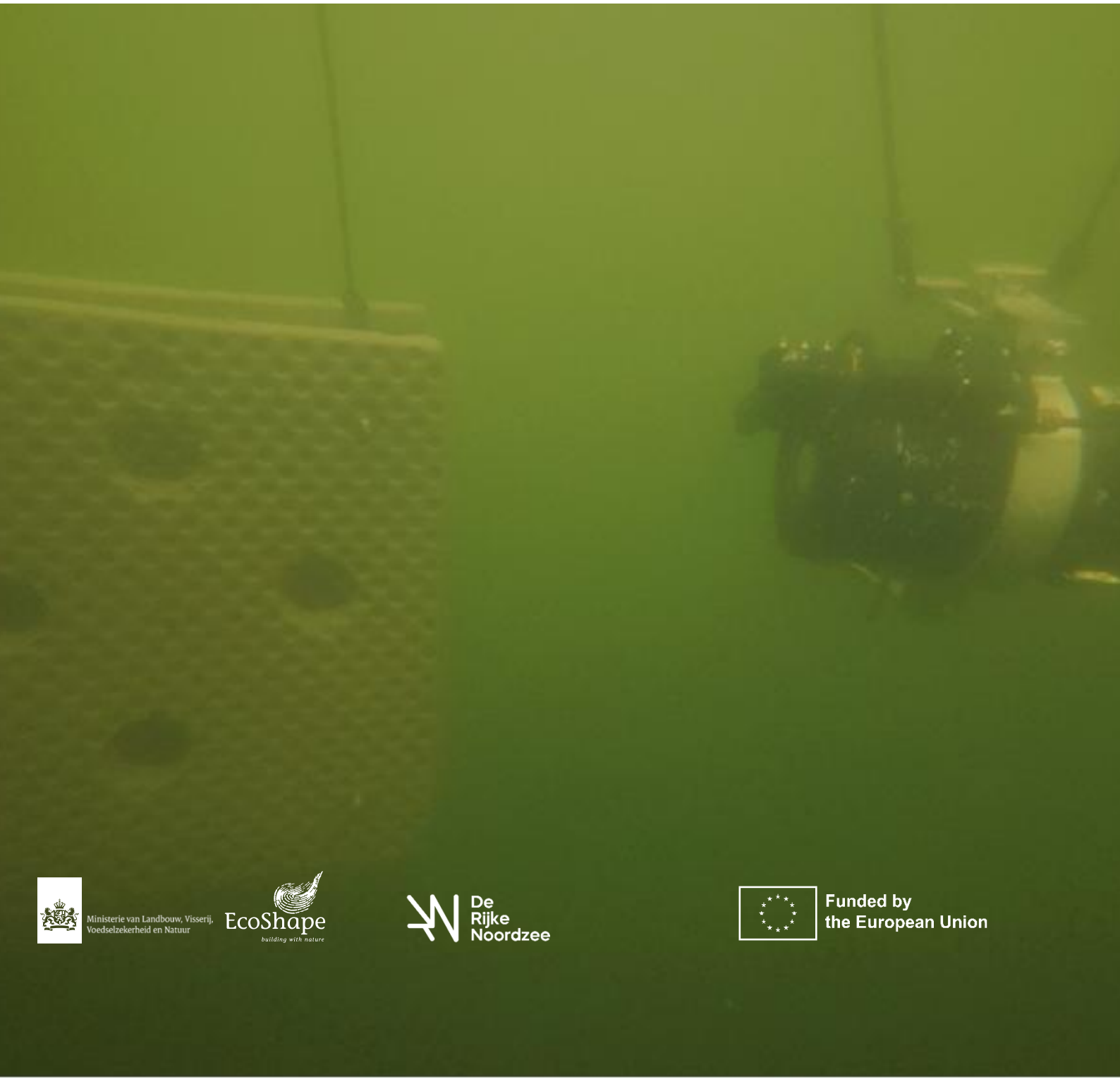
Natuurversterking NOORDZEE

ECOMUG – FINAL REPORT

25 september 2026



Ministerie van Landbouw, Visserij, Voedselzekerheid en Natuur

EcoShape building with nature

De Rijke Noordzee

Funded by the European Union

ECOMUG – FINAL REPORT

Versie ten behoeve van
[Onderwerp]

Opgesteld door Eva Strothotte, Tim Staufenberger

25 september 2026

Ministerie van Landbouw, Visserij, Voedselzekerheid en Natuur
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D.2.2 Final Report

1. Executive summary

The ECOMUG (Ecological Modular Attached Multi-Use Growth System) project developed and tested modular Nature-Inclusive Design (NID) habitat units for the ecological enhancement of existing marine infrastructure. The project combined ecological design, technical development and field testing to investigate whether negative impacts of lost habitats can be mitigated by providing additional habitat complexity on existing submerged structures while maintaining flexibility for future deployment and removal. The work was conducted under accessible nearshore conditions in Kiel Fjord, with a clear focus on future transfer to offshore structures such as wind-turbine monopiles.

Two complementary habitat-unit concepts were developed and assessed: modular gabion units containing BESE elements and oyster shells, and stacked concrete-biochar plate units. Both designs remained structurally intact during the January–September assessment period and were colonised by diverse organisms. They provided habitat for sessile organisms as well as mobile fauna, including fish, crabs, shrimp and starfish. The gabion-based units developed a particularly heterogeneous three-dimensional habitat with numerous cavities and interstitial spaces and supported a comparatively diverse assemblage of mobile organisms. Their low weight, modular construction and flexible filling options also provide practical advantages for deployment and future adaptation. The staked-plate units demonstrated high mechanical stability and provided larger sheltered cavities but were considerably heavier and less flexible to handle and modify.

The results indicate that the gabion-based design provides a promising basis for further development where modularity, structural complexity and adaptable habitat functions are required. Its flexible construction allows different filling and settlement substrates to be incorporated without fundamentally changing the overall structure. Although the inclusion of oyster shells did not result in visibly enhanced blue mussel settlement under the brackish conditions of the Kiel Fjord test site, this result cannot be directly transferred to higher-salinity environments where European oyster (Ostrea edulis) naturally occurs. Further testing under North Sea conditions is therefore required to investigate oyster recruitment and the application of the system for oyster restoration.

A second major project outcome was the development of a remotely controlled magnetic attachment and retrieval system. The system enables habitat units to be attached to existing submerged steel structures without drilling, welding or other permanent modifications. The nearshore test demonstrated the integrated operation of magnetic attachment, acoustic communication, remote control and retrieval, allowing installation and removal without divers. This provides a potential retrofit solution for existing offshore structures and allows habitat units to be inspected, replaced, relocated or removed as required. The economic and operational benefit by just using an app on the mobile to attach or detach the system and adapt the design to any vessel and different site-specific requirements are considered very high based on the experience of past and ongoing offshore projects.

The project also established a monitoring approach combining permanently installed interval cameras, targeted drop-in camera observations and looked into suitability for automated image analysis. The monitoring successfully documented habitat development and the presence and use of the structures by flora and fauna. Future remote monitoring options are already prepared and integrated in the innovative attachment system.

Overall, ECOMUG demonstrated the technical feasibility of modular habitat structures combined with reversible, remotely controlled attachment to existing steel infrastructure. The results provide a field-tested basis for further development of nature-inclusive applications on coastal and offshore structures. The next development phase should progress from the demonstrated nearshore system towards controlled hydrodynamic testing and a full offshore demonstration in the North Sea. This should include testing of the habitat, attachment, release and monitoring system under different wave, current and weather conditions.

The North Sea demonstration should additionally investigate the recruitment and settlement of European oyster (*Ostrea edulis*). The modular gabion design is particularly suitable for this purpose because oyster shells and other settlement substrates can be incorporated, exchanged and rearranged between deployments. Following technical and ecological validation, the system can be further upscaled and evaluated for deployment on multiple units per offshore foundation. In the longer term, the combination of modular habitat structures, reversible attachment and automated monitoring could provide a flexible framework for biodiversity enhancement, restoration and the creation of mussel, algal and oyster habitats on both existing and newly developed offshore infrastructure.

2. Introduction

Nature-inclusive design (NID) and artificial reef approaches offer opportunities to enhance the ecological value of increasingly widespread coastal and offshore infrastructure with the goal to provide replacement for lost habitats as hard substrates. However, their ecological benefits can only be demonstrated when ecological design objectives, technical implementation and suitable monitoring are considered together. ECOMUG (Ecological Modular Attached Multi-Use Growth System) addresses this need by developing and testing modular habitat units that can be attached to existing aquatic infrastructure and increase structural complexity for marine organisms where it was before. The project combines ecological design with engineering development and field testing under accessible nearshore conditions in Kiel Fjord, while maintaining a clear perspective towards later transfer to offshore infrastructure such as wind-turbine monopiles. Two complementary habitat concepts were developed, constructed and deployed: gabion-based units with BESE elements and oyster shells, and stacked concrete-biochar plate units. In parallel, ECOMUG investigates non-invasive attachment and release concepts and develops a sound monitoring approach for technical performance, colonisation and habitat use. As a prototype and feasibility project, the work focuses on practical implementation, iterative optimisation and initial ecological responses rather than on demonstrating long-term restoration success.

2.1. Objectives of ECOMUG

The overall objective of ECOMUG is to develop, implement and evaluate a modular, scalable and adaptable NID system for the ecological enhancement of existing aquatic infrastructure. Based on previous experience, the project applies a site-specific design approach and tests technical functionality, attachment, robustness and handling under coastal conditions in Kiel Fjord. A central ecological objective is to create structurally complex refuge, nursery and feeding habitat, particularly for juvenile fish, while using materials and configurations that minimise potential negative environmental impacts.

The project further aims to generate technical knowledge that can support transfer to offshore applications. This includes the development of a non-disruptive attachment concept for vertical steel infrastructure, with the long-term aim of enabling installation and removal without diver operations. ECOMUG also evaluates the multi-use potential of existing marine infrastructure and develops a monitoring concept linking project objectives to measurable indicators and suitable methods. The intended outcome is therefore not large-scale restoration within the project period, but a technically documented and field-tested basis for scalable follow-up applications and scientifically sound ecological evaluation.

3. Overview of previous deliverables

Although this final report is a stand-alone document with the aim to be understandable in itself, a short overview of all deliverables generated during the ECOMUG project is given below.

3.1. D.1 – Implementation plan and coordination report for optimal design and material selection

Deliverable D.1 established the implementation and coordination framework for ECOMUG. It defined the site-specific conditions, ecological and technical design requirements, candidate materials and preliminary attachment concept for the planned NID modules. The selected pilot site at the “Seefischmarkt” marina in Kiel Fjord provided accessible nearshore conditions and representative existing infrastructure for deployment before potential transfer to offshore conditions. Two prototype pathways were specified: gabion-based habitat units using BESE-type structural material/oyster-shell filling, and stacked plate habitat units based on concrete/biochar elements. D.1 also introduced a preliminary magnet-based, non-invasive attachment concept for vertical marine infrastructure. By documenting the test site, stakeholder coordination, ecological design objectives, material pre-selection and implementation planning, the deliverable established the boundary conditions and design logic for the subsequent technical optimisation and construction phase.

3.2. D2.1 – Optimised system design and construction

Deliverable D.2.1 translated the design framework from D.1 into fully specified, constructed and deployment-ready habitat prototypes. Two complementary systems were fabricated: porous gabion units combining Galfan-coated cages, BESE elements and oyster shells, and modular stacked plate units made from concrete-biochar composite plates. The deliverable defined system geometry, material composition, structural and habitat design principles, construction and assembly procedures, and interfaces for attachment. Ecological functionality, structural stability, manufacturability and installation feasibility were considered jointly during optimisation. A two-stage attachment strategy was incorporated, using ropes for rapid initial field deployment while in parallel the magnet-based attachment solution was developed for later retrofitting. Monitoring requirements were also integrated into the system design, including compatibility with stationary and drop-in cameras and reference observations. D.2.1 therefore marked the transition from conceptual planning to physically realised systems ready for field testing and iterative evaluation.

3.3. D.2.2 – Iterative system evaluation and adaptation

Deliverable D.2.2 documented the iterative evaluation, optimisation and maintenance of the deployed NID systems during the test phase. Three replicates of each habitat type were deployed, and their technical performance, operational handling and first biological responses were assessed. The rope-based installation enabled early field deployment to use the full season from February to end of September, while onshore tests advanced the non-invasive magnetic attachment system. Tests with an optimised six-magnet configuration demonstrated reliable holding and an electrically triggered release, providing the basis for further development towards a remotely controlled acoustic release concept. The monitoring setup was iteratively improved, particularly the positioning and use of stationary underwater

cameras, complemented by drop-in cameras and an unmodified harbour pile as reference. Initial observations documented colonisation and use of the habitat units by adult and juvenile fish starting to appear in May. The deliverable also established evaluation criteria covering technical functionality, monitoring performance, scalability and transferability, and provisional ecological performance.

3.4. D.3 – Installation and technical testing

Deliverable D.3 documented installation and technical testing of the habitat prototypes under realistic nearshore conditions in Kiel Fjord. Three gabion-based and three concrete plate units were deployed with ropes, allowing testing throughout the biologically relevant season from February to September while the magnetic attachment and acoustic release system were developed in parallel. Both habitat designs remained structurally intact during the reported period and showed early colonisation and use by marine fauna. Stationary cameras, drop-in cameras, environmental data loggers and multiparameter measurements provided suitable monitoring data. In parallel, the magnet attachment concept was successfully demonstrated under controlled onshore conditions. D.3 translated the deployment experience into a reproducible installation approach and assessed handling, structural stability and resilience under environmental conditions, thereby identifying the technical requirements for subsequent underwater validation and future offshore-compatible deployment.

3.5. D.4 – Development of a monitoring concept

Deliverable D.4 developed a scientifically reasoned and practically applicable monitoring concept for assessing the habitat units. Project objectives were translated into measurable indicators, and suitable methods, reference conditions and spatial and temporal scales were defined. The concept covers four main indicator groups: environmental conditions, physical and structural performance, sessile colonisation, and habitat utilisation by mobile fauna. Complementary methods include structural inspections, stationary and drop-in underwater cameras, photographic assessment of sessile coverage, continuous data logging and multiparameter measurements. Initial observations documented substantial colonisation, frequent use by juvenile fish and no apparent structural damage during the reported period. Particular attention was given to the further automation of camera-based monitoring, including image-quality filtering, fish detection and counting and, where feasible, species classification. D.4 thus provides the monitoring basis for comparing prototypes, documenting early ecological responses and preparing more comprehensive future coastal and offshore assessments.

4. Analysis and evaluation of habitat units

The two habitat unit designs were assessed from January to September with regard to their technical and structural performance and their ecological function. The ecological assessment considered sessile colonisation, the occurrence of fish and other mobile fauna, and

observations from both permanently installed interval cameras and targeted drop-in camera surveys. The results were interpreted in the context of the prevailing environmental conditions and compared with an long term existing mooring pole. Both habitat unit types remained structurally intact throughout the assessment period. Differences were nevertheless observed in their physical configuration, colonisation patterns and the diversity and abundance of associated fauna.

4.1. Gabion-based habitat units

The gabion-based habitat units consisted of Galfan-coated metal cages filled with biodegradable BESE Type 2 elements made from potato starch (Figure 1). The BESE elements were designed to provide a complex three-dimensional structure and are expected to biodegrade over a period of approximately two to four years. In addition, Oyster shells were added within the BESE elements to provide potential enhanced settlement ground for mussels.



Figure 1: Gabion-based habitat unit. Left: before deployment in January 2026; right: after decommissioning from Kiel Fjord in September 2026.

4.1.1. Technical and structural assessment

The gabion units provided numerous attachment and fixation opportunities while remaining comparatively lightweight. Their modular construction allowed the units to be transported, assembled, disassembled and potentially reused with relatively little effort. The cages also allow for variation in the filling material, providing flexibility for the integration of different habitat-forming substrates or additional materials. The relatively low amount of material required to create a comparatively large internal volume was considered an additional advantage.

The gabion cages remained mechanically intact throughout the testing period from January to September, with no structural failure or significant deterioration of the metal cages. The BESE elements showed some visible deterioration towards the end of the assessment period. This was expected and is consistent with their intended biodegradable character rather than representing a structural failure of the habitat unit. The elements remained sufficiently stable to maintain the overall habitat structure throughout the observation period.

The fine-meshed BESE structure also provided opportunities to retain and integrate additional materials, such as oyster shells. The units could potentially accommodate monitoring equipment, including integrated camera systems. Their low weight and modularity would facilitate assembly prior to deployment or during a vessel-based operation and allow the units to be stored and transported comparatively easily.

The addition of oyster shells did not result in visibly enhanced colonisation by regional blue mussels during the assessment period. The oyster shells themselves remained largely intact. This observation does not exclude a potential settlement effect under different environmental conditions, particularly in higher-salinity areas where oysters occur naturally and where oyster shells have been reported to provide suitable settlement substrate (Varley et. al. 2026[1]).

4.1.2. Ecological assessment

Automated image analyses

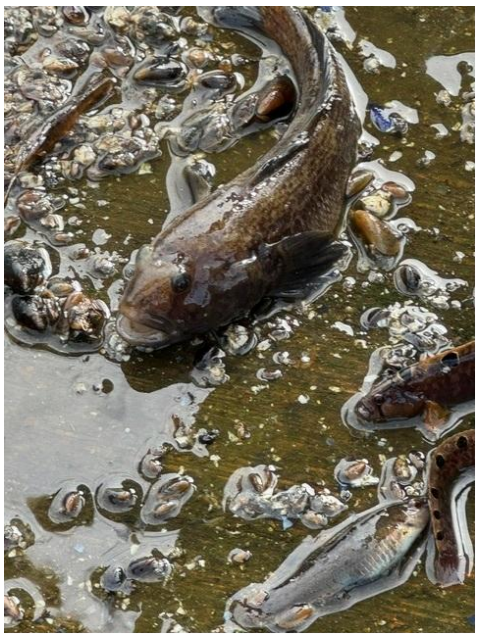


Figure 2: Various fish species observed at the nature-inclusive design in Kiel Fjord

There have been 14,000 photos stored of the concrete habitat unit, 17,500 of the gabion designs and 16,000 of the reference summing up to a total of approx. 47,500 photos of all underwater cameras. The photos of the underwater camera were reviewed and assessed in terms of image quality and the presence of fish. Based on this, a two-stage classification strategy was developed: first, the identification of usable and unusable photos; second, the detection of fish in usable photos. Python scripts catalogue the images and link them to their timestamps and locations via unique IDs. A collection of 9,000 photos were then specifically divided into training, validation and independent test datasets; separating photos taken at similar times is crucial to avoid biased performance evaluations. The required photo tags were assigned manually in CVAT and imported into the pipeline via exports. Task-specific YOLO classification datasets were created from the annotations, and pre-trained models have been developed and fine-tuned. Model selection was based on the validation data, whilst the final performance evaluation was based on held-out test photos.

So the obtained trained model was applied to 9,000 photos of the gabions, 9,000 photos of the concrete NIDs and to 6,500 photos of the reference analysing the occurrence of fish.

A drop-in camera (45 min adaptation time for fish after installation followed by a 45 min recording time) produced videos suitable for quality checks and behaviour of fish.

[1] Varley et. al. 2026; Oyster settlement is enhanced by confamilial cues, substrate complexity and orientation: A hatchery experiment; Ecological Engineering,ISSN 0925-8574, https://doi.org/10.1016/j.ecoleng.2026.107921. (https://www.sciencedirect.com/science/article/pii/S0925857426000315)

Compared with the reference site, fish sightings at the habitat units occurred earlier in the year and were more frequent. From the end of July onwards there was no difference in frequencies between the reference and the NIDs. It cannot be exclude that these were the same fish schools, which were sighted at both locations due to the proximity of the gabion units and the reference site and photos are limited to detect the occurrence of fish but not the abundance. From mid-June to the end of August, the frequency and number of fish observed increased. A seasonal trend was correlating with the development and occurrence of juvenile fish stages.

The gobies, species with the highest reccorded number, showed no significant preference between concrete and gabion habitat units. The gabions showed a higher preference for all other recorded fish species.

Observed impact for other organisms based on samples

The gabion units developed a structurally diverse habitat with substantial biological activity within the numerous small cavities and interstitial spaces. Sessile colonisation included mussels and other organisms, while small algae and filamentous algae were also present. No larger macroalgae such as sugar kelp or bladderwrack were observed on the units during the assessment period.

The small cavities of the BESE structure were frequently occupied by mobile fauna. Starfish were observed in considerable numbers, while crabs and small local shrimp also used the cavities. Fish were regularly associated with the habitat units from late spring onwards. Among the fish observed during deinstallation were European eel, gobies, European eelpout, burbot, wrasses and rockfish (Figure 2), demonstrating that the structure was used by a diverse assemblage of mobile fauna. In addition, numerous crabs and regional shrimp were found.



Figure 3: Underwater still image of Gabion with algae, starfish and fish in Kiel Fjord summer 2026.

The permanent underwater camera provided regular still images at predefined intervals. These images documented the presence or absence of fish around the habitat units (Figure 3). Targeted observations with a drop-in camera provided additional information on fish behaviour and habitat use.

Overall, the gabion structure appeared to provide a comparatively diverse range of small-scale habitat features. The combination of cavities, interstitial spaces and different substrate surfaces created numerous potential shelter and attachment sites for marine organisms. The presence of crustaceans, echinoderms and several fish taxa indicated that the structure was actively used by mobile fauna and no deterrent effect was observed.

4.2 Stacked plates habitat units

The second habitat design consisted of stacked concrete plates that created larger cavities and sheltered spaces within the structure. The geometry was intended to reproduce some of the characteristics of natural rocky crevices and provide a stable hard substrate for marine colonisation.



Figure 4: Plate based habitat unit. Left: before deployment in January 2026; right: after decommissioning of Kiel Fjord in September 2026.

4.1.3. Technical and structural assessment

The stacked plate habitat units remained structurally intact throughout the complete assessment period from January to September. No cracking, significant deterioration or other structural failure was observed. The units therefore demonstrated a high degree of mechanical stability under the prevailing environmental conditions.

Compared with the gabion-based design, the stacked plate units were considerably heavier and consequently more demanding to transport and install. Opportunities for varying the internal filling material is not given. Due to the very stable nature of the design, attachment and fixation features needed to be considered beforehand and during the production of the plates and their assembly into the final habitat configuration.

The use of conventional concrete also represents an environmental consideration. To reduce the CO_2 footprint biochar was added to replace upt to 10 -13 % of concrete and therefore obtaining an environmentally optimised concrete.

4.1.4. Ecological assessment

The stacked-plate habitat was colonised by a range of sessile and mobile marine organisms during the assessment period. Blue mussels and barnacles were the dominant sessile organisms, although mussel coverage remained patchy rather than continuous. Small and filamentous algae were also present, while Ulva (sea salat) growth could be observed, no other larger macroalgae, such as sugar kelp or bladderwrack, were present. Only a few starfish were recorded in association with the structure.

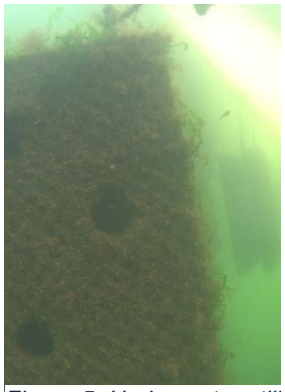


Figure 5: Under water still image of Stacked-plate habitat with algae growth and surrounding fish in Kiel Fjord in summer 2026.

The larger cavities created by the stacked plates provided sheltered spaces that were used by fish (only European eelpout, goby and wrasses were observed) and crustations. During removal of the habitat, several fish, shrimp and crabs were observed within and around the structure. The fish were observed using the cavities as shelter, indicating that the habitat provided functional refuge space (Figure 5). However, the number and diversity of mobile organisms observed remained relatively limited during the assessment period.

Overall, the stacked plate habitat developed a stable biological community dominated by blue mussels and barnacles, with additional colonisation by small algae and use by fish and crustaceans.

Compared with the gabion habitat, the associated fauna was less diverse, with fewer fish taxa and fewer starfish recorded.

4.2. Comparison of habitat units and reference

Both habitat approaches remained mechanically intact during the assessment period from January to September and therefore demonstrated their basic suitability as durable submerged habitat structures. The principal differences concerned weight, modularity, habitat complexity and the associated biological assemblage. The gabion-based approach was considerably lighter and could be assembled from modular components before deployment or during a vessel operation. The stacked-plate approach provided a stable and comparatively

spacious structure but required substantially more material and was more demanding to transport and install.



Figure 6: From left to right: Stacked plate habitat visited by fish schools, pipefish visiting the stacked plate habitat, fish school surrounding the Gabion habitat, Starfish crawling over the overgrown Gabion habitat in Kiel Fjord in summer 2026.

Ecologically, both habitat types supported sessile colonisation and were used by mobile fauna (

Tabel 1). The selection of materials and the development of these two designs proved to provide habitat for typical native fish species with a preference for habitats with options to hide. A highlight is the abundant number of European eel, which has a special statutory protection status “Critically Endangered” (Rote Liste 1) and strictly regulated fishing bans in Germany. The EU wide conservation status of this species is Critically Endangered (CR) according to CITES Appendix II / EU Annex B. The second national protected species is the burbot listed as “Endangered (Red list 2) with harvest bans or seasonal closures under state fishery laws.

A rising criticism and risk, that needs to be considered when planning and implementing any NID is the provision of habitat also for introduced species that may become invasive species with the help of NIDs. The threat of spreading invasive species to areas, where they haven´t settled before the existence of NIDs is also a risk, that needs to be managed from the beginning.

There were no invasive or introduced species observed within the ECOMUG project.

However, the gabion units supported a more diverse assemblage during the observation period. Their numerous small cavities and interstitial spaces were used by starfish, crabs, shrimp and several fish taxa, including eels, burbot and rockfish. The stacked plate habitat was also used by fish and crustaceans, but these observations were less frequent and fewer taxa were recorded. The gabion structure therefore appeared to provide a greater diversity of small-scale habitat niches under the conditions investigated (Figure 6). Water Temperatures rose quite high in beginning of May, coinciding with warm weather and sunny days (Figure 7)

and stayed high during summertime due to the warm weather, this did not seem to affect the community settling and use of juvenile fish, typically appearing at this time of the year. However, due to the runtime of only one season no longtime comparison was possible, and no assessment of temperature influence can be made.

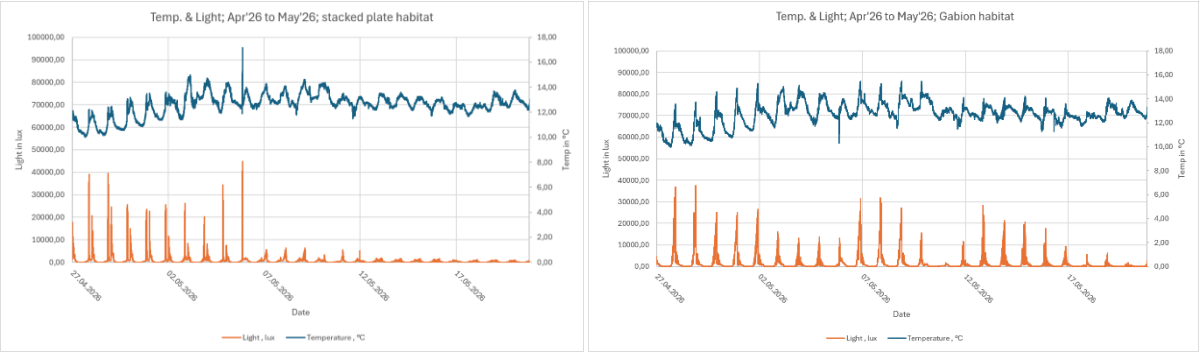


Figure 7: Light and water temperature at the stacked plate and gabion habitat in Kiel Fjord during May 2026

A mooring pole that had been submerged at the site for several years was used as a reference. Its overall degree of biological overgrowth was comparable to that observed on the habitat units towards the end of the assessment period. The mooring pole appeared to support somewhat more algal growth and comparatively less recent mussel colonisation. This may partly have reflected the limited availability of uncolonized surface area, as remnants of mussel and larger barnacle growth from previous years were already present on the pole. Assessment of the associated fauna within or around the structure indicated a lower number of appearance of fish compared to the NID structures. However, the permanently installed camera did not indicate differences in numbers of crabs or shrimp compared with the habitat units.

Targeted drop-in camera observations provided an additional assessment of fish behaviour. No clear differences in behaviour were observed between the two habitat types and the reference structure. Fish were observed using and moving around the habitats, but there was no apparent indication of either strong attraction to or avoidance of the structures. The observations therefore provided no evidence of a deterrent effect of the installed habitat units during the study period (Figure 8).



Figure 8: Still from drop in camera, left to right stacked plate habitat, gabion habitat, reference. In all stills of the videos fish schools visiting the structures are viewable in Kiel Fjord in summer 2026.

Tabel 1: List of species observed in/on the habitats in Kiel Fjord during January – September 2026, brown = sessile organisms, dark blue = fish, light blue = mobile crustaceans, green = algae, NCR = National conservation status critically endangered; CR = EU conservation status critically endangered; NE = national conservation status endangered

Name	Scientific Name	Stacked plate habitat	Gabion habitat
Mud anemone	*Segartiogeton undus*	Yes	Yes
Seasquirt	*Ciona intestinalis*	Yes	Yes
Barnacle	*Amphibalanus* sp.	Yes	Yes
Blue mussels	*Mytilus edulis*	Yes	Yes
Starfish	*Asterias rubens*	Yes	Yes
Rockfish	*Scorpaena* sp.	No	Yes
Pipefish	*Syngnathus* sp.	Yes	No
Wrasse	*Ctenolabrus* sp.	Yes	Yes
European Eel, NCR, CR	*Anguilla anguilla*	No	Yes
Burbot, NE	*Lota lota*	No	Yes
Three-spined stickleback	*Gasterosteus aculeatus*	Yes	Yes
Two-spotted goby	*Gobiusculus flavescens*	Yes	Yes
Eelpout	*Zoarces viviparus*	No	Yes
Shrimp	*Palemon adspersus*	Yes	Yes
Crab	*Carcinus maenas*	No	Yes
Seat Lettuce	*Ulva* sp.	Yes	No
Filamentous red algae	*Plysiphonia* sp. /*Ceramium* sp./	Yes	Yes
Filamentous green algae	*Cladophora* sp.	Yes	Yes

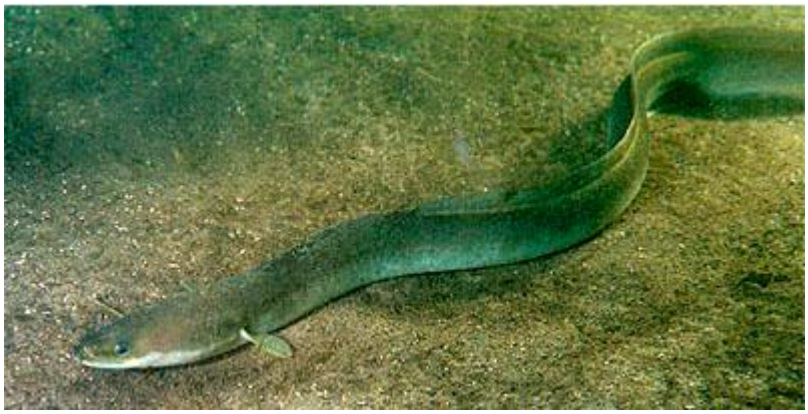


Figure 9: European eel, Anguilla anguilla



Figure 10: Burbot, Lota lota

Overall, the gabion-based design showed several advantages for potential future applications. Its comparatively low weight, modular construction, flexible filling options and greater structural heterogeneity facilitated deployment and provided a broad range of habitat features. The ecological observations also indicated a comparatively diverse associated fauna. The stacked concrete plate design provided a stable and functional habitat with larger internal spaces, but its greater weight and less flexible construction reduced its practical flexibility.

The inclusion of oyster shells within the gabion units did not result in visibly increased settlement of regional blue mussels during the study period. Further investigation would nevertheless be warranted under higher-salinity conditions where oysters are naturally present. In such environments, the availability of oyster shell as a settlement substrate may produce different colonisation patterns. The present results should therefore be considered site-specific and should not be interpreted as evidence against the potential use of oyster shell as a settlement substrate under suitable environmental conditions.

5. Magnetic attachment system

A remotely controllable magnetic attachment system was developed to enable non-invasive installation and retrieval of habitat units on existing submerged steel structures. The system was designed so that no diver intervention is required for either installation or removal. Habitat units can be lowered from a vessel using ropes and a crane or even by hand, attached to the supporting structure by remotely activated magnets, and subsequently released and retrieved from the surface.

Following initial development and assembly under laboratory conditions onshore, the complete final system was tested in a nearshore marine environment at the marina. The testing included the magnetic attachment mechanism, the remote-control components, the acoustic communication system and the retrieval mechanism.

The nearshore test demonstrated that the complete system could be operated as an integrated remote-controlled installation and retrieval system. In particular, the test demonstrated the functional interaction between the surface control system, acoustic communication, the submerged control module, the magnetic attachment mechanism and the retrieval system. The habitat unit could be attached and released remotely, without direct physical access or diver intervention.

5.1. Magnetic attachment

The test-habitat unit was equipped with remotely switchable magnetic anchors that could be activated and deactivated by applying an electrical current (Figure 11). The magnetic attachment provided a non-invasive connection to submerged steel structures, such as monopiles, jacket structures or other steel piles, without requiring drilling, welding or other permanent modifications.



Figure 11: Gabion habitat with magnetic attachment system (black round magnets, connected with cables to micro controller) and recovery buoy system (red round buoy, on left side connected to separate magnet on the Gabion)

During the nearshore test, the magnetic attachment system successfully established and released the connection to the steel structure through remote electrical control. The system therefore demonstrated the required basic attachment functionality under submerged conditions. Once activated, the magnets maintained the connection of the habitat unit to the steel structure during the test period.

The system was designed to be installed from the surface. During deployment, the habitat unit was lowered to the desired depth using ropes. The magnets then established the connection between the habitat unit and the steel structure.

After successful attachment, the deployment ropes could be removed, leaving no physical connection between the habitat unit and the surface.

The submerged control unit can be installed directly at the magnetic attachment system on the habitat unit. The control unit contained a small microcomputer, switches for controlling the magnets, and an acoustic sender and receiver for communication with the surface and can cover a distance of 100m for this nearshore design but much more is possible for offshore deviices. All components required for attachment and release can therefore be incorporated into the submerged system and remained underwater during operation.

The magnetic system provided a reversible attachment method that did not require modification of the supporting infrastructure. This is particularly relevant for existing offshore structures where permanent modifications may not be desirable or permitted. The system also allowed habitat units to be positioned at defined depths and subsequently removed, relocated or replaced without direct access by divers.

5.2. Remote controlled installation and release

The remote-control system enabled (Figure 12) the complete installation and retrieval process to be carried out from the surface. The surface control system consisted of an acoustic sender and receiver array, a modem and a microcomputer. The modem was connected via Bluetooth

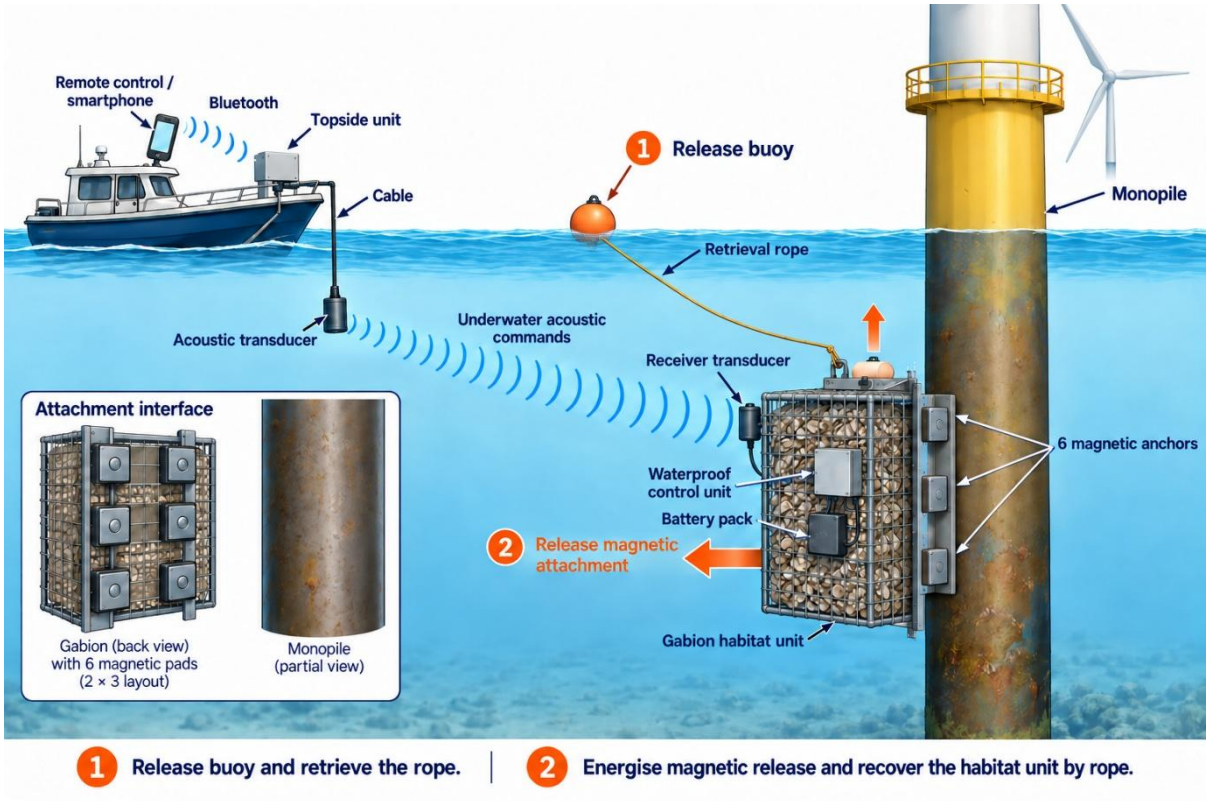


Figure 12: Final future system as an overview

to a surface-based mobile device, allowing commands to be transmitted wirelessly from the operator to the underwater system.

During installation, the habitat unit will first be lowered into the water using ropes and positioned against the steel structure at the intended depth.

A **retrieval mechanism** was integrated into the habitat unit to enable removal without diver assistance. In addition to the anchoring magnets, the system includes a separate small buoy (also connected by a switchable magnet) and a retrieval rope. These components remain submerged together with the habitat unit during normal operation.

For **decommissioning**, a release command will be transmitted acoustically from the surface controller to the submerged system. The operator then sends an activation command from the surface mobile device. The command is transmitted via the Bluetooth-connected modem to the acoustic communication system and acoustically through the water to the sender/receiver unit installed on the submerged habitat module. The submerged microcomputer receives the command and deactivates the magnetic anchors. Once attachment has been confirmed, the retrieval mechanism is first activated, causing the small buoy to be released and rise to the surface. The buoy could then be located and recovered from the vessel. The retrieval rope connecting the buoy to the submerged habitat unit is then subsequently secured from the surface. A further acoustic command is then transmitted to deactivate the magnetic anchors. Once the magnets are switched off, the connection to the steel structure is released and the habitat unit can be retrieved by pulling the recovery line.

The complete sequence therefore allows installation, attachment, release and retrieval without diver intervention and without a permanent physical connection between the submerged habitat unit and the surface. All operational commands are transmitted wirelessly via Bluetooth to the acoustic communication system and subsequently acoustically through the water.

The submerged control module is already also designed to serve as data transmitting unit for future integration of additional sensors. In addition to receiving commands, the system was designed for transmitting of data acoustically back to the surface. This provides a basis for future remote monitoring of integrated sensors, for example to check system status, environmental parameters or other operational data without retrieving the habitat unit.

The connection of several NIDs with sensors transmitting data at once to one receiver in one maintenance operation is possible for further projects. This decreases significantly expensive and risky offshore ship time while also quadruples the number of suitable weather windows for working offshore.

Overall, the nearshore test demonstrated the functional performance of the developed remote attachment system and its main operating sequence. The magnetic attachment, acoustic command transmission, submerged control unit and retrieval mechanism operated together as an integrated system. The test therefore confirmed the feasibility of the proposed diver-free installation and retrieval concept. Further testing under representative offshore conditions is

required to quantify the system's operational limits, including acoustic communication reliability at greater distances and depths, magnetic holding capacity under realistic hydrodynamic loads, long-term durability of the submerged components, and reliable retrieval under adverse environmental conditions.

6. Conclusions and future recommendations

The development and testing activities demonstrated the technical feasibility of two different habitat-unit concepts and a remotely controlled magnetic attachment and retrieval system. Both habitat prototypes remained structurally intact throughout the testing period from January to September and developed biological colonisation and associated mobile fauna. The results also demonstrated that habitat units can be attached to existing steel structures without permanent modification and can be remotely released and retrieved without diver intervention. Together, the modular habitat structures, reversible attachment system and remote monitoring approach provide a basis for further development of nature-inclusive applications on offshore structures.

6.1. Habitat units

Both habitat prototypes provided functional submerged habitat and supported biological colonisation, but they offered different advantages. The gabion-based habitat provided a comparatively complex and heterogeneous three-dimensional structure with numerous small cavities and interstitial spaces. These were used by a diverse range of organisms, including mussels, starfish, crabs, shrimp and several fish taxa. Its comparatively low weight, modular construction and flexible filling options make the gabion concept particularly suitable where structural complexity, flexible configuration and ease of handling are important.

The stacked concrete plates created larger cavities and provided a stable hard substrate. The structure was successfully colonised, particularly by blue mussels and barnacles, and the cavities provided shelter for fish and other mobile fauna. Its main advantages were structural stability and the creation of comparatively large refuge spaces. However, the higher weight and more demanding handling and installation requirements should be considered when selecting this design.

Based on the results obtained, the gabion-based design is favoured for further development where a flexible and modular habitat solution is required. Its construction allows the filling material to be adapted to specific restoration objectives without substantially changing the overall structure. In particular, the gabion can readily accommodate additional substrate materials, such as oyster shells, which could be relevant for future oyster restoration applications.

The present test did not show enhanced blue mussel settlement resulting from the inclusion of oyster shells. However, this result was obtained under the brackish conditions of the test site and should not be considered representative of higher-salinity environments where

European oysters (*Ostrea edulis*) naturally occur. The suitability of the gabion design for oyster restoration should therefore be assessed under appropriate North Sea conditions.

The stacked concrete-plate concept may remain relevant where robust structures with larger cavities and high mechanical stability are required. Future material development should also consider lower-carbon concrete formulations while maintaining the required structural and ecological performance.

For the automated image analyses blind spots of the camera angle should be minimised or standardised. So a school of fish that remains permanently at the rear of a habitat unit would never be photographed even though the habitat unit might well be functioning. So a careful selection of the camera angle (or, where necessary, multiple angles) depending on the space being monitored is required to ensure comparability as schools of fish do not swim evenly around protective habitat units, but tend to favour certain sides. This has a huge impact on the frequency with which they are recorded. Drop-in cameras are very useful to verify the photo recordings.

6.2. Anchoring and release system

The remotely controlled magnetic attachment system successfully demonstrated the principle of non-invasive and reversible attachment of habitat units to submerged steel structures. The system can be installed from the surface using ropes and a crane, remotely attached to a steel structure and subsequently released and retrieved without diver intervention. The acoustic communication system enabled commands to be transmitted between the surface and the submerged control module, while the integrated retrieval mechanism provided a means of recovering the habitat unit from the surface.

An important advantage of the system is its potential for retrofitting existing offshore structures. Existing monopiles and jacket structures could potentially be equipped with habitat units without drilling, welding or other permanent modifications. Habitat units could therefore be added to infrastructures that were not originally designed to accommodate nature-inclusive features.

The reversible attachment also allows installations to be inspected, replaced, relocated or removed without modifying the supporting structure. This flexibility is particularly relevant for pilot installations and retrofit applications on operating offshore infrastructure.

6.3. Monitoring

The monitoring approach combined stationary cameras with targeted drop-in camera observations. The permanently installed camera allowed repeated observations of habitat development and the presence of mobile fauna over the deployment period, while the drop-in camera enabled targeted observations of habitat structure, fish presence and behaviour.

An automated image-analysis system was started during the project. The system successfully progressed to the stage of automatically identifying images containing fish. This represents an important first step towards automated biological monitoring.

It is recommended that cameras have a defined fixed attachment to ensure the same perspective and distance after maintenance work to minimise variation of photos before and after being maintained.

In addition, the submerged control module with its prime function to retrieve the habitats also provides an opportunity to integrate additional environmental sensors and transmit selected information acoustically to the surface.

Innovative development saving costs and reducing risks:

The current acoustic attachment system with a bi-directional communication part provides already the option to transfer data of a whole system of several NIDs. Possible parameters for technical and environmental monitoring are: Turbidity, water current, weight to detect growth, light, water temperature, electrical current to infer material strength, corrosion. All of these and many more parameters could be transmitted by just using an app on the mobile phone. This would replace costly and risky offshore operations with retrieval of the whole system to download data or exchange SD cards.

6.4. Next development steps

The next development phase should progress from nearshore demonstration towards controlled testing and offshore validation. Wave-channel testing could first be used to assess the hydrodynamic behaviour of the habitat prototypes, including stability, loading and potential movement or deformation under controlled conditions.

This should be followed by a full offshore demonstration in the North Sea. The complete system, including habitat unit, magnetic attachment and release mechanism and monitoring components, should be tested under representative wave, current and weather conditions. Particular attention should be given to the reliability of surface-based installation and retrieval and to the performance of the magnetic and acoustic systems under offshore conditions.

The North Sea deployment should also provide an opportunity to investigate the recruitment and settlement of European oyster (*Ostrea edulis*). The gabion habitat is particularly suitable for this purpose because oyster shells or other settlement substrates can be easily incorporated into the modular structure and exchanged or rearranged between deployments. This would allow different substrate configurations to be tested under higher-salinity conditions and provide a basis for evaluating the potential of the habitat units for oyster restoration.

Once the structural and ecological performance has been validated, the habitat units should be upscaled. An important development step will be to estimate the habitat area and volume that could realistically be created using multiple units per offshore foundation. A scenario with

four habitat units per monopile should, for example, be assessed in terms of available attachment area, habitat volume, deployment depth, spacing and practical installation requirements.

The automated monitoring system should be developed alongside these physical tests, progressing from fish-image detection towards species recognition and abundance estimation. This would support more efficient analysis of larger datasets generated during offshore deployments.

The long-term goal is to establish nature-inclusive habitat installations as a practical component of both existing and future offshore infrastructure.

For existing offshore wind farms, the magnetic system provides a potential retrofit solution that does not require permanent modification of the supporting structure. This could enable habitat and restoration measures to be added to operating infrastructure and subsequently removed or adapted as required.

In the longer term, the modular habitat concept could be adapted to different environmental conditions and restoration objectives, including biodiversity enhancement, mussel and algal habitat creation and European oyster restoration. The combination of purpose-designed habitat units, reversible attachment and automated monitoring provides a flexible framework for integrating ecological enhancement into both existing and newly developed offshore infrastructure.