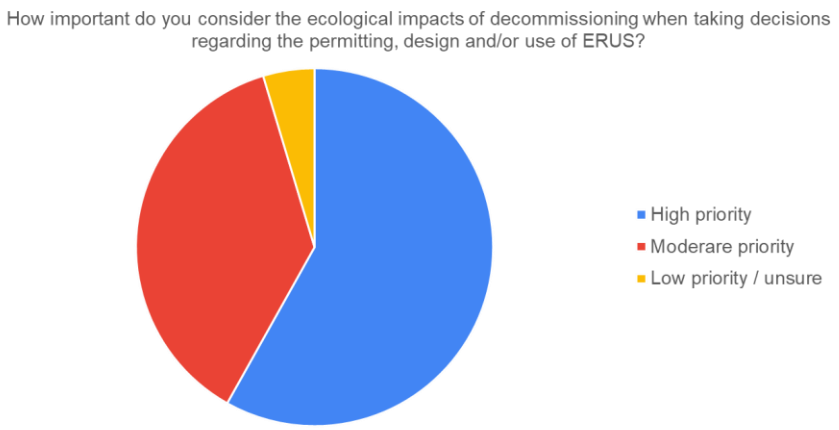


Figure 12. Answers of the stakeholders to the question whether ecological impacts of decommissioning should be considered when taking decisions regarding the permitting, design and/or use of ERUS.

Habitat provisioning and ecological connectivity are considered important indicators of ecological values of ERUS, while their importance for commercial species was the least important indicator (Figure 13).

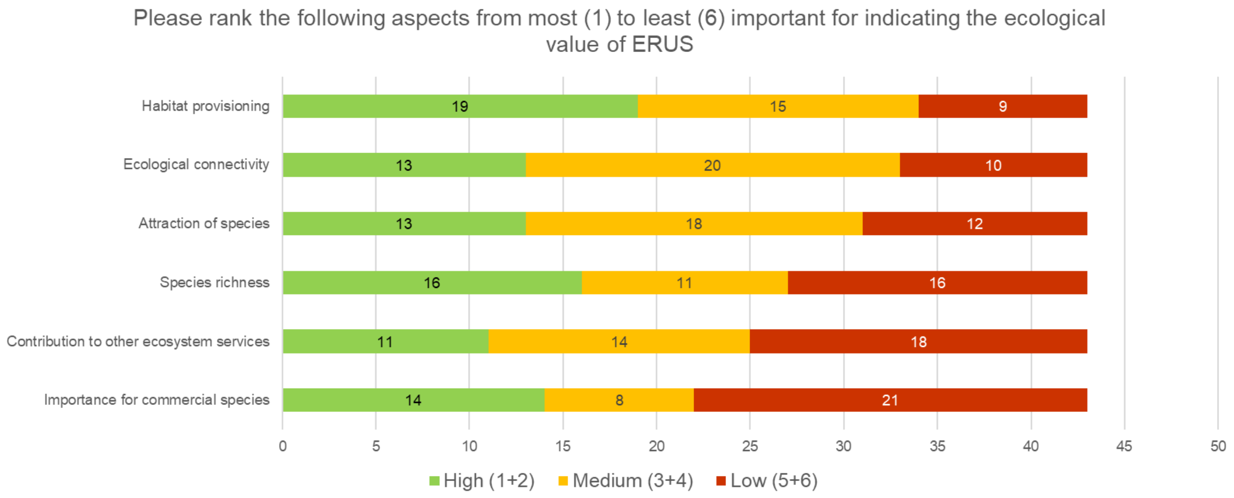


Figure 13. Ranking provided by the stakeholders when asked to indicate the importance of the ecological value of ERUS.

Partial decommissioning with removing the entire monopile and leaving ERUS and cables in place was the most preferred decommissioning scenario, while full decommissioning of all offshore wind farm infrastructure was the least preferred scenario (Figure 14). The survey participants indicated that ERUS should be removed if they are providing stepping-stones for invasive species or if they accommodate different biodiversity than the natural biodiversity in the surrounding environments (Figure 15).

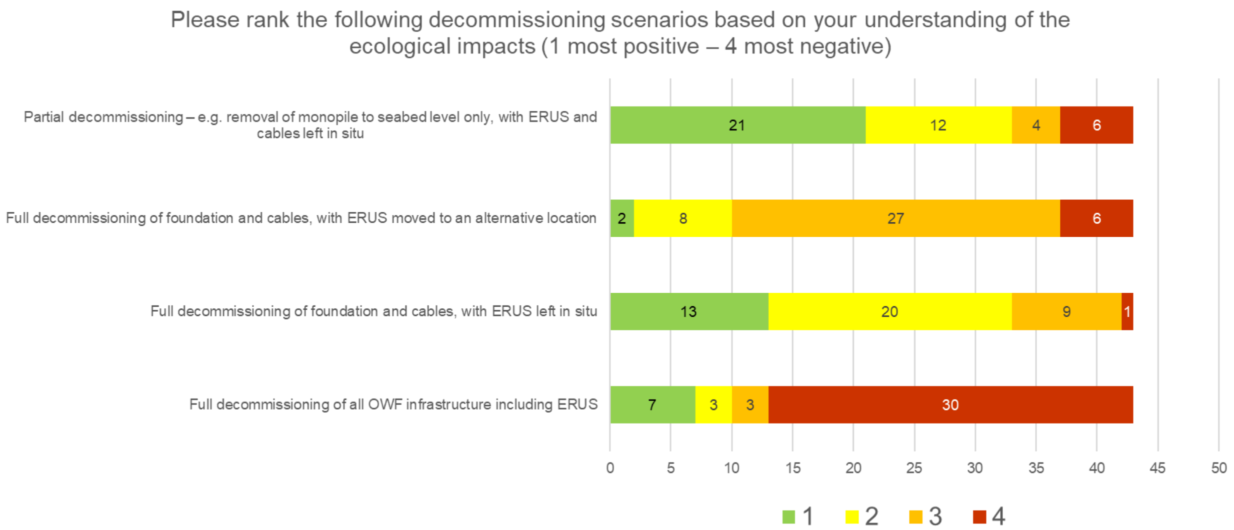


Figure 14. Ranking provided by the stakeholders when asked to indicate which decommissioning scenario would be the best when considering ecological impacts.

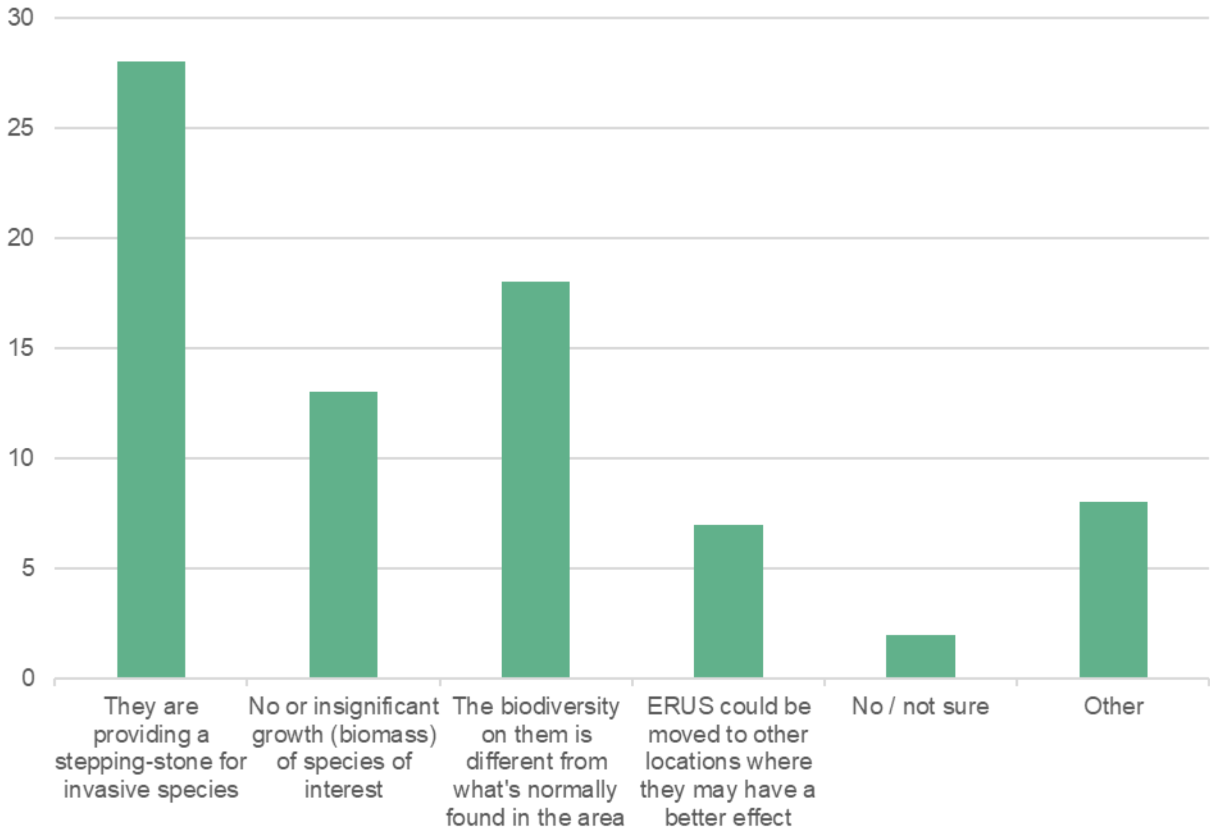


Figure 15. Answers of the stakeholders when asked under which circumstances ERUS should be absolutely removed.

Most of the participants indicated that ecological monitoring of the area after decommissioning is highly important, while the frequency of ecological monitoring should be adaptive depending on the findings (Figure 16).

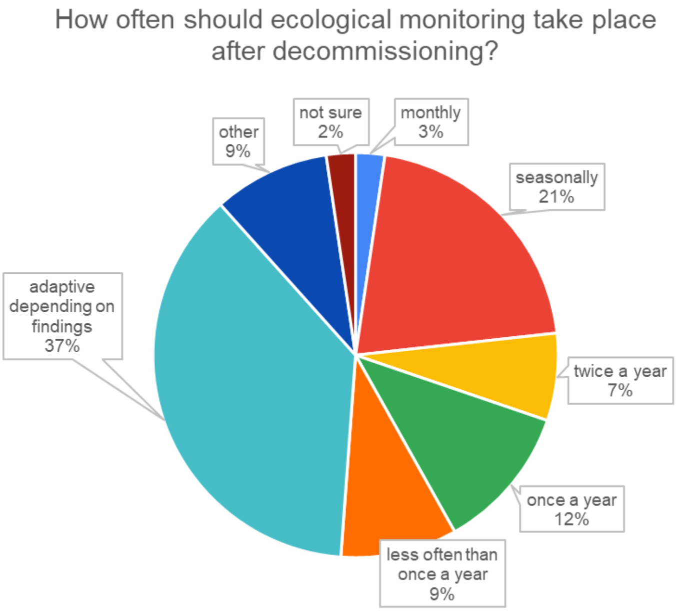


Figure 16. Frequency of ecological monitoring following decommissioning based on the answers of the stakeholders.

When thinking of the concerns about the end of life of ERUS units, the participants mainly considered the value of the seabed for other users and the carbon release from seabed disturbance, while they indicated that long-term ecological monitoring of existing projects and impact assessments from similar projects are needed to understand the effects of decommissioning of these units.

6.5.2 Workshop outcomes

After an introductory session in which the SPREE project was presented and Tine Miet van Maele shared insights on current decommissioning practices in Belgium, participants were divided into three groups to discuss key topics: (a) the circumstances under which ERUS should be fully or partially decommissioned, (b) what should be leading determinants for not decommissioning ERUS units, and (c) monitoring requirements following decommissioning.

6.5.2.1 Under what circumstances should ERUS (not) be decommissioned?

Decommissioning strategies should consider whether the environmental impact of removal is likely to be greater than the potential negative effects of leaving ERUS in place. As suggested in Chapter 3, workshop participants highlighted that ERUS can facilitate specific ecological functions, making this a key consideration in decommissioning decisions. The retention of ERUS is particularly important if they fulfil a functional role for endangered species, support diverse and dynamic ecosystems beyond mere biomass accumulation, enhance ecosystem connectivity by acting as stepping-stones across marine environments and contribution to habitat creation or biodiversity enhancement relative to the wider area. The presence of endangered (Red List) species utilizing these structures, or the provision of nursery grounds for marine species, can indicate such ecological value and should be a crucial factor in decommissioning decisions. Similarly, where ERUS exhibit strong ecological connectivity with adjacent natural reefs (in terms of species composition and biodiversity) or contribute positively to the natural ecosystem functions and services (e.g., fisheries) of the area they can be considered as enhancing the broader ecosystem value, rather than fostering the development of novel, artificial ecosystems. Hence, participants put a strong emphasis on the specifics of each installation site of ERUS. Only where marine growth on ERUS is compatible with the surrounding environmental conditions and substrate types, partial or no decommissioning should be considered. In the absence of these types of value additions, the recommendation was for ERUS removal.

Moreover, even if positive ecosystem enhancement effects can be found, participants suggested that they should be weighed in light of ERUS' potential to facilitate the spread of non-indigenous species, a risk associated with leaving such structures in place. Invasive species could occupy ecological niches traditionally held by native species, thereby altering ecosystem functionality.

Another aspect of consideration was the material of ERUS compared to conventional rock structures. The material composition of ERUS was questioned given the potential for degradation (especially in the case of concrete) and subsequent environmental contamination. ERUS are often constructed using innovative techniques and materials for which knowledge on their long-term performance in offshore environments is limited. The uncertainties surrounding their material degradation, reusability, and recyclability was stressed as a point of consideration and further research focus.

In addition to net environmental impacts, participants suggested a more comprehensive and site-specific assessment of the impact of decommissioning will always be required. National legislation was identified as a significant factor in determining whether artificial reefs are currently permissible, often reflecting ecological, societal, or combined priorities regarding the deployment of artificial structures. Within the North Sea, the United Kingdom and Belgium prioritizes the protection of existing ecosystems, while the Netherlands has adopted a strategy aimed at enhancing the marine environment and restoring historic hard substrate ecosystems. These differences are shaped by broader ecological goals, such as biodiversity restoration and addressing the impacts of historical human activities. In contrast, on the U.S. Atlantic East Coast, offshore wind farms are more widely spaced and exposed to harsher environmental conditions. Here, extensive commercial and recreational fishing within offshore wind farms complicates ecological dynamics, such as the proliferation of black sea bass, a species that preys on already declining lobster populations. Moreover, in the U.S., legislative frameworks and ecological understanding regarding ERUS are still less developed than in Europe. Such differences also highlight the necessity for cross-border cooperation if ERUS are to be effectively used to restore marine ecosystems at a larger scale.

Lastly, the end-of-life management of decommissioned ERUS should be included in decommissioning decision-making. If onshore disposal is likely to generate environmental impacts, leaving the structures in place at sea (where they may continue to deliver ecological benefits) could be a more sustainable option. Clear consent procedures and administrative frameworks are necessary, which account for factors such as energy input for removal, benthic disturbance, stakeholder input, and the end-of-life management plan for the ERUS structures should be applied.

6.5.2.2 Monitoring strategies for ERUS locations under different decommissioning options

The survey results identified habitat provisioning as the most important ecological feature of ERUS. This is unsurprising given that ERUS are designed to provide habitat, directly influencing species richness and abundance. However, while habitat provisioning is crucial, it is complex and therefore not the best sole indicator of ERUS performance. More relevant measures include species diversity, ecosystem viability, and food web impacts. Some caution was also noted by participants regarding potential bias in terminology, as habitat provisioning intuitively sounds positive compared to habitat destruction. Additional indicators, such as food provisioning and ecological connectivity, were recommended for more robust ecological assessments.

Participants agreed that effective monitoring must focus on biodiversity metrics (e.g., species richness, benthic communities, habitat use) and that specific monitoring strategies need to adapt to site-specific environmental conditions (substrate type, hydrodynamics, depth). To allow comparison of performance of ERUS between different sites, participants proposed that the focus should be on ensuring that these physical factors were fully accounted for and that this was more important than developing new policy metrics (such as 'marine net gain' or 'biodiversity positivity') to allow cross-site comparisons.
Monitoring should compare sites before and after decommissioning, as well as decommissioned and non-decommissioned sites. Key variables could include long-term material degradation (e.g., leaching), changes in seabed use (e.g., reopening to fishing), and sediment dynamics following structure removal. Establishing a post-decommissioning environmental baseline is important for understanding ecological shifts.

Adaptive monitoring was the most supported strategy by the workshop participants, supplemented by seasonal surveys. A minimum of 2–3 years of post-decommissioning monitoring was suggested by participants as necessary to detect real ecological changes, with a strong preference for at least 5 years of data collection. Monitoring should begin pre-installation, continue throughout operations, and be sustained after decommissioning, ideally following a decision-tree framework that uses ecological goals as guideline. Monitoring may initially be frequent (seasonal) but could be reduced over time unless key triggers, such as the emergence of invasive species, are observed. Monitoring may initially be frequent (seasonal) but could be reduced over time unless key triggers, such as the emergence of invasive species, are observed.

6.5.2.3 Overall outcomes of the workshop

It was clearly indicated that location is the key aspect when considering decommissioning of any type of offshore artificial hard structure. Further conclusions of the discussion include:

- ERUS should remain if they support ecosystem connectivity and native species.
- Risks of promoting invasive and non-indigenous species should always be considered.
- Material degradation and pollution risks must always be taken into account.
- National legislations and end-of-life options influence decisions.
- Species diversity, ecosystem viability and food web impacts should be included in monitoring strategies.
- Adaptive, long-term monitoring (preferably ≥5 years) recommended.
- Monitoring should be site-specific and contribute from pre-installation through post-decommissioning.
- The presence of red list/endangered species, nursery habitat provisioning, overall contribution to biodiversity and ecosystem services and net ecological benefits can be considered as determinants for not decommissioning.
- Cross-border cooperation is needed for effective ERUS deployment and decommissioning strategies.
- Further research is needed on ERUS material behaviour, ecological impacts and post-decommissioning processes.

6.6 Recommendations and policy considerations

Ecosystems react differently to the presence of artificial infrastructure (i.e. offshore wind farm foundations, ERUS, scour protection layers, etc.) depending on their location. For example, leaving foundations (for example rigs) intact in the North Sea impacts marine life differently than abandoning rigs off the coast of Thailand. Whether these changes are beneficial enough to justify alternatives to removal depends on regional stakeholder priorities (Knights et al. 2024b). In the United States, protecting cowcod is a significant concern, while in the North Sea, maintaining access to fishing grounds can take precedence (Knights et al. 2024b). As a result, artificial structure decommissioning should be approached on a local, case-by-case basis rather than applying a universal strategy.

6.6.1 Ecological best practices of decommissioning

Ecological communities from both artificial and natural habitats interact in intricate ways that influence ecosystem functions and services (Hobbs et al., 2014). These interactions must be taken into account when evaluating decommissioning options (Sommer et al., 2019). A pragmatic approach to offshore decommissioning that sets realistic objectives and considers a broader range of options, including partial removal, is more likely to deliver positive environmental outcomes (Fowler et al.,, 2018). Ecological best practice requires evaluating each structure individually rather than applying a one-size-fits-all policy (Fortune & Paterson, 2020). Based on the same authors, factors that should be considered when talking about ecological best practices of decommissioning include depth, orientation, biodiversity supported, and ecological connectivity.

There are benefits and disadvantages to any type of decommissioning. Focusing on partial removal (e.g. topping), we can retain up to 80% of the fish biomass and support reef-like ecosystems, preserving habitat and food webs (Fortune & Paterson, 2020). Leaving structures in place or opting for partial removal may help avoid the emissions and habitat destruction linked to full decommissioning. Such approaches could also be ecologically more beneficial than full removal, particularly in deeper waters where structures are extensively colonized (Fortune & Paterson, 2020). However, these potential benefits have not yet been scientifically proven.

Policy and management should incorporate up-to-date ecological data rather than adhering strictly to existing legislation (e.g. OSPAR Decision 98/3). Epifaunal and fish communities that develop on and around offshore artificial structures offer important ecosystem services and should be included in environmental impact assessments (EIAs).

Lack of baseline ecological data hinders accurate assessment of impacts (Fortune & Paterson, 2020). Ecological best practice should include long-term, systematic monitoring before and after decommissioning. Methods like eDNA sampling, acoustic sensors, and ROV imagery can enhance data collection. Furthermore, offshore artificial structures serve as stepping-stones and refuges for marine life, affecting regional biodiversity and population dynamics (Schroeder & Love, 2004) and understanding the connections, both biological and physical is highly important for determining the implications of decommissioning structures (Fortune & Paterson, 2020).

Marine growth (biofouling) is often treated as waste, but has ecological value, which should be considered when deciding about decommissioning. Drill cuttings should be assessed for contaminants and in some cases, they should be left undisturbed to avoid spreading pollution (Fortuner & Paterson, 2020).

To conclude, ecological best practice in offshore decommissioning emphasizes adaptive, science-driven management, incorporating local ecological values, enhanced monitoring and recognition of offshore artificial structures as part of functioning of the marine ecosystems.

6.6.2 Need for future research

The evidence that is available up until now shows both benefits and risks in leaving anthropogenic structures in place and this needs to be investigated further (Fortune & Paterson, 2020). There is a lack of baseline ecological data from before the installation of offshore artificial structures. Future studies should aim to establish reference conditions for impacted areas to properly assess the ecological consequences of decommissioning. Studies should also explore how communities interact and vary across anthropogenic structures. The connectivity between offshore artificial structures and natural habitats (whether these are soft-bottom or natural reefs) is poorly understood. Research should for instance explore larval dispersal pathways, movement of mobile fauna and even potential risks of creating ecological 'prey halos' or depletion zones (Fortune & Paterson, 2020). Anthropogenic structures may facilitate the spread of invasive, non-native species via larval dispersal and vessel movement. Research is needed to map the presence of current non-indigenous species, model dispersal routes and develop rapid detection and monitoring methods. Comparative studies of full removal, partial removal, and re-use are scarce. Future research should assess the recovery times of benthic and pelagic communities in different decommissioning scenarios, long-term ecosystem function changes and socio-ecological trade-offs of each approach.

6.7 Conclusions

The decommissioning of offshore artificial structures (whether these are offshore renewables, nature-inclusive designs or anything else) is a complex and context-dependent process that requires balancing ecological, technical, societal and regulatory considerations. As some marine infrastructure across the southern North Sea and beyond approaches the end of its operational lifespan, a site-specific, science-driven, and site-specific approach to decommissioning is essential. A case-by-case approach should be prioritized over full removal policies, acknowledging the diversity of offshore installations and their environmental contexts. Partial removal or leave-in-place strategies may offer ecological benefits, but these are highly location-dependent (for example in locations where natural rocks are abundantly present), and they cannot be applied globally. Ecological connectivity, structural complexity, and the role of each structure in supporting native species must guide decommissioning decisions, rather than relying solely on logistical or cost-based criteria.

Offshore structures act as habitat providers and connectivity corridors, influencing biodiversity, foraging behaviour, and ecosystem functioning. While they may promote biodiversity, this often represents 'new nature', which must be weighed against the loss or disruption of native soft-sediment communities. There is a risk of facilitating the spread of invasive species, especially through intertidal zones or when structures are relocated. Mitigation strategies must be integrated into planning. The potential for contaminant release from material degradation, drill cuttings, or operational residues must be considered in both full and partial removal scenarios.

Long-term and adaptive ecological monitoring (before, during and after decommissioning) is important for evaluating impacts and informing management. A minimum of 2-3 years, preferable. Improved baseline data is needed, especially from pre-installation period, to better understand the ecological shifts caused by offshore structures. Further research should focus on: (1) ecosystem functions of microbial, cryptic, and mobile species associated with structures; (2) the dynamics of ecological connectivity and larval dispersal; (3) the socio-ecological trade-offs of various decommissioning options, especially regarding stakeholder values; and (4) the degradation, recyclability, and end-of-life fate of novel materials, such as those used in ERUS. A collaborative, cross-border governance framework will be needed for managing decommissioning strategies across shared marine regions like the North Sea.

In conclusion, offshore decommissioning should be reframed from a purely technical challenge to a strategic ecological opportunity. A pragmatic, evidence-based approach that includes ecological monitoring and policy flexibility will yield better outcomes for marine biodiversity, ecosystem services, and societal values.

7 Parameters, indicators, and methodologies for offshore monitoring

Here we give an overview of potential ecological monitoring goals for offshore structures, which serve as the basis for selecting indicators and appropriate measurement methodologies. It then describes the methods used to assess these indicators. The chapter concludes with an outlook on future opportunities for monitoring of ERUS within pilot projects.

7.1 Introduction

As the OWF industry expands, there is an increasing need for monitoring that assesses the endurance of scour protection measures and their ecological impact (Kingma et al., 2025). Understanding the biodiversity enhancement potential of these structures requires methodologies to evaluate ecological indicators such as species presence, community composition, and overall marine ecosystem health (Isaksson et al., 2025). Monitoring campaigns/efforts could include both abiotic factors, such as temperature, nutrient concentrations and hydrodynamic conditions, and biotic indicators, including species diversity, population dynamics, and habitat use. Additionally, advancements in video and image analysis, along with artificial intelligence (AI) driven species detection and classification, offer tools for ecological assessments (Kingma et al., 2025).

This chapter begins with an overview of potential ecological monitoring goals that dictate the ecological indicators and methodology for measurements. It then outlines various methods, to assess individual ecological indicators, and expected outputs for offshore monitoring techniques that focus on the ecological impact of offshore structures such as scour protections. The chapter concludes with an outlook on possible future monitoring of ERUS within pilot projects.

7.2 Ecological monitoring goals

Ecological monitoring is necessary to evaluate the ecological shift(s) associated with the introduction of artificial structures. To document these expected shifts and potential impacts a monitoring program must be designed to compare changes to specific ecological metrics (e.g., indicators) following the artificial structure's installation relative to baseline conditions (prior to installation) and to other marine habitats (e.g., nearby natural habitats, control areas).

Defining the ecological goal(s) and/or potential impacts associated with the introduction of particular artificial structures into the marine environment is critical. These goals and/or impacts drive which indicators or parameters should be measured during monitoring studies and how the monitoring studies should be designed and implemented.

In general, when considering enhancing artificial structures using nature inclusive design concepts, the ecological goals typically involve increasing biodiversity, habitat value, and/or ecosystem health above background and/or in comparison to nearby natural habitats. Biodiversity is here described as the number of species in a given location (species richness) and can also encompass the relative abundance of species within a community or location (species evenness).

Conversely, habitat value and ecosystem health are more challenging to define, as these goals are broader, can be site-specific, and tend to describe how an ecosystem is functioning, beyond simply the species composition (biodiversity) of an area.

However, clear definitions of these ecological goals, on a project-by-project basis, are imperative to identify appropriate monitoring indicators/parameters. For example, habitat value may be defined as the promotion of a particular species of interest (e.g., commercially or policy relevant species) in an area. Ecosystem health may be defined as the increase in productivity in an area, or an increase in resiliency. Productivity and resiliency can then be measured using various indicators, such as biomass or functional redundancy, respectively. These are only example definitions linked with these broad ecological goals to demonstrate the variety of outcomes that may be targeted when designing particular artificial structures.

Below we discuss particular indicators/parameters that can be measured during monitoring programs and the common ecological goals these indicators are associated with. Next, we describe the tools that can be used to measure these indicators/parameters.

7.3 Monitoring indicators/parameters

In ecological monitoring, indicators are often used to assess the status of marine environments over time or relative to other marine environments (temporal and spatial comparisons). These indicators can, for instance, provide valuable data on species presence, community composition, habitat use, and the broader ecological impacts of scour protection in comparison to natural environments. This chapter outlines the key ecological indicators often used in offshore monitoring, focusing on fish, benthic community, and environmental factors.

7.3.1 Ecological indicators

7.3.1.1 Species abundance and diversity

Ecological monitoring of offshore structures commonly includes determining the abundance and diversity of species present around or on the structures.

- Diversity indicators: *species richness* (number of species), *species evenness* (distribution of individuals among species), *total abundance*, and *functional group/trait diversity* (e.g., deposit feeders, filter feeders, predators, habitat mode)
- Biomass

Some example studies can be found in Boon et al. (2010), ter Hofstede et al. (2022), Kingma et al. (2024), Mavraki et al. (2020).

7.3.1.2 Benthic coverage (sessile organisms, algae, filter feeders)

The coverage of benthic habitats by sessile organisms also helps understand the ecological health. Monitoring the distribution and coverage of these species helps assess the effectiveness of offshore structures in creating new habitats.

- Indicators: percent *coverage* of benthic habitats by sessile species, presence of *policy relevant species* (e.g., *Flat oyster* and *Sabellaria*), and *diversity* of benthic flora
- Estimation of biomass for dominant benthic species. This gives an understanding of the productivity of this trophic level - or energy content.

Some example studies can be found in Kingma et al. (2024), Coolen (2017), Zupan et al. (2024).

7.3.1.3 Fish behaviour and habitat use

Understanding fish behaviour and habitat use is important for assessing how offshore structures function as artificial habitats. Fish behaviour indicators include movements, feeding patterns, spawning sites, and shelter preferences. These indicators help understand how fish interact with the substrate provided by scour protection and whether it is used as a habitat or simply as a physical feature in the environment.

- Behavioural indicators: *feeding activity* and *interaction* with artificial structures
- Habitat use indicators: Frequency of *habitat visits*, *duration* of stay, and *spatial distribution* of fish around structures

Some example studies can be found in Van den Driessche et al (2013), Mavraki et al. (2021), Bergström et al. (2013), Berges et al. (2024), Dahlgren et al. (2019).

7.3.1.4 Size distribution and biomass

The size distribution and biomass of fish populations are important indicators for assessing the health and productivity of reef systems. The presence of different size classes within a population suggests a stable environment, while the absence of juvenile or mature fish can indicate ecological imbalances. Biomass, which refers to the total weight of fish in a given area, helps determine the overall productivity of the ecosystem.

- *Size distribution*: measurement of fish length classes to evaluate population structure
- *Biomass*: estimation of total fish weight or energy content within a given area

An example study can be found in Van den Driessche et al. (2013).

7.3.2 Environmental indicators

7.3.2.1 Water quality parameters (temperature, salinity, turbidity, dissolved oxygen)

Key water quality parameters in monitoring campaigns include temperature, salinity, turbidity, nutrient levels, chlorophyll-a, and dissolved oxygen, that affect the survival, growth, and distribution of marine organisms. Monitoring these parameters is essential for understanding the broader environmental context in which scour protection systems are deployed.

- Temperature: influences metabolic rates, species distribution, and reproductive cycles
- Salinity: affects species tolerance
- Turbidity: high turbidity influences light penetration
- Dissolved oxygen: low oxygen levels can lead to conditions that impact the marine life
- Nutrient levels: determines the productivity of the system
- Chlorophyll-a concentration: determines food availability for various organisms

Some example studies can be found it Lindeboom et al. (2011), Degraer et al. (2020), Hicock et al. (2002), Coolen et al. (2024).

7.3.2.2 Sediment characteristics and organic content

Sediment characteristics such as grain size, organic content, and sediment stability are important indicators. Offshore structures can alter sediment dynamics by stabilizing or redistributing sediments, and increasing organic matter (i.e., food) supply to the sediments. Analyzing sediment parameters around these structures helps evaluate their impact on the local benthic functions (nutrient and carbon cycling).

- Indicators: sediment grain size distributions, organic content (carbon, nitrogen), sediment compaction, resistance to erosion

An example study can be found in Whitehouse et al. (2011).

7.3.2.3 Structural integrity of artificial habitats

Scour protection systems themselves can evolve into complex habitats over time. Monitoring the structural endurance of these habitats is important for determining long term ecological impact. This involves assessing how well scour protection systems maintain their intended function, both as structural components and as ecosystems that support marine life.

- Indicators: physical *stability* of the structures (e.g., erosion, displacement), *habitat complexity* (e.g., surface area for colonization), and *colonization* by marine species

7.4 Monitoring methodologies

This chapter describes several monitoring techniques used in ecological assessments of offshore structures, such as scour protections. The methods focus mostly on monitoring species presence, abundance, and habitat use. They range from acoustic surveys to genetic analysis, and thereby create an understanding of how offshore infrastructure interacts with marine ecosystems.

7.4.1 Acoustic surveys

Acoustic surveys are a common monitoring method for assessing fish presence and abundance in offshore environments. This technique uses sound waves to map and track fish populations, as well as other marine organisms, within a specified area. Acoustic sensors, such as single-beam and multi-beam sonar, are deployed from vessels or stationary platforms to emit sound waves, which bounce off marine life and structures. The reflected signals are then analysed to estimate the size, depth, and location of the fish.

Advantages:
- Non-invasive and can cover large areas quickly
- Capable of detecting fish in real-time (snapshot of fish abundance)
- Useful for both pelagic and benthic species

Limitations:
- Limited ability to identify species individually and at genus level specifically
- The accuracy of fish detection can be affected by environmental factors such as turbidity
- Requires specialized equipment and skilled interpretation of data

7.4.2 Telemetry and tagging

Telemetry and tagging techniques involve attaching small electronic tags to fish or marine animals, which transmit data on their movements, behaviour, and habitat use. These tags can provide insights into how fish interact with scour protection structures and the habitats they create. Acoustic telemetry, for example, uses underwater receivers to detect signals from tagged animals, while satellite or GPS tags can track species over larger distances.

Advantages:
- Provides real time data on animal movement and habitat use
- Allows for long term tracking of individual animals
- Useful for understanding species interactions with offshore infrastructure

Limitations:
- Tagging can be invasive and may affect animal behaviour
- Requires specialized equipment and can be costly
- Tags have limited battery life and may only provide data for a limited time
- Is limited by a small sample

7.4.3 Underwater video monitoring (ROVs/AUVs)

Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) can be equipped with high resolution cameras and other sensors to conduct direct visual observations of species and habitat use around offshore structures. These vehicles can be deployed to specific locations such as scour protection, to capture real time footage of marine/benthic life.

Advantages:
- Provides high resolution images of species and their distribution
- Can be used at locations where diving is difficult or impossible
- Allows for the collection of both ecological data and structural assessments in the same operation
- Can be used for photogrammetry: capturing a series of overlapping images and then processing these images with specialized software to generate detailed 3D models or maps of the seafloor, objects, or structures.

Limitations:
- Limited by the range of the vehicles
- Costs associated with ROV/AUV deployment, especially in deeper or more remote areas
- Video data analysis can be time consuming and requires expert interpretation
- Computational power and data management requirements can become cost prohibitive

7.4.4 Baited Remote Underwater Video (BRUV)

Baited Remote Underwater Video (BRUV) systems are stationary video setups deployed on the seafloor and equipped with bait to attract fish and other mobile species. Occasionally, a ROV is used with bait in the gripper arm. These systems record footage over a set period, allowing for the identification and quantification of species attracted to the bait. BRUVs are particularly effective for surveying fish communities in areas where active sampling methods (e.g., trawling) are not feasible or wanted.

Advantages:

- Non-invasive and does not disturb the seafloor or fauna present
- Attracts a wide range of mobile species
- Allows for standardized sampling across multiple sites
- Enables species identification and relative abundance estimation from video

Limitations:

- Attracts only scavengers or species responsive to bait, possibly skewing community representation
- Limited spatial coverage due to stationary nature
- Visibility and camera angle can affect data quality

7.4.5 Diver surveys

Diver surveys involve trained underwater divers conducting *in situ* observations of benthic species and habitat conditions. This method allows for direct hands-on assessment of the species living around offshore structures. Divers can collect data on species diversity, abundance, and coverage, as well as document any physical changes to the substrate or habitat caused by scour protection measures.

Advantages:

- Provides detailed observations of species and habitat conditions
- Divers can collect samples (rocks or scrape) for species identification. Allows for more detailed inspection compared to video processing (smaller organisms identifiable)
- Flexible and can be adapted to various depths and conditions

Limitations:

- Limited by diver accessibility and safety concerns, particularly in offshore areas and deeper waters
- Time consuming and logistically challenging in larger scale studies
- The data is subject to the diver's skill and may introduce observer bias

7.4.6 Sampling (grab samples and sediment cores)

Benthic sampling techniques, such as grab sampling and sediment coring, involve collecting physical samples from the seabed to assess macrofauna and sediment conditions. Grab samplers collect surface sediments, while sediment cores provide deeper insights into the composition and structure of the seabed. This method can help monitor changes in sediment composition.

Advantages:

- Provides physical samples that can be analysed in the lab for species identification and sediment analysis

Limitations:

- Sampling constrained by environmental conditions (such as strong currents or the presence of other infrastructure) or by the nature of the seabed
- Potentially missing mobile species
- Expensive and time-consuming processing

7.4.7 Environmental DNA (eDNA) analysis

eDNA is a technique that relies on the detection of genetic material shed by organisms into the surrounding water. By collecting water samples around offshore structures, species present in the area can be identified without the need for direct observation or physical capture. In addition, eDNA may detect species that might otherwise be missed through more traditional survey techniques.

Advantages:
- Non-invasive and can detect a wide variety of species in a short time frame
- Enables the detection of species that may be difficult to observe visually or acoustically
- Fast and easy collection of field samples (however processing is time consuming)
- Can be used to assess biodiversity in remote or difficult to access areas

Limitations:
- The method requires precise processing and analysis of water samples, which can be costly and time consuming
- Interpretation of results may be challenging due to the presence of contaminants or degradation of DNA
- Does not provide information on the abundance or behaviour of species, only presence/absence
- Results can be biased towards specific species depending on the rate of DNA shedding, rate of DNA degradation in the environment (which varies by species and environmental conditions), efficiency and specificity of primer sets particularly in the presence of environmental inhibitors, and representation in reference libraries
- Temporal and spatial inferences are challenging given the unknown and variable degradation rate of genomic material in the environment (can be species and environment specific)

7.4.8 Sediment Profile Imagery

Sediment profile imagery (SPI) provides a holistic view of benthic function, preserving the physical structure of the sediment column and allowing for the description of biological processes associated with organic matter processing and benthic productivity. SPI, coupled with downward facing drop camera imagery, is an effective approach to assess changes in the benthic function of soft sediments in response to offshore wind development. SPI provides information on the depth at which oxygen is depleted within the sediment column, a well-known proxy for sediment respiration rates, and related to the rate of organic matter supply. SPI can also provide information on the infaunal successional stage, using a well-established paradigm relating to bioturbation activity and small-scale features at the sediment-water interface with infaunal community stability and maturation. Sediment grain size major mode can also be obtained from SPI.

Advantages:
- Rapid assessment of soft sediment conditions
- Near real-time evaluation allowing for adaptive adjustments to field sampling during survey
- Non-extractive technique

Limitations:
- Does not provide infaunal community structure metrics (abundance, composition)

7.4.9 Stomach content analysis

Stomach content analysis is a method used to assess the diet and trophic interactions of fish and other marine animals by examining the contents of their digestive tract. This approach can help determine which species are for instance feeding on or around offshore, thereby providing insights into local food web dynamics.

Advantages:
- Provides direct evidence of recent feeding activity and prey types
- Helps understand trophic interactions
- Can indicate ecological connectivity between locations
- Supports the evaluation of habitat functionality (e.g. offshore infrastructure as artificial reefs)

Limitations:
- Requires the capture and often sacrifice of target species
- Only reflects short-term diet (recent meals), potentially missing seasonal or longer-term patterns
- Prey identification can be difficult due to digestion (some soft-bodied organisms may be underrepresented)
- Time-consuming and requires taxonomic expertise

7.4.10 Stable isotope analysis

Stable isotope analysis involves measuring the ratios of naturally occurring isotopes, most commonly carbon ($^{13}C/^{12}C$) and nitrogen ($^{15}N/^{14}N$), in tissues of marine organisms. These ratios reflect long-term dietary intake and trophic level. This method is useful for understanding food web structures, especially when combined with stomach content analysis (Chapter 7.4.9). In the context of offshore infrastructures, stable isotope data can reveal how artificial structures can contribute to local trophic networks and whether species are relying on the substrates for feeding.

Advantages:
- Provides long-term dietary information (weeks to months)
- Can detect subtle shifts in food web structure and habitat use
- Useful for comparing different locations

Limitations:
- Requires laboratory processing and mass spectrometry equipment (costly an)
- Interpretation can be complex and may require reference baselines from local environments
- Cannot identify specific prey items (only broad trophic positions and carbon sources)
- May be confounded by variation in isotope baselines across regions

7.5 Monitoring of ERUS

ERUS are NID elements which function as artificial habitat structures. They are strategically placed on or around scour protection systems in offshore environments to enhance local biodiversity and ecological functioning. Monitoring of these units is important to evaluate their effectiveness both in ecological value and structural integrity.

7.5.1 Monitoring objectives

The monitoring of ERUS should aim to:

- Assess colonisation and succession of benthic species.
- Quantify biodiversity and species richness associated with the structures.
- Measure habitat complexity and structural integrity of ERUS.
- Monitor environmental conditions influencing ecological performance.
- Determine the added ecological value compared to unmodified scour protection.

7.5.2 Monitoring methodologies

Several complementary monitoring methodologies can be used to meet above described monitoring objectives for ERUS. The following list is not an complete overview of all possibilities, but presents an overview for considerations.

1. Visual Surveys (video and photogrammetry)
Carried out using ROVs or AUVs.
- Provide high-resolution imagery for qualitative and quantitative assessment of species presence, abundance, and behaviour.
- Mosaicking (stitching together) images to map larger area.
- Projection lasers can assist in scaling for the processing, enabling measurements of growth forms and reef structure dimensions.

2. Side-scan Sonar and Forward-Looking Sonar
- Can be used for broader mapping of ERUS locations, reef extent, and structural changes over time.
- Allows for detection of sedimentation patterns and scour related shifts.

3. Multibeam Echosounder (MBES)
- To monitor bathymetric changes and detect sediment deposition or erosion around ERUS.
- Enables volumetric analysis of reef growth or degradation.

4. Environmental Sensors
    - Parameters such as temperature, salinity, turbidity, dissolved oxygen, nutrients, and chlorophyll-a are critical to understanding the ecological context.
    - These can be integrated into UUV platforms or placed on static moorings near the ERUS.

5. Physical samples
    - Grab samples collected from ERUS by diver or ROV for biodiversity assessments.
    - Water samples for eDNA analyses.

8 Conclusion

The SPREE project has provided a comprehensive assessment of how scour protection structures in offshore wind farms can contribute to ecological enhancement. By combining desk research, expert interviews, comparative evaluations, and design-focused reviews, this work has demonstrated that offshore infrastructure, long considered purely functional, has the potential to contribute to marine habitat creation as well.

The comparison between the Dutch North Sea and the U.S. East Coast revealed both the promise and the challenges of adopting NIDs in the form of ERUS. The Dutch setting, characterized by shallow waters, mature OWF development, and structured regulation, provides a controlled ground for ecological experimentation. By contrast, the U.S. East Coast offers a more dynamic and still-developing landscape, with still evolving regulatory approaches. These differences show the importance of adaptable site-specific design, as solutions that succeed in one region may need rethinking in another.

Ecologically, ERUS present a promising opportunity. Their engineered characteristics such as porosity, surface heterogeneity, and relief create diverse niches for various taxonomic groups, complementing sandy environments where biodiversity is naturally limited. These design features can support settlement, shelter, and feeding functions across a range of marine organisms, especially for sessile bivalves, polychaetes, hydrozoans, bryozoans, and small crustaceans, which benefit from the increased microhabitat complexity and internal cavities provided by ERUS. For larger crustaceans and demersal fish, ERUS offer modest improvements, particularly in shelter and food availability, though limitations remain in supporting adult reproductive behaviours due to size constraints.

The design flexibility and larger volumes assumed for ERUS based armour layers in the SPREE project's case, distinguishes them from conventional armour rock, which supports ecological functions only incidentally. Yet these opportunities are not without risk. By creating new connectivity between offshore structures, ERUS may accelerate the spread of non-indigenous species by forming a stepping-stone effect. Their long-term material endurance and possible contaminant release remain uncertain, and there is a possibility that ecosystems surrounding ERUS may diverge from natural baselines, taking on characteristics of artificial reef assemblages instead.

The regulatory and policy dimension is equally important. Under current OSPAR rules, full removal of offshore structures remains the default requirement at decommissioning, placing ERUS in a regulatory grey zone. At the same time, offshore wind tenders in the Netherlands and internationally are increasingly including ecological criteria, creating momentum for NID options to be embedded into project design. To fully realise their potential, ERUS must be integrated into policy frameworks in a way that recognises their ecological contribution while still addressing governance, liability, and stakeholder concerns. In this line of thinking, decommissioning should no longer be treated as an afterthought but considered from the outset of project design and permitting, with leave-in-place or partial removal options explored alongside ecological objectives, legal constraints, and societal acceptability. Lessons from oil and gas decommissioning demonstrate that such scenarios can deliver biodiversity gains, but careful case-by-case evaluation and more empirical *in situ* data is required.

The absence of long-term, in-field validation remains one of the largest barriers to widespread adoption of ERUS. While early evidence suggests they may enhance colonisation and increase species richness compared to conventional scour protection, the lack of empirical data prevents large scale use. Long-term comparative field studies are therefore needed, and should be supported by shared datasets across regions/settings to enable cross-comparisons. Therefore, it is recommended to conduct more monitoring to fully understand the ecological potential of ERUS. Standardised protocols focusing on species richness, biomass, habitat use, benthic coverage, and structural integrity must be developed and applied consistently across projects. Innovative tools such as photogrammetry using ROVs and AUVs, environmental DNA, and AI-driven video analysis could help to improve the efficiency.

In conclusion, ERUS represent a promising step toward operationalising NIDs in offshore wind energy. To progress from experimental deployment to large scale practice, more empirical evidence is required, policy and tendering frameworks must place stronger emphasis on ecological criteria, and decommissioning scenarios need to be integrated into project design.

8.1 Recommendations

Looking ahead, several recommendations stand out for the use of ERUS. First, dedicated pilot projects and long-term monitoring campaigns are needed to generate empirical data comparing ERUS with conventional armour rock under different ecological and hydrodynamic settings. Second, policy and tendering frameworks should more explicitly reward ecological innovation, embedding NID criteria into permitting, deployment, and evaluation processes. Third, decommissioning planning must shift upstream, with (partial) leave-in-place and adaptive strategies considered early in project design to ensure that ecological value is not lost at end-of-life. These recommendations will help the transition from experimental trials to ecologically integrated and policy-supported ERUS in offshore wind infrastructure.

9 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. The organisation has been certified since 27 February 2001. The certification was issued by DNV.

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Justification

Report:C004/26
Project Number: 4315100231

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

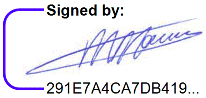
Approved: dr. O Bos
Marine Ecologist

Signature:

Date: 21-01-2026

Approved: dr. A.M. Mouissie
Business Manager Projects

Signature:



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