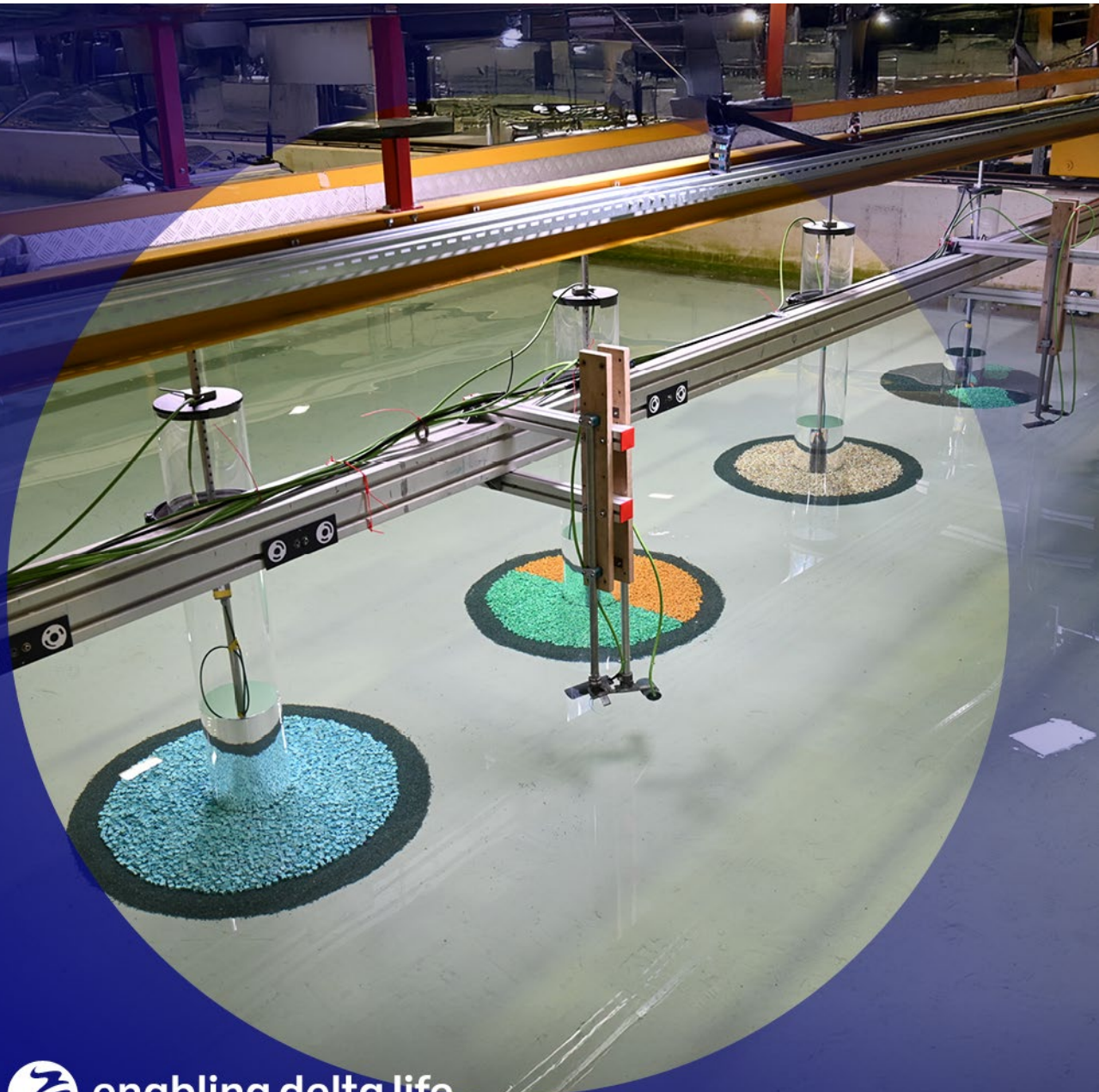


Synthesis Report: Joint-Industry Project Scour Protection for Ecological Enhancement (SPREE)

A Comparative Study of Armour Rock and Engineered Reef Units (ERUS) as
Scour Protection



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Client	TKI Offshore Energie
Contact	TKI
Projectreference	TKITOE_WOZ_2402_Deltares_SPREE
Keywords	Engineered Reef Units (ERUS), artificial reefs, scour protection, CPS stabilization, cable protection, offshore wind, ecology, LCA, CO ₂ emissions




Document control

Version	1.0
Date	04-12-2025
Project nr.	11210847-000
Document ID	11210847-000-HYE-0001
Pages	37
Classification	
Status	Final

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Summary

This synthesis report presents the results of the Joint-Industry Project (JIP) – SPREE. The project evaluated **Engineered Reef Unit Solutions (ERUS)** as alternatives to conventional rock for offshore wind farm (OWF) scour protection, by bringing together twelve industry and research partners: **BAM, Boskalis, Coastruction, Deltares, Geowall, Holcim, INSPIRE Environmental (Venterra Group), Reefy, RWE, TenneT, Vattenfall and Wageningen Marine Research.**

The project responded to growing regulatory and ecological demands **for nature-inclusive design (NID)** in offshore infrastructure, and to the demand for scour protection material in rock scarce areas. ERUS are engineered reef units, typically made from concrete, and specifically designed to enhance nature. Unlike conventional rock, they can be customized in terms of shape, porosity, surface roughness, and material composition. These can be designed in alignment with NID guidelines to support and enhance marine life while maintaining structural integrity.

JIP-SPREE compared conventional rock used for scour protection with ERUS as alternative units to be used as armour layer protection in scour protection of OWF infrastructure. The project conducted its assessments specifically for use in the North Sea (Dutch sector) and the western North Atlantic (U.S. East Coast). The project consisted of physical model tests, a life cycle assessment, ecological evaluation and stakeholder engagement to assess aspects of installation feasibility (WP1), hydraulic stability (WP2), sustainability (WP3), and ecological enhancement potential (WP4) and found the following results:

WP1 The evaluation found that ERUS can be installed with existing equipment, such as fallpipe vessels, for units up to 0.6m in size. However, full-scale pilot tests are essential to validate results of the expert judgement and assumptions based on test interpretation, e.g. regarding breakage and displacement estimates.

WP2 Results showed that ERUS designs tested in this study perform within acceptable limits for scour protection in terms of hydraulic stability, though with slightly more deformation than rock. Deformation estimates can be made using existing tools for loose rock (HaSPro – Handbook Scour and cable Protection methods) adjusted to account for ERUS characteristics. Design aspects such as interlocking, shape, and weight can enhance stability and should simultaneously consider design aspects that align with ecological enhancement objectives. To further the Technology Readiness Level (TRL) of ERUS to level 6 and above and to validate the findings on the use of established tools for rock, research through offshore pilots with at real scale ERUS units in operational environments is required.

WP 3 assessed the environmental cost indicators (ECI) of ERUS compared to rock, including CO₂ emissions. The life cycle stages assessed included material extraction, processing, transport and installation (A1-A5). For the two idealized case studies representative ERUS produced with CEM III cement achieved the lowest Environmental Cost Indicators (ECI) for the functional unit of one cubic meter, while rock had the lowest ECI for the functional unit of one full armour layer for one monopile. The difference in ECI was less than 10% indicating that ERUS and rock can achieve comparable ECI outcomes. CEM I cement had the highest ECI in all cases and is therefore environmentally not considered comparable. Cement accounts for approximately 75–80% of the emissions in the production stage which could be reduced by using emerging cement types, recycled concrete and different productions methods further improving their ECI performance.

WP4: The customization potential of ERUS (e.g. surface roughness, shape, material composition, porosity), offers opportunities to engineer in alignment with NID

principles for specific ecosystem services and species. These features can support habitat creation and biodiversity increase and should be validated through long-term in-field monitoring to quantify the added ecological value and incorporated into decommissioning frameworks.

Together, these findings support further investigation of ERUS as a promising **multifunctional scour protection solution** that aligns with the offshore wind sector's transition toward sustainable and ecologically responsible practices. The report provides indications for further ERUS TRL enhancement and considerations that should be taken into account by developers, regulators, and innovators seeking to implement NID principles at scale. It also provides direction for further research to be conducted.

The JIP-SPREE project was supported through research funding provided by [Topsector Energie](#) as well as the contributions of all partners. In addition to financial contributions, the project benefited significantly from their expertise, experience and extensive time and effort dedicated to the project realisation.

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Glossary of Terms and Acronyms

Armour Layer	The top layer of a scour protection that should be sufficiently stable against hydrodynamic forcing and should prevent erosion of the underlying material
BOEM	Bureau of Ocean Energy Management – U.S. agency overseeing offshore energy development and decommissioning
BRUV	Baited Remote Underwater Video – a method for observing marine life using underwater cameras
Berm	Raised barrier with engineered dimensions used in offshore applications for scour protection, stabilisation of assets and protection from loads
CEM I / CEM III	Types of concrete with different mixture. CEM I is made of ordinary Portland cement while CEM III is a blastfurnace cement containing less clinker
CPS	Cable Protection System – infrastructure shielding submarine cables
Critical Shields parameter (θ_{cr})	Dimensionless parameter that quantifies the threshold of shear stress at which sediment particles begin to move
Deformation Depth	Vertical change in armour layer thickness due to displacement of elements from the area
ECI	Environmental Cost Indicators
eDNA	Environmental DNA – genetic material from environmental samples used to monitor biodiversity
Equivalent Sphere Method	Design-independent method to schematise ERUS for calculation and design purposes
ERUS	Engineered Reef Unit Solutions – units made of different material mixes (often concrete) and different shapes for protective purposes in coastal and offshore protective areas
Fallpipe Vessel	Vessel used to install materials by guiding them through a pipe to the seabed
HaSPro	Handbook of Scour and cable Protection methods , a manual describing the state-of-the-art in scour and cable protection methods, developed together with and for the industry during multi-year research project.
Interlocking	Physical connection between units that limits the ability of an individual unit to move independently from its neighbours
JIP-SPREE	Joint Industry Project – Scour Protection for Ecological Enhancement, a multi-partner study evaluating ERUS
KC_{tot}	Combined Keulegan–Carpenter Number for waves and currents
LCA	Life Cycle Assessment – evaluates environmental impacts across product life stages
MOB_{top}	Relative Mobility Number on top of the scour protection
MP	Monopile
NID	Nature-Inclusive Design – design options integrated into infrastructure to achieve pre-defined ecological benefits.
OSPAR	A mechanism by which 15 Governments and the European Union cooperate to protect the marine environment

OWF	Offshore Wind Farm – wind energy installations located in marine environments
ROV/AUV	Remotely Operated Vehicle / Autonomous Underwater Vehicle – robotic systems for underwater inspection
Rigs-to-Reefs	Programme converting decommissioned oil & gas platforms into artificial reefs
Scour Protection	Measure to prevent erosion around offshore structures caused by water movement
Shields parameter (θ)	Dimensionless number representing flow induced shear stress on sediment particles. When a critical value is reached (expressed by the critical Shields parameter, θ_{cr}) sediment particles begin to move
TRL	Technology Readiness Level – a scale for assessing technological maturity
Winnowing Requirement	Requirement to reduce the hydrodynamic load at the seabed in order to prevent sediment escaping through the scour protection's pores
WP	Work Package

1 Introduction

Offshore wind farms (OWFs) are a vital contributor to global energy transition strategies. The Netherlands plans to install 30–40 GW of offshore wind energy capacity by 2040 (Wind Power NL 2025) while the U.S. has federal offshore wind targets of 30 GW by 2030 and 110 GW by 2050 (U.S. Department of Energy (DOE) 2023). Global goals aim to scale from current 83 GW capacity to 2.000 GW by 2050 (International Renewable Energy Agency 2025). To achieve these ambitions, in some cases requires OWFs to be built in dynamic marine environments, where scour protection is essential to safeguard turbine foundations and associated infrastructure such as cables.

Currently, loose rock is typically used for scour protection. Research found that rock can form artificial reefs habitats (Degraer, Carey, et al. 2020) (Glarou, Zrust and Svendsen 2020). This potential to enhance reef ecology is gaining attention as a measure to promote nature-inclusive design (NID) of OWFs, especially in areas of degraded marine environments (see e.g. regulatory requirements for OWFs in The Netherlands, e.g. Hollandse Kust-West OWF¹, IJmuiden Ver²) and due to international guidelines and recommendations promoting NID (e.g. the offshore-wind-energy-roadmap-2030³, the EU State Aid Guidelines⁴, the Net Zero Industry Act promoting non-price criteria⁵, the OCEaN's support for ecological criteria in offshore wind farm auctions⁶ and the EU Nature Restoration Law⁷). In parallel, the limitations of suitable rock sourcing in sufficient proximity to geographic areas used for OWF developments have prompted the search for alternative materials.

Nature-inclusive design (NID) of OWFs 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 [...] has been degraded or reduced. [...] NID options can be part of [...] a scour protection layer or a cable protection measure.” (Hermans, Bos and Prusina 2020)

To address these challenges, the Joint-Industry Project (JIP) – SPREE (Scour Protection for Ecological Enhancement)⁸ brought together twelve research and industry partners - [BAM](#), [Boskalis](#), [Coastruction](#), [Deltares](#), [Geowall](#), [Holcim](#), [INSPIRE Environmental](#), [Reefy](#), [RWE](#), [TenneT](#), [Vattenfall](#) and [Wageningen Marine Research](#). Between March 2024 and October 2025 the partners collaborated to evaluate **Engineered Reef Unit Solutions (ERUS)** as a multifunctional alternative to conventional loose rock. JIP-SPREE defined ERUS as units made from various concrete mixes that can be customised in terms of shape, porosity, surface roughness, and material composition to meet both structural and NID principles. To date, ERUS and other NID elements have primarily been deployed as ‘add-ons’ on top of conventional scour protections or within OWF sites (e.g. artificial reef blocks or fish cages). With JIP-SPREE, the partners sought to advance the TRL level of ERUS as full armour layer elements for scour protection by researching:

Work Package 1 (WP1): the installation feasibility of ERUS using existing methods and equipment currently applied for rock installation;

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://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1991&qid=1722240349976>

⁸ [Testing innovations to enhance nature-inclusive design of offshore wind farms | Deltares](#)

Work Package 2 (WP2): the hydraulic stability of protection armour layers comprised fully of ERUS;
Work Package 3 (WP3): their production and deployment sustainability; and
Work Package 4 (WP4): their ecological NID performance and their implications for monitoring and decommissioning decision-making.

1.1 JIP – SPREE Objective

The objective of the JIP-SPREE was to generate insights into (i) the hydraulic stability of ERUS as an alternative material for armour layer scour protection of OWFs, (ii) their potential for ecological enhancement, and (iii) their environmental sustainability to inform the ERUS TRL advancement. The project study concentrated its evaluation efforts on two offshore regions: the North Sea (especially the Dutch sector), and the western North Atlantic (U.S. East Coast). Through physical model testing, a life cycle assessment, ecological evaluation, and stakeholder engagement, the project sought to provide practical guidance for developers, regulators, and innovators aiming to implement NID principles at scale and advance the TRL of ERUS.

1.2 JIP – SPREE Assessment Context

Given the promotion of NID in the North Sea, especially the Dutch sector, and the growth potential for OWFs in the North Sea and U.S., the JIP-SPREE focused its comparative research in these two offshore regions. Since currently, armour rock is being used where scour protection is required, the JIP-SPREE focused on comparing conventional armour rock with ERUS, rather than comparing individual ERUS designs with each other.

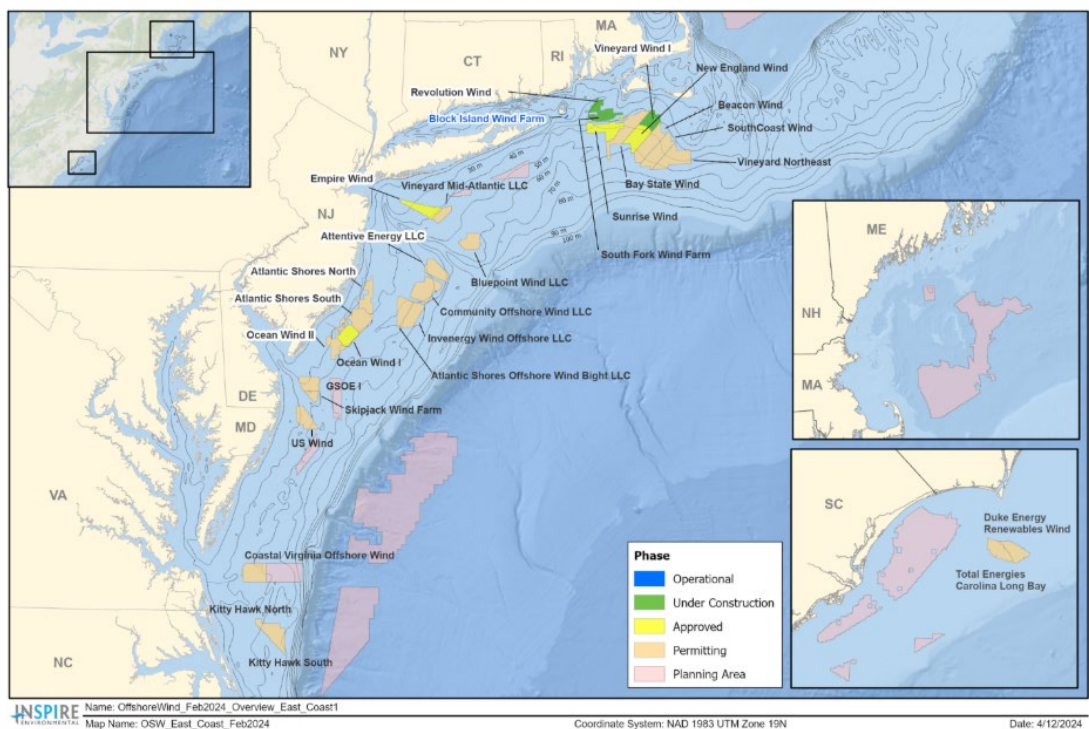


Figure 1-2 Existing, on-going and planned OWF in the western North Atlantic (U.S.) as of April 2024 (source: Inspire Environmental (Venterra Group))

Environmental and structural boundary conditions were derived from information on hydrodynamics, wave and current profiles, and soil conditions representative of the North Sea and the western North Atlantic. Representative storm conditions with various return

periods (1 year, 10 years, 50 years) were selected based on a range of metocean conditions at various anonymized locations in the North Sea and the western North Atlantic expressed as combinations of MOB_{top} and KC_{tot} (coloured markers in Figure 1-3)⁹

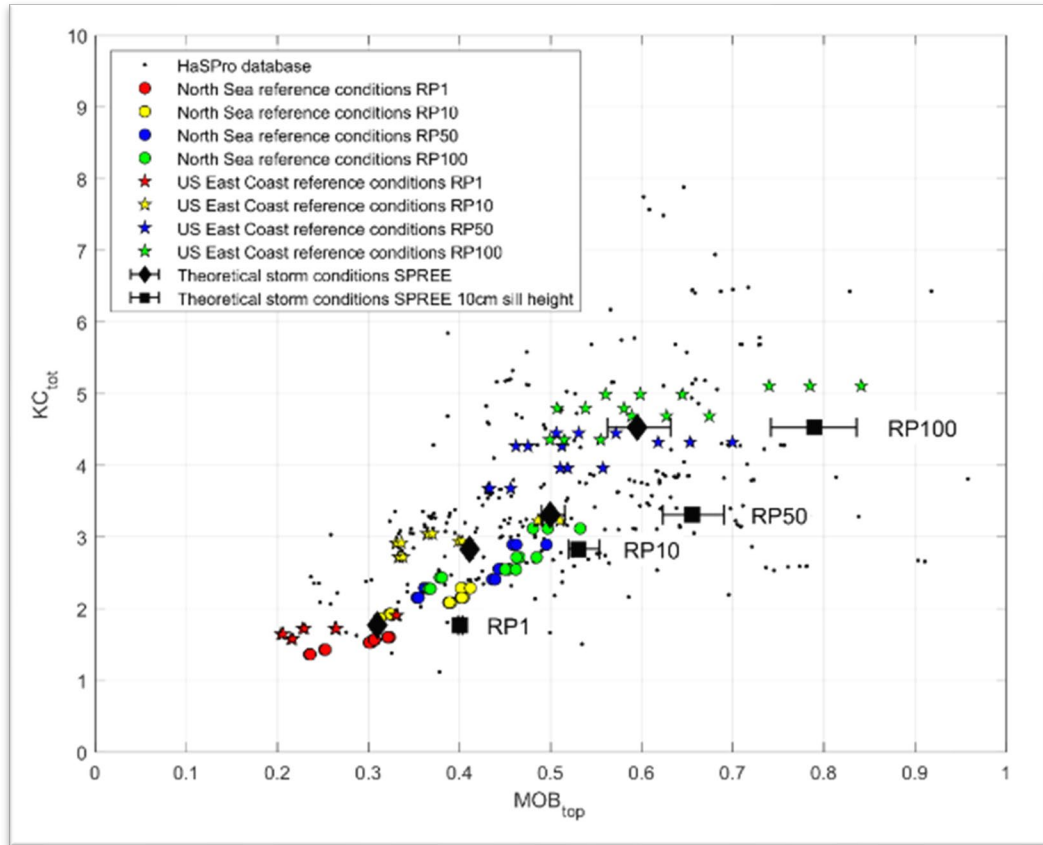


Figure 1-3 - Reference conditions for the North Sea and the US East Coast area, incl. MOB_{top} and KC_{tot} combinations of the storm conditions for JIP SPREE (source: Deltares)

The test conditions were chosen to reflect a realistic range of storm impacts, based on two key parameters: MOB_{top} , which measures how mobile the top layer of scour protection is, and KC_{tot} , which combines the effects of waves and currents. The selected test conditions reflect the North Sea and north Western Atlantic reference conditions as visualised in the figure. The test conditions used in this project are shown as the black diamond and square markers, with an added variation band to account for differences in the size of the ERUS. These conditions were then compared visually with existing data from the JIP HaSPRO loose rock database to confirm their representativeness.

The LCA's geographic scope and ecological performance evaluation used more specific site characteristics based on location specifics for the OWFs IJmuiden Ver (NL) and Revolution OWF (U.S.). For the LCA, the closest sourcing locations and loading sites were assumed. For the IJmuiden Ver case, Eemshaven in the Netherlands and Stavanger in Norway were assumed for ERUS and rock respectively. For the case of Revolution OWF, St. John's, Canada, and Sheet Harbour, Canada were assumed.

⁹ This is based on the work of (Broekema, et al. 2024) which showed that storm impact, thus storm severity, can be quantified by combinations of MOB_{top} and KC_{tot} , therefore representative test conditions can be selected based on known conditions in the areas of interest. Four combinations of MOB_{top} and KC_{tot} , which are equivalent to storm conditions with a return period of 1, 10, 50 and 100 years were selected for JIP-SPREE (black diamond markers in Figure 1-3).



Figure 1-4 - Map of IJmuiden Ver OWF location (left) and Revolution OWF (right) (sources: [RWS](#) and [BOEM](#))

The project conducted the research on the basis of four specific ERUS designs, as well as one innovative 3D production method, as shown in Figure 1-5 and Figure 1-6. The units from BAM, Holcim, and Reefy were tested in WP1&WP2 while all designs, including Geowall's were used as basis for WP3 and WP4 evaluations. Moreover, Coastruction's 3D production method and material mix were included in the evaluations of WP3 and WP4.

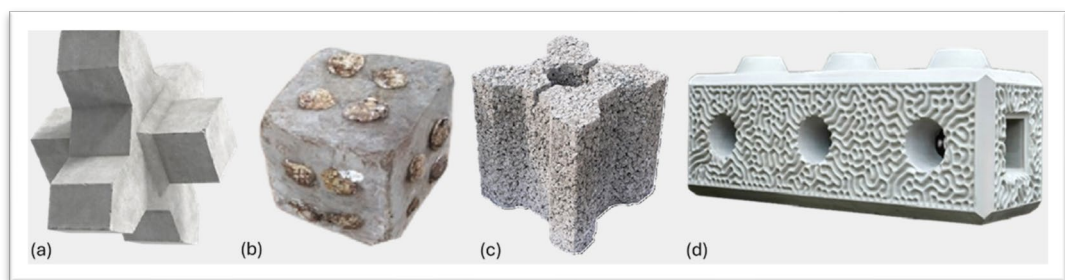


Figure 1-5 - ERUS designs of participating partners from left to right ((a) BAM, (b) Geowall, (c) Holcim, (d) Reefy). The ERUS designs have a dimension ratio of 1H:1V:1L, except Reefy which has a ratio 1H:1V:3L. The ERUS sizes can vary [length (height, width for cubes) may range between 0,2 – 0,5 m.]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

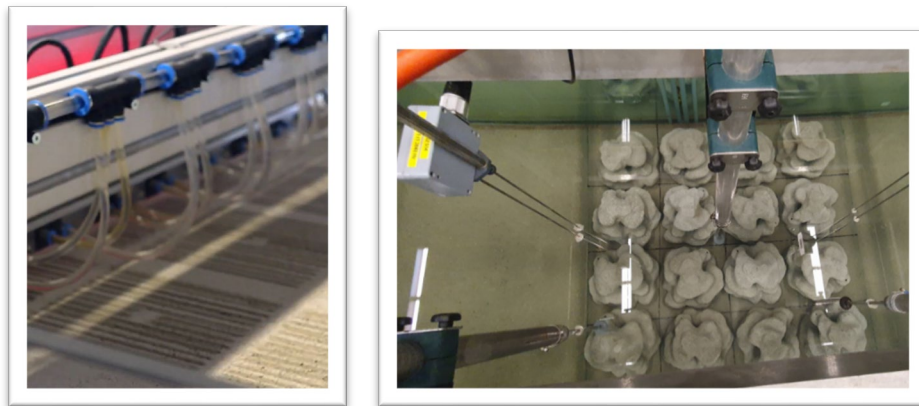


Figure 1-6 - 3D production method developed by Coastruction and example units printed (source: Coastruction)

2 WP1: Installation assessment

2.1 Objective

WP1 evaluated the installation possibilities for ERUS, from quay to offshore, using existing methods and equipment available in the market. It focused on two main knowledge gaps: (1) ERUS' installation limits (e.g. cargo volume and weight, equipment functionalities etc.) and (2) ERUS' falling behaviour in the water column during installation operations.

2.2 Methods

Given the lack of at-scale installation data for ERUS, expert judgement and calculation methods commonly used for rock installations were applied for conditions representative of the North Sea and western North Atlantic to evaluate the installation feasibility.

Installation limitations refer to the suitability of a particular method to place scour protection on the seafloor and the maximum size of an element that can be placed by that method. They include estimating the impact energy upon landing of an element (rock or ERUS) on the seabed or assets (e.g. cables). The WP also supplied information on transport requirements and layout options as input for WP3's LCA.

Physical model tests conducted in the [Deltares research facilities](#) provided insights into ERUS' falling behaviour. The tests simulated free falling ERUS plumes and plumes during installation of ERUS by fallpipe (see Figure 2-1).

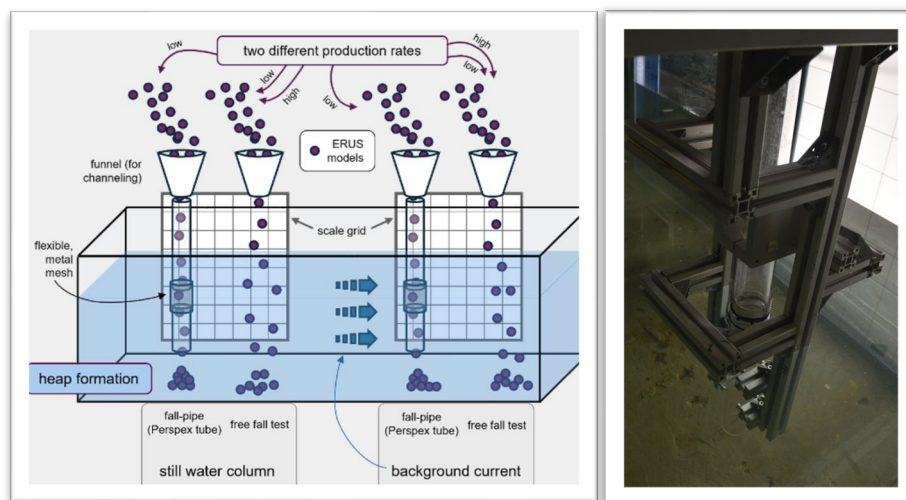


Figure 2-1 – Left: setup of installation (fall) tests, including two different production rates, free falling tests and fall-pipe imitations, as well as tests in a still water column and under a moderate background current. Note: this schematic is not to scale, Right: test set-up image of the fall-pipe installation from the tests conducted at the Deltares facilities (source: Deltares)

The three ERUS units from BAM, Holcim and Reefy were tested as scaled-down models in this experiment for different production rates as an important boundary condition; larger production rates could trigger larger terminal velocity, which in turn could have an impact on the possible breakage of the units.. Through these tests, the terminal fall velocity, heap formation, and shape of ERUS were evaluated, as well as their effect on the layout of protection.

Installation feasibility was assessed for these locations based on commonly used vessels for bulk installation, including fallpipe vessels. Alternative or innovative installation methods were

excluded from consideration, due to the absence of any practical experience and the endless possibilities for innovative methods, which are often project specific.

2.3 Results

The assessment concluded that installation via a fallpipe vessel is the most suitable existing method for all the applications considered in this project, capable of installing a maximum ERUS size in the order of 0.6 m. However, current loading methods require ERUS to be able to withstand large drop heights, which may lead to breakage. This requirement could potentially be reduced by applying alternative loading and handling methods specific to ERUS designs. Some degree of breakage is expected to occur during loading and installation. This may affect the hydraulic stability, the cavity sizes, and the required protection volume. Due to the absence of relevant field data, assumptions on behaviour and operational feasibility (e.g. loading speed, breakage, loss estimates, etc.) were made based on experience with rock.

Physical test results showed that ERUS' behaviour was similar to that of rock in several aspects. For single-graded ERUS, group falling behaviour and achieved group terminal velocity depended on individual ERUS' shape tested in this WP (by affecting the drag force), background current, and installation method. However, compared to rock, ERUS appeared less affected by the background current and they showed smaller heap spread with higher angles of repose. The latter was highly affected by interlocking features between elements, which are further enhanced with increasing installation speed. In general, steeper slopes will flatten out more quickly. However, due to the enhanced interlocking, it is likely that the stable slope will also be steeper compared to loose rock. It can therefore not be stated with certainty that this will impact overall scour protection behaviour, although it is expected that any impact is likely to be limited.

2.4 Limitations and future research

The study provided a valuable first estimate of ERUS installation behaviour, though several limitations were identified. The results are dependent on individual ERUS designs and largely based on desk assessments and expert-based assumptions. Field experiments will provide more data on the degree of breakage due to large drop heights, loading speed, and loss estimates. The physical test campaign was relatively short in duration, resulting in a limited number of data points, and considerable difficulties in results processing. Consequently, a definitive interpretation and comparison between the installation methods was challenging, and obtaining spatially resolved plume falling velocity data was not feasible. Further research and testing are required to achieve a comprehensive understanding of the parameters affecting the ERUS behaviour. Future steps could include pilot studies of ERUS offshore installation to obtain input on the assumptions made on loading, handling, and installation process, as well as observations on the falling behaviour and achievable footprint, in order to verify and optimise the theoretical work and experimental results. In addition, the scope could be extended to include the exploration of alternative installation and handling methods that are tailored to ERUS, which was not covered in this project.

3 WP2: Hydraulic performance of ERUS

3.1 Objective

WP2 evaluated the hydraulic performance of (scour) protection armour layers comprising entirely of ERUS around monopiles, in cable crossings, and as protection berms over cable protection systems (CPS). The assessments' focus was on ERUS' external stability (i.e. the stability of an element itself against wave/flow load) and how they compare to conventional loose rock protections.

3.2 Methods

In the absence of guidelines for ERUS, the assessment applied available state-of-the-art tools developed for loose rock, such as the loose rock deformation model of HaSPro (Broekema, et al. 2024) along with aspects of the loose rock design methodology. The shape of the tested ERUS deviates from the typical shape of loose rock, but can be directly compared, by schematising ERUS as spheres of equal density and solids' volume as the units (Saxoni, et al. 2025).¹⁰ Schematised ERUS were used for calculation and layout designs in the same manner as for rock. The approach relied on several assumptions, most importantly:

- An ERUS can be schematised in the same way as a rock, which involves selecting a representative grain diameter of a sphere that has the same mass and density as the ERUS. This is especially relevant for ERUS that have a shape where one of the three size dimensions (length, width, height) is different from the others.
- Interlocking effects between ERUS and rock are similar, such that we can rely on the Shields' curve for initiation of motion. Naturally, this is not entirely correct, since it is expected that the ERUS will show different interlocking properties. This assumption is therefore used as a starting point.

Overall, the choices made represent a conservative approach that requires further research, especially on how ERUS shape affects movement and interlocking.

To obtain insights into the initiation of motion of ERUS, a test campaign was conducted in [Deltares research facilities](#) to inform the calculations for the external stability investigation (see also Figure 3-1). The primary aim of this initial test campaign was to get a feeling for the differences in behaviour around the threshold of motion between ERUS and loose rock.

¹⁰ Equivalent sphere method was applied, where an equivalent sphere diameter is calculated per ERUS accounting for the unit's porosity, n (% of air relative to the full cube or rectangle, depending on which geometric shape fits best the ERUS shape). The method is design independent which also accounts for the ERUSs' physical properties.

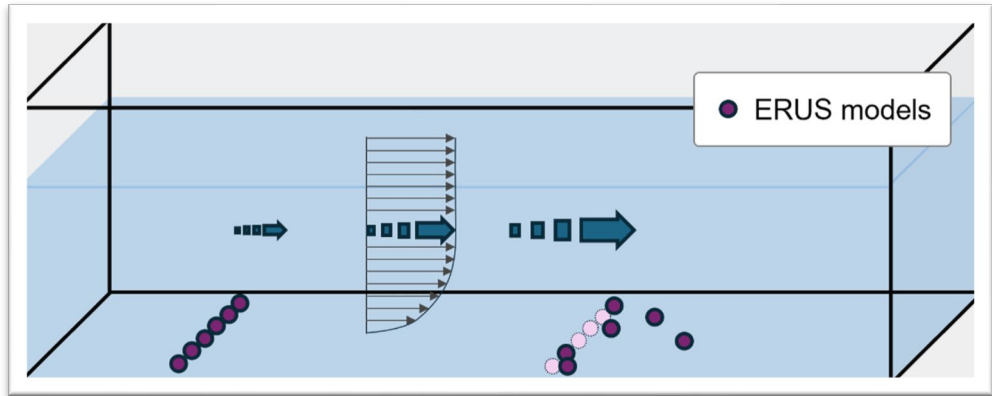


Figure 3-1 - WP2 Threshold of motion test set-up schematic JIP SPREE

The external stability was evaluated through three series of physical model tests in the test facilities (see also Figure 3-2 and Figure 3-3). During each test, multiple armour layer scour protections around monopiles and CPS were tested in line with typical dimensions for loose rock layouts.¹¹



Figure 3-2 - External stability test set-up for JIP SPREE around monopiles (source: Deltares)

¹¹ Scour protections have an extent of 3 pile diameters and a thickness of 3 armour layers, crossings have a thickness of 2 armour layers, and CPS berms have a thickness of 5 armour layers close to the pile face (to compensate for the increased deformation due to higher flow intensity in that area) and 3 armour layers further from the monopile. The armour layer thickness was determined based on the ERUS equivalent sphere and accounting for vertical overlap of the ERUSs as per the Rock Manual (CIRIA, CUR, CETMEF 2007).



Figure 3-3 External stability test set-up for JIP SPREE (cable crossings) (source: Deltares)

Alternative layouts targeting specific ERUS design aspects were also investigated (see further below in Figure 3-6). They comprise of:

- conical layouts with smaller extent than conventional armour layer designs, looking at whether stronger interlocking (due to the elements being in a slope) is beneficial for stability by breaking of the horseshoe vortex
- layouts with large elements (4 times bigger in size than the main unit), in various configurations optimised for ecological requirements, looking at whether these can form a different type of open armour layer that does not allow flow penetration to the filter layer to avoid erosion of the filter layer and as a result sand escaping through the pores of the protection.

Flow velocities and wave heights were measured by electromagnetic flow meters (EMSs) positioned near-bed, and resistance-type wave gauges, respectively. Armour layer deformation was quantified by differences in bathymetry measurements taken before and after each test by means of 3D stereophotography (Raaijmakers, et al. 2012).

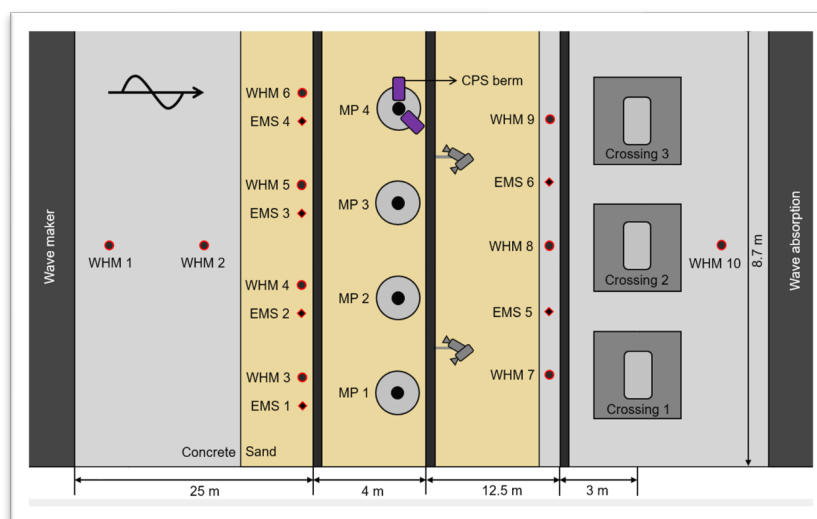


Figure 3-4 - WP2 Hydraulic stability test set-up schematic for JIP SPREE (schematic not to scale), WHM (Wave Height Meter)

The hydraulic performance of the ERUS armour layers was examined in terms of deformation pattern and deformation depth using the methodology outlined in Van Steijn et al. (2023).

3.3 Results

The test results showed that ERUS are a viable alternative to conventional rock armour layers in terms of stability. The hydraulic stability of ERUS is the result of the combination of mass and other design properties. It is expected that that interlocking plays a larger role than skin friction for ERUS as opposed to for rock. The degree of interlocking affects the protection's expected deformation pattern and the degree of dynamic behaviour. For stronger interlocking, more dynamic reshaping of the protection is observed; more elements stay within the protection as they lock with other elements while moving across the protection, rather than eroding away. Also, the stronger the interlocking, the lighter the elements can be as more dynamic behaviour is allowed since less elements erode. With decreasing interlocking, "rocking" motion increases, less elements lock with others, with the effect that more elements eventually escape the protection. ERUS design research at the next TRL should consider interlocking and mass properties to achieve stability while optimizing material use which could benefit reduced environmental costs (see also WP3 in section 4).

In scour protections around monopiles similar to conventional layouts, ERUS protections show slightly more deformation and different deformation patterns than loose rock (under similar hydrodynamic conditions expressed in MOB_{top} and KC_{tot}). This is visualised in Figure 3-5. This figure shows the scour protection deformation depth normalised with the pile diameter for the various tested ERUS around monopiles. In the background, deformation data for loose rock scour protections around monopiles (Broekema et al. (2024) is shown with the coloured semi-transparent markers. The results for the ERUS are shown for two different calculation methods for roughness. The black markers treat the elements exactly the same as rock for calculating roughness. The red markers are computed using an alternative roughness calculation method that (rudimentarily) accounts for the shape of the ERUS, specifically for differences in length, width and height compared to assuming the element is schematised as a sphere. This also means that not all ERUS are affected similarly by using this different calculation method, which also becomes apparent from the figure.

The majority of the data points seem to fall between the S50% and S90% lines of the scour protection deformation formula (Broekema, et al. 2024). Differences in shape between the various ERUS types may account for the observed variability. This has not been analysed in detail, since the emphasis of this project was to understand generic behaviour and trends. The consistency between observed deformation depth in loose rock and for the tested ERUS solutions is a positive observation for the application of the proposed schematisation and towards practical application of ERUS in the field. When selecting an appropriate schematisation of an ERUS, a 90% non-exceedance prediction with the deformation model derived in (Broekema, et al. 2024) should give a good first indication of the anticipated scour protection dynamics. This consistency suggests that the Broekema et al. (2024) model could be used during next TRL operational tests as a first approximation for predicting ERUS deformation, to validate these findings in appropriate test environments to validate these findings.

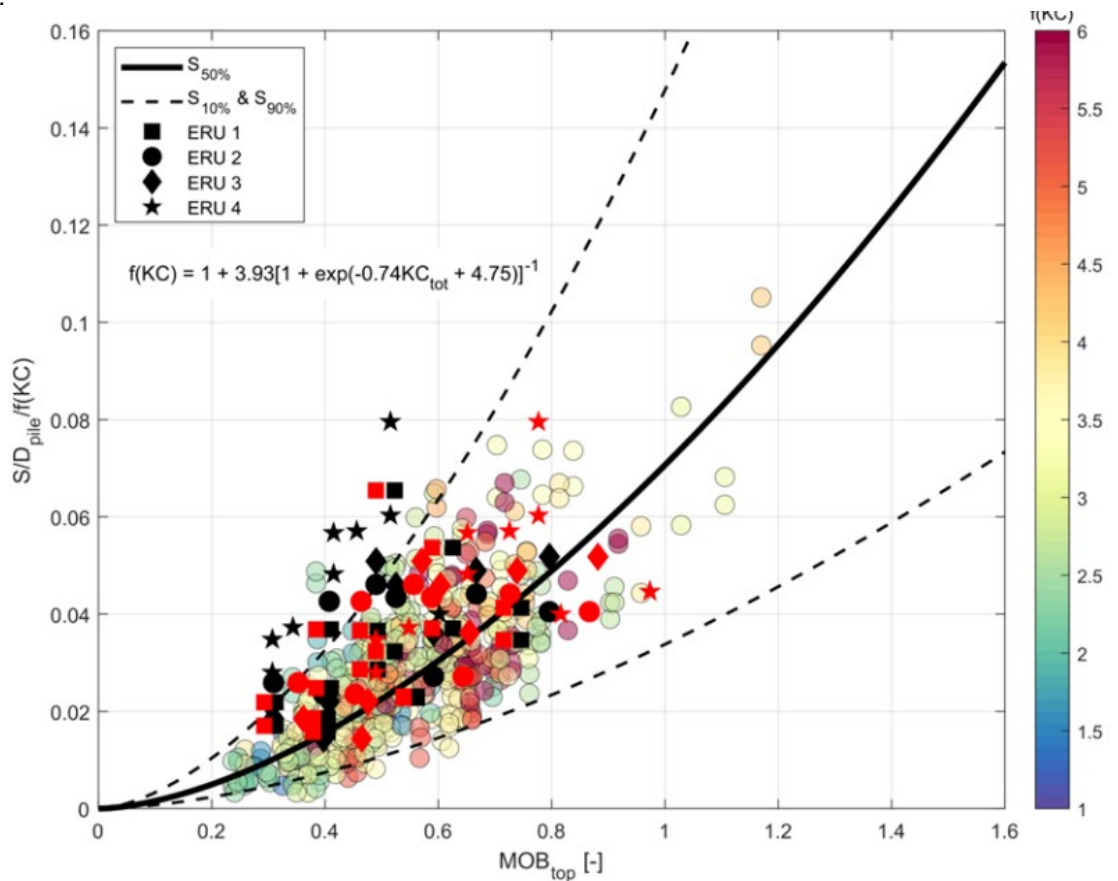


Figure 3-5 - Deformation depth for tested ERUS (black and red markers) and for the loose rock database of (Broekema, et al. 2024). The plotted lines denote the scour protection deformation model for 50% non-exceedance prediction and for 10-90% non-exceedance prediction. The black markers denote roughness height calculated using $D_{50,sphere}$, the red markers denote roughness height calculated using L_{ERUS} (Saxoni, et al. 2025))

The conical layouts showed larger absolute deformation depth near the pile face compared to a conventional scour protection layout. Yet, the remaining layer thickness near the pile face after the most severe storm test was between 35% and 100% of the initial layer thickness of the conventional scour protection layout.

Tests with larger elements placed directly on the filter layer were mostly stable, and only some individual units were displaced. However, the underlying filter layer deforms so that it no longer fulfils the winnowing requirement. A scour protection layout with larger ERUS elements would require a larger filter layer thickness, such that enough filter material is left after a design storm. Using ERUS as CPS protection, the tests found that they behave similarly to rock overall and as it seems from the test results, ERUS perform slightly better. Berms perpendicular to the flow show the most deformation, both for rock and ERUS. Even with highly interlocking units, the inner berm slope close to the monopile collapses and some material removal and reshuffling-flattening occurs.

For cable crossings, the ERUS designs experienced slightly more deformation compared to loose rock berms. A comparison of the crossings to the state-of-the-art was not possible, as it was not applicable to the specific test set-up. A single-layer armour could potentially be a more stable solution than the tested two-layer set-up. Yet, that would not comply with the (rock-based) criteria of two layers remaining after deformation of a protection.

Initiation of motion highly depends on object shape (affecting the drag and resistance of the element) and mass. The high-level tests conducted in this project did not yield enough data points to capture the drivers of the ERUS behaviour and the non-linear dependency on mass, as all tested elements have different masses and shapes. However, the observed flow velocities of movement initiation of ERUS are, on average, similar to that of rock. So, as a first step, it was selected to use the critical Shields stress of rock for ERUS as an initial estimate. Further testing is needed to verify this assumption or obtain ERUS-specific critical Shields stress values.

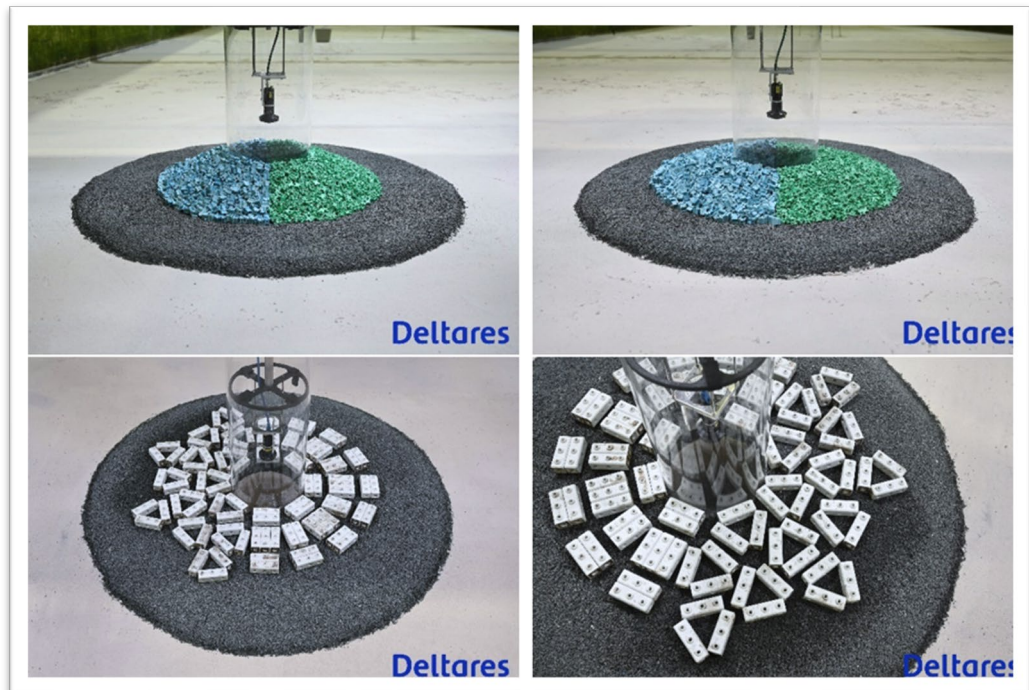


Figure 3-6 - Alternative test layouts - two conical layouts for highly and medium interlocking elements (top images) and two layouts with large elements in bundled configurations (bottom images)

The alternative layouts tests showed promising results and highlighted the potential of tailor-made configurations targeting specific ERUS design aspects.

3.4 Limitations and future research

The findings suggest that a rock-based methodology for schematising and predicting deformation offers a viable means for initial performance assessments of ERUS scour

protections, even when specific ERUS properties (such as density and size) or offshore conditions vary. However, this is only a first rough estimate and a starting point for engineering practice. Additional research is necessary to fill knowledge gaps and establish correlations between the initiation of motion and ERUS characteristics. Furthermore, the transferability of the adapted methods and tools to ERUS shapes significantly different from those investigated in this study remains uncertain and requires further validation. At present, there are no dedicated design criteria or requirements tailored to ERUS protections; therefore, rock-based criteria were employed for this evaluation. These may be refined for ERUS applications to facilitate non-conventional layouts, provided that more comprehensive data and advanced calculation methods become available. In such innovative configurations, ERUS-specific design details must be addressed, and direct comparison with traditional rock approaches is not appropriate. While these configurations show considerable promise, physical model testing is essential to advance understanding of the new ERUS protection concepts.

Potential areas for future research to enhance understanding of the behaviour and dynamics of ERUS protections include: investigations of rock-ERUS mixtures, exploration of additional non-conventional layouts (beyond those examined in this study), evaluations involving varying sizes and designs of ERUS elements, and assessment of the effects of damaged ERUS—resulting from handling or installation—on overall system stability.

4 WP3: Life Cycle Assessment

4.1 Objective

Stability aspects of ERUS are crucial to determine the feasibility of using ERUS instead of rock as scour protection elements e.g. in rock-scarce locations. It is equally important to understand environmental costs that the production and use of ERUS would incur compared to conventional rock material, in order to make informed decision between these alternatives. The objective of WP3 was to compare the environmental impact of ERUS and traditional armour rock to gain initial insights into key differences that characterize these two solutions along the product life.

4.2 Methods applied

The project's WP3 evaluated ERUS and armour rock through a Life Cycle Assessment (LCA) for the two specific case studies, IJmuiden Ver OWF in The Netherlands and Revolution OWF in the U.S. as described in Section 1.2. The LCA assessed the environmental costs, including the carbon footprint, using the Environmental Costs Indicators or Milieu Kosten Indicators (ECI/MKI) commonly used in the Netherlands. The ECI method translates a broad range of environmental effects (impact categories such as CO₂ emissions, acidification, resource depletion or ecotoxicity) into a single monetary value, i.e. it represents a monetized environmental impact measurement. However, the costs derived from the ECI are unrelated to CAPEX or OPEX cost associated with the installation and maintenance of scour protection materials.

The LCA received input from WP1 on transport and installation parameters, as well as input from WP2 on the armour layer design based on findings in the stability tests. The basis for the study were two functional units: one cubic meter of installed bed protection, and the armour layer of scour protection required for a single monopile foundation. In both cases, the analysis covered the phases of material extraction, processing, transport, and installation (life cycle stages A1–A5 according to LCA standard EN 15978 (BSI 2011)). Later phases such as operation, maintenance, decommissioning, and recycling (stages B-D according to EN 15978) were excluded due to limited data availability, which would introduce too much uncertainty.

The LCA comparison was intended to be generally applicable to ERUS-type of designs and rock. Therefore, an illustrative cube-shaped unit was defined representative of key design parameters of the ERUS designs tested in WP1&2 (functional unit of 1 m³ of installed scour protection) illustrated in Figure 4-1 and characteristics described in Table 4-1.

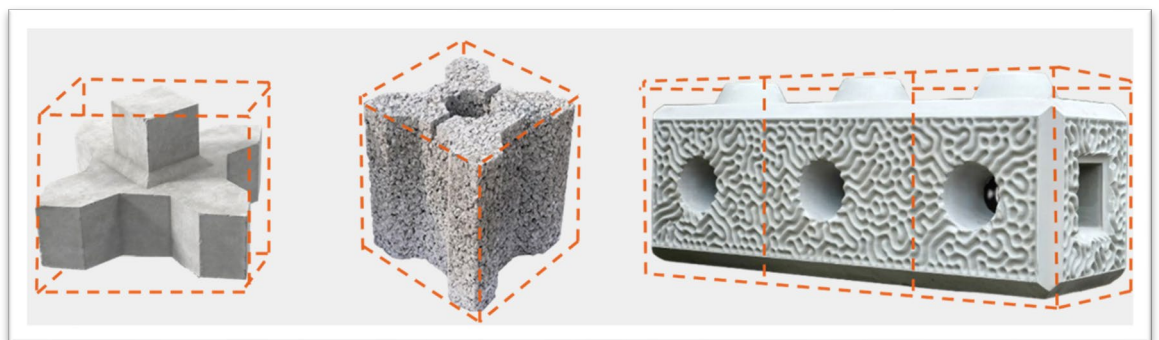


Figure 4-1 - Illustration of a broadly representative cube-shaped ERUS used for the LCA based on some average design features of the tested ERUS in the JIP-SPREE (Image left: BAM, image middle: Holcim, image right: Reefy)

Table 4-1 Representative ERUS unit characteristics

Indicator	Value
Cube dimension ⁴	0.43 m
Average unit porosity⁵	0.42 (42% air/full cube)
Average unit volume	0.0795 m ³
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)

Individual material mixtures are proprietary information and were replaced with two standard concrete mixes common in the use of offshore concrete structures: conventional CEM I concrete and a lower-emission CEM III concrete with 30% recycled aggregates. In addition, a sensitivity analysis considered alternative production methods (3D printing). The CEM III mix is the most comparative one for use in marine environments and outperforms CEM I in terms of bioreceptivity (Bone, et al. 2022). The mix also represents the closest standard concrete to the proprietary mixes and for which information is publicly available.

The extent of the armour layer assumed for the LCA was 10m from the monopile and a slope of 2:1. The resulting minimum layer thicknesses assessed were 0.7m and 1m for rock (LMA 10/60kg) and the representative ERUS respectively for the case of IJmuiden Ver. For Revolution OWF, a 1m and 1.2 m armour layer thickness was assessed for rock (LMA 40/200kg) and the representative ERUS respectively.

4.3 WP3 Results

The LCA of the representative ERUS and rock showed that both perform comparably in terms of environmental impact costs.

The representative ERUS using CEM III achieved a lower ECI than rock when assessing the functional unit of one cubic meter (Figure 4-2). This is the case for both the Dutch and the U.S. study sites, though slightly more pronounced in the former. The key driver of ECI costs for one cubic meter of the representative ERUS (CEM III) were phases A1-A4 (production) while phase A4 (transport) and phase A5 (installation) contributed much less to the total ECI in the IJmuiden Ver case. Meanwhile, key emissions driver for the representative ERUS in the case of the U.S. was phase A4 (transport) due to larger volumes required. For rock, emissions were consistently driven by costs accumulated in the transport phase and to a lesser degree the installation phase.

When looking at a full armour layer for one monopile (Figure 4-3), rock had a lower ECI than the representative ERUS, in both the Dutch and the U.S. case. This outcome was due to the higher ECI resulting from phase A1-A3, as more volume is required for the armour layer design for representative ERUS compared to rock.

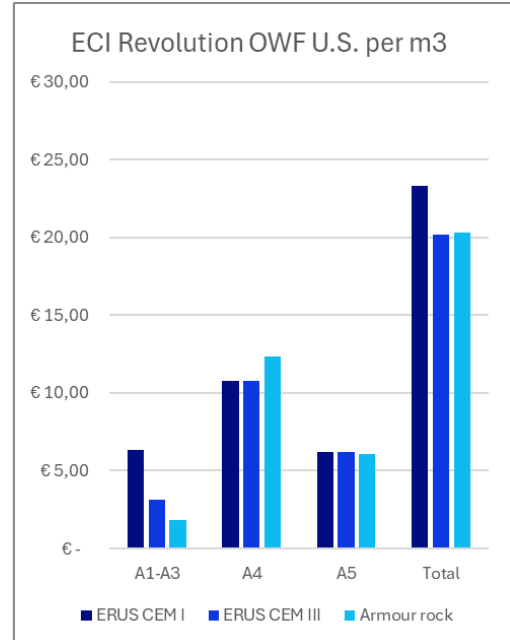
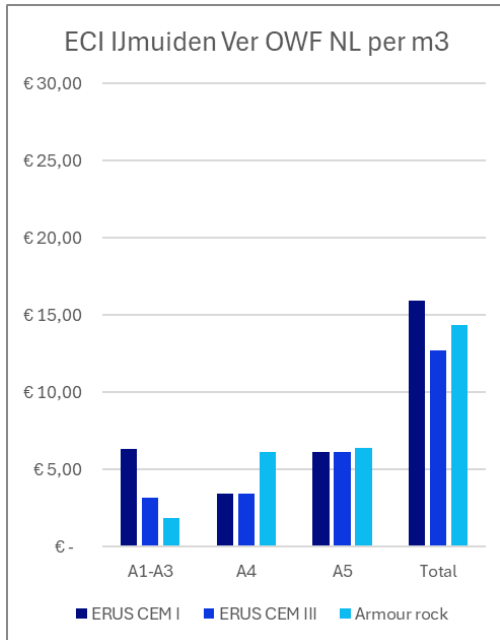


Figure 4-2 - ECI per cubic meter for ERUS (produced with CEM I or CEM III) and rock (grading 10-60kg for Ijmuiden Ver OWF and 40-200kg for Revolution OWF), Phases: A1- Raw Material Sourcing, A2 – Transport, A3 – Manufacturing, A4 – Transport, A5 – Construction and Installation

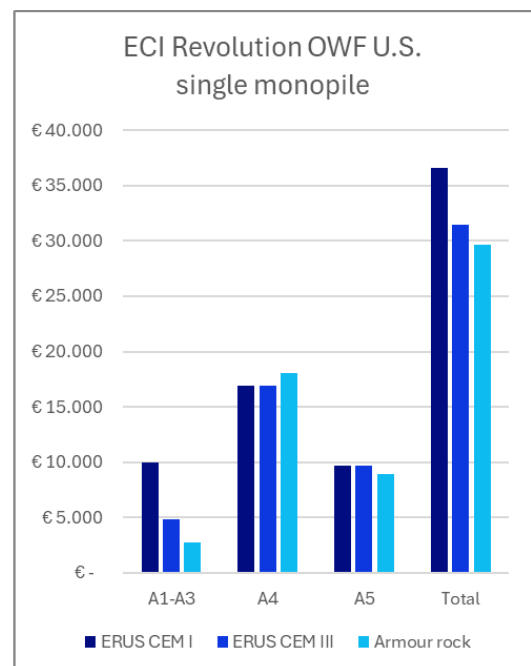
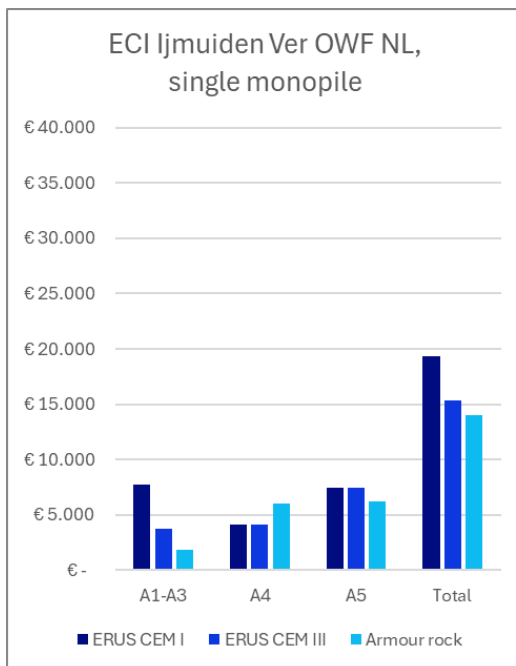


Figure 4-3 - Environmental Cost Indicators (ECI) per armour layer for one monopile for ERUS (produced with CEM I or CEM III) and rock (grading 10-60kg for Ijmuiden Ver OWF and 40-200kg for Revolution OWF), Phases: A1- Raw Material Sourcing, A2 – Transport, A3 – Manufacturing, A4 – Transport, A5 – Construction and Installation

Overall, the ECI results differed in the order of magnitude of 10% between the representative ERUS (CEM III) and rock, for both functional units and case studies. This comparison between functional units and locations underscored the contextual dependencies of any LCA analysis being conducted. Overall, the ECI costs for the U.S. case

were higher than for those for the IJmuiden Ver case. To a significant extent, this higher ECI outcome can be attributed to increased transport distances, a consequence of the Jones Act, which limits U.S. domestic transport of goods to U.S. vessels only. Therefore, sourcing in the U.S. case was assumed to be undertaken in Canada which increased transport costs. In addition, the increased ECI for the U.S. case was due to higher rock gradings and layer thicknesses being required due to the harsher hydrodynamic conditions. Optimizing armour layer designs for each location can thus contribute to reducing ECI outcomes.

Looking specifically at CO₂ emissions for both functional units and in both case studies (Figure 4-4 and Figure 4-5), armour rock achieved a lower emissions (in kg) than the representative ERUS. The differences were smaller for the functional unit of a cubic meter than for the full armour layer and overall higher for the U.S case than for the Dutch case. The production emissions due to concrete used in ERUS were the key driver in both case studies.

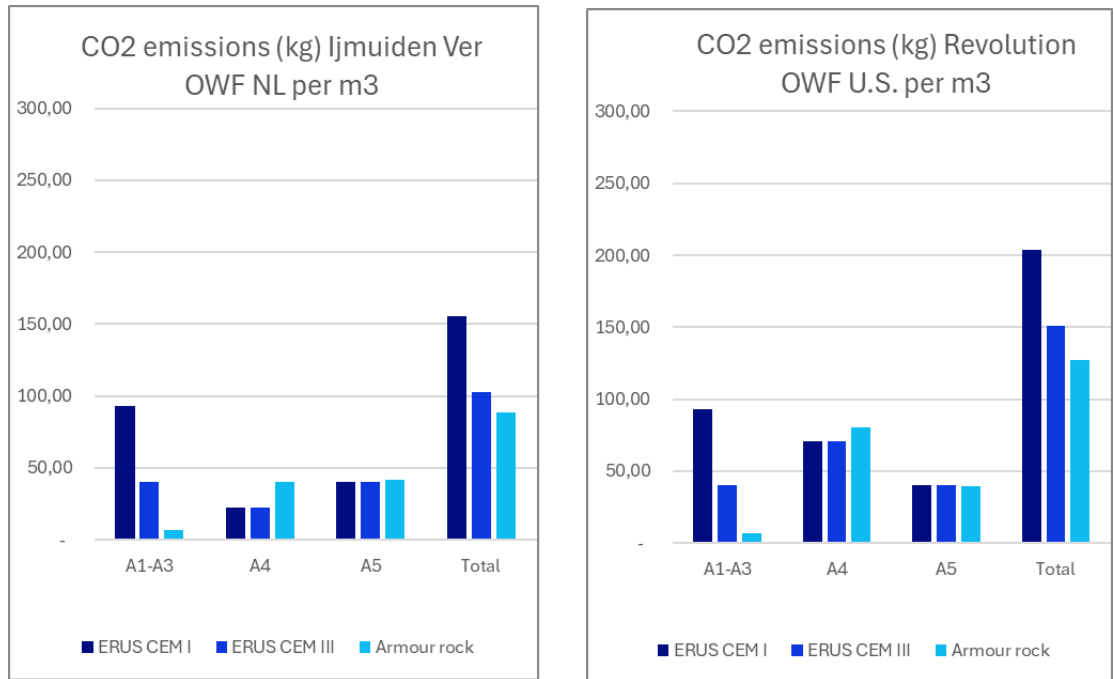


Figure 4-4 - CO₂ emissions expressed in thousand kg per cubic meter for ERUS (CEM I and CEM III material based) and rock, for the case studies of IJmuiden Ver OWF (NL) and Revolution OWF (U.S.) Phases: A1- Raw Material Sourcing, A2 – Transport, A3 – Manufacturing, A4 – Transport, A5 - Construction and Installation Phase

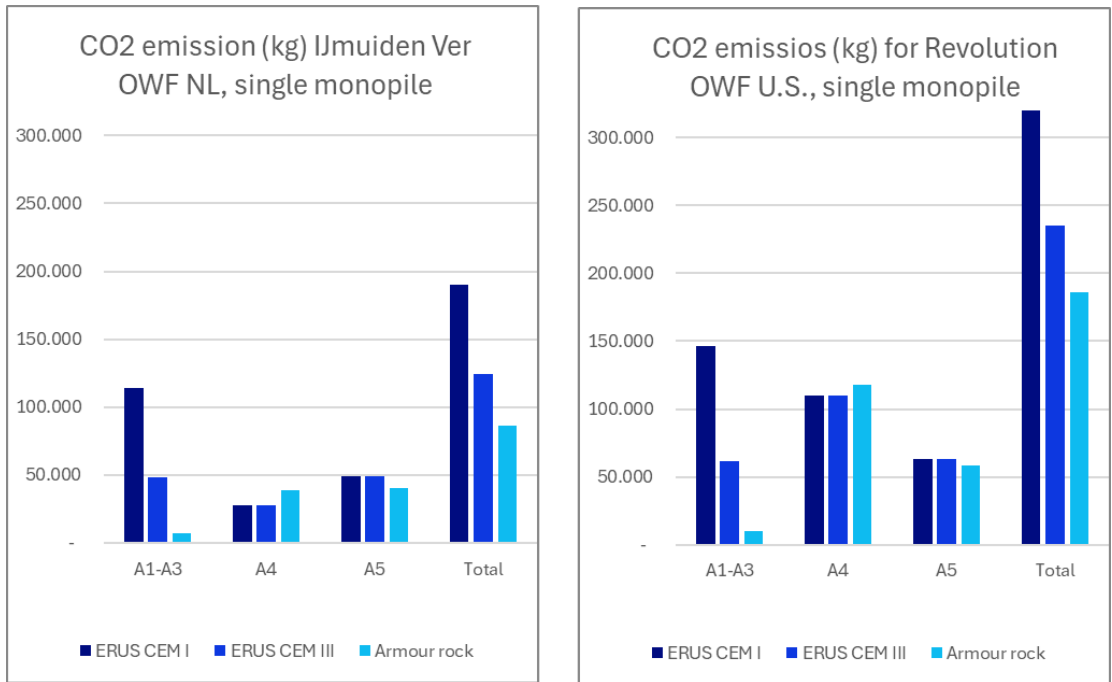


Figure 4-5 - emissions expressed in thousand kg per armour layer for one monopile for ERUS (CEM I and CEM III material based) and rock, for the case studies of IJmuiden Ver OWF (NL) and Revolution OWF (U.S.) Phases: A1- Raw Material Sourcing, A2 – Transport, A3 – Manufacturing, A4 – Transport, A5 - Construction and Installation

The CO₂ emissions are only one factor in the ECI. CO₂ emissions are a useful indicator to assess, but the ECI reflect a broader environmental impact, accounting, e.g. for resource use, toxicity, and ecosystem effects, that can occur beyond CO₂. Additionally, the ECI uses weighting factors in terms of euros per kg for each effect category that impact the overall score.

The overall results provide a useful indication where emissions lie in the production stage and where optimization potential can be realized. Beyond armour layer designs, emerging cement types, recycled concrete and different production methods have the potential to achieve even lower emissions than CEM III. Given that cement accounts for approximately 75–80% of the emissions in stage A1, these advancements could significantly enhance the environmental performance of ERUS in future applications as comparable alternatives to rock. Preliminary sensitivity analyses of alternative material mixes and production methods (3D printing, pressing methods) achieved even lower ECI outcomes.

4.4 Limitations & future recommendations

The above results are highly idealized and should be considered a first indication only. The LCA conducted as part of the JIP-SPREE considered an “illustrative” ERUS unit. Meanwhile, existing ERUS vary in design, material and production methods which will impact required layer designs. Moreover, ERUS can be customized to an optimal element with regards to stability as well as NID guidelines for individual locations. Therefore, an adequate and fair comparison between ERUS and rock will depend on many variables, including, but not limited to, material, design, environmental conditions, resource availability, and installation means.

Given the limited availability of empirical data on ERUS design and performance, the LCA also relied significantly on estimations from expert judgment. For similar reasons, ERUS lifetime, maintenance needs, and decommissioning options were excluded from the LCA, though in future these phases should also be considered.

This first step in comparative LCA evaluation of ERUS and rock highlights several areas for future research. Firstly, material developments should be explored, to assess the impact on ECI of lower-carbon and recycled material mixes for ERUS. Optimised designs for ERUS for specific locations and their effect on reduce material demand holds potential for further reducing the ECI. With developments in the debate about full, partial or leave in decommission options of OWF infrastructure (Directorate-General for Environment 2025) and first at-scale offshore pilots deploying different ERUS designs, emerging new data can be utilized to expand the LCA to cover additional life cycle stages. Lastly, ecological performance and impacts on biodiversity should be taken into account in future LCAs to provide a more holistic analysis of ERUS and rock ECI and monitoring pursued over several years (recommendations ranged from 2-5 years but on-going work in Belgium shows that ecological community establishment could take more than a decade (Degraer, Brabant, et al. 2023).

5 WP4: Ecological performance and biodiversity potential of ERUS

5.1 Objective

The potential to engineer ERUS in alignment with context-specific NID recommendations is considered to provide advantages over other materials and thus pursue targeted ecosystem enhancement objectives. The JIP-SPREE WP4 evaluated the ecological performance of ERUS compared to conventional armour rock as scour protection armour layer for OWF foundations, and assets to advance insights into this ecological potential specifically for the cases of the Dutch North Sea and U.S. East Coast parts of the Northern Atlantic.

5.2 Methods

For the two case studies, WP4 defined policy and environmental conditions that would inform NID requirements, and specifically aimed to conduct (i) a comparison of ERUS and armour rock in terms of their capacity to enhance marine life, (ii) an evaluation of possible ecosystems enhancements to inform decommissioning decision-makings, and (iii) propose monitoring indicators and methodologies for future ERUS pilots. WP4 combined multiple methods to conduct the different aspects of this comparative evaluation:

1. Literature review: the review was used to define the specific ecosystem boundaries for the two reference sites Ijmuiden Ver and Revolution OWFs. The desk study provided information on seabed conditions, ecological baselines, relevant frameworks and existing knowledge guiding NID for scour protection. Based on this review, evaluation criteria to compare the ecological performance of rock and ERUS were defined by the ecological experts of JIP-SPREE partners.
2. Comparative qualitative evaluation of ERUS and rock: expert interviews were conducted using a qualitative assessment framework for an idealized North Sea and western Atlantic cases considering exclusively protection design aspects - surface area/volume, rugosity, relief, porosity, geometry and orientation, material composition- and their impact on enhancing specific ecosystem functions (settlement, shelter, feeding, reproduction, stepping stone effects) for various taxonomic groups. No biotic or other environmental conditions were included, such as food availability, water temperature, currents etc. which affect the ability of species to use a habitat for various functions.
3. Stakeholder engagement on decommissioning: a desk review of regulatory frameworks for decommissioning in the EU and U.S., lessons learned from oil and gas platform decommissioning were combined with stakeholder engagement through an online survey and workshop to assess if ecological benefits of rock and ERUS should have any implications on decommissioning.
4. Monitoring methodologies: literature review on offshore monitoring indicators and methodologies for future ERUS pilots.

5.3 Results

Armour rock in scour protection layer has been found to be colonized over time creating artificial reef habitat that can support diverse benthic and fish communities (Buyse, Reubens, et al. 2023, Buyse, Hostens, et al. 2022, Coolen, et al. 2020, Glarou, Zrust and Svendsen 2020, Kingma, et al. 2024, Mavraki, et al. 2020, Zupan, et al. 2024). The Dutch North Sea represents

a mature offshore wind landscape¹² in shallow waters with well-established regulatory frameworks that actively promote the ecological reef potential through the integration of non-cost indicators for NID elements (e.g. Kavelbesluit for Hollandse Kust Noord¹³, Hollandse Kust-West OWF¹⁴, IJmuiden Ver¹⁵). Meanwhile, the offshore wind sector along the U.S. East Coast is still emerging and shaped by evolving permitting regimes but research into ecological benefits of rock and ERUS is on-going.

To date this ecological value of artificial reefs has mostly been achieved incidentally rather than intentionally as scour protection layers have been designed and installed with stability in mind mostly. Rock installations are more uniform, and individual elements cannot be intentionally shaped or designed. ERUS, by contrast, can be engineered to incorporate specific design aspects. The aspects can fulfil particular ecological functions for specific target species or ecosystem services (e.g. customisation on porosity can create refuge holes for juveniles, surface roughness can facilitate fast colonization, material chemistry and crevices can attract colonizers, and spatial complexity can create habitat for different types of species) (Korniejenko, et al. 2025) (Margheritini, et al. 2021). As a result, experts suggested that ERUS could be advantageous, though the degree of impact will depend on specific contexts and additional environmental drivers that go beyond the design customization of ERUS (e.g. oxygen and food availability, water temperature, currents etc). The main advantages were associated with ERUS' greater surface area, porosity, and habitat diversity that could support settlement, shelter, and feeding for various marine organisms. These benefits mostly support sessile bivalves, polychaetes, hydrozoans, bryozoans, and small crustaceans due to the microhabitat complexity and internal cavities of ERUS. Larger crustaceans and demersal fish could also benefit, though further studies are needed to determine effects on these mobile taxa. Meanwhile, this advantage may also contribute to greater risks of more easily facilitating a stepping stone effect for invasive species and should be carefully considered. Experts also recommended diversifying ERUS designs by mixing materials and element sizes, and creating gradual transitions between hard and soft substrates to maximize ecological effects. The results of the expert interviews are summarized in Table 5-1. However, the performance of ERUS depends heavily on several site-specific factors, such as sediment mobility, biofouling potential, hydrodynamics, and exposure to currents or storms. These conditions must be integrated into both design and siting strategies. Furthermore, the lack of long-term empirical data limits certainty around potential trends and will require additional monitoring investment.

¹² <https://english.rvo.nl/topics/offshore-wind-energy/operational-wind-farms>

¹³ RVO's Kavelbesluit [Project-and-Site-Description-HKN--Appendix-A--Applicable-Law---version-February-2020.pdf](#)

¹⁴ [Letter to Parliament Ministerial Order granting offshore energy permits sites VI VII Hollandse Kust west Wind Farm Zone.pdf](#)

¹⁵ [Conceptregeling vergunningverlening windenergiegebied IJmuiden Ver kavel Alpha 0.pdf](#)

Table 5-1 - Summary overview of expert judgement ecological evaluation on armour rock and ERUS (green indicating the fulfilment of the ecological function, yellow indicating the possibility to fulfil this function and red indicating that this function is not fulfilled. It should be noted that this qualitative approach leaves room for interpretation and can only be understood as providing an indication.

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	settlement	settlement	settlement		settlement	settlement	settlement	
Bivalves	shelter	shelter	shelter		shelter	shelter	shelter	
Sessile Bivalves - flat oyster		settlement shelter	settlement shelter	settlement		settlement shelter	settlement shelter	settlement
sessile polychaetes	settlement feeding	settlement	settlement feeding	settlement	settlement	settlement	settlement	settlement
		shelter			feeding	shelter	feeding	
	stepping stone	stepping stone	stepping stone		stepping stone	stepping stone	stepping stone	
Hydrozoans & Bryzoans	settlement feeding	settlement feeding	settlement	settlement	settlement	settlement feeding	settlement	settlement
	feeding		feeding				feeding	
small crustaceans	settlement shelter	settlement shelter	settlement shelter	settlement	settlement shelter	settlement shelter	settlement shelter	settlement
		feeding reproduction	feeding reproduction			feeding reproduction	feeding reproduction	
		stepping stone	stepping stone			stepping stone	stepping stone	
large crustaceans	settlement	settlement reproduction	settlement			settlement reproduction	settlement	
		shelter stepping stone	shelter			shelter stepping stone	shelter	
	feeding	feeding		feeding	feeding	feeding		feeding
Flat Fish	settlement feeding	settlement feeding	settlement feeding	settlement feeding	settlement feeding	settlement feeding	settlement feeding	settlement feeding
	shelter	shelter	shelter feeding	shelter	shelter	shelter	shelter	shelter
Benthopelagic Fish	settlement feeding			settlement feeding				
	reproduction							

The lack of long-term empirical data was also identified as a key constraint to decommissioning decision-making. Current decommissioning frameworks (e.g. OSPAR in EU¹⁶ and BOEM in the U.S.¹⁷) generally assume full removal of OWF infrastructure and offer limited mechanisms for recognizing the ecological value of these structures. While leave-in-place or partial removal scenarios remain debated, they may better preserve the marine life developed on ERUS or

¹⁶ OSPAR Decision 98/3 [98-03e decision consolidated text disposal offshore installations.pdf](#)

¹⁷ BOEM white paper on “Supporting National Environmental Policy Act Documentation for Offshore Wind Energy Development Related to Decommissioning Offshore Wind Facilities” [Decommissioning White Paper.pdf](#)

armour rock. Lessons from oil and gas, such as the Rigs-to-Reefs programmes¹⁸, demonstrate that multifunctional infrastructures can continue to provide ecosystem services after production ends. Unlike oil and gas rigs, the renewable wind source means that energy harvesting can continue past an OSF's infrastructure meets its end-of-life stage. Therefore, options to recycle and re-use this space (footprint) for continued wind harvest should be considered ecologically-friendly, and preferred over introducing more infrastructure in different areas, even if the process of recycling the space leads to temporary disruption of the benthic habitat created by ERUS. Liability and permitting frameworks for OWFs which are still underdeveloped, need to take these aspects into account. Additionally, stakeholders stressed the importance of integrating decommissioning considerations early in the design and permitting process.

Stakeholders consulted as part of the JIP-SPREE generally supported allowing ERUS to remain after their operational life if they enhance ecosystem connectivity, support native species, use safe materials, and do not facilitate invasive species. However, long-term local monitoring, both before and after installation, was identified as a key necessity to inform future decommissioning decisions.

Such monitoring should be undertaken in-situ over the span of several years, including pre-installation, during operations and after decommissioning. Key indicators relevant to OWF sites monitoring for ecological value include biodiversity (species richness, evenness, functional traits), biomass, presence of policy-relevant species, benthic coverage, behavioural and habitat-use patterns, size distribution, food web interactions, water quality (e.g. salinity, nutrients, chlorophyll), sediment characteristics, seabed morphology/bathymetry, and the physical stability and complexity of structures. These can be monitored through diverse methods such as acoustic surveys, tagging, ROV/AUV footage, BRUV, diver surveys, grab samples, eDNA, SPI, and trophic analyses. Together, these indicators and methods provide a baseline for future ERUS pilot monitoring.

5.4 Limitations and further research

The results of WP4 provide promising insights, that need to be validated through full-scale field trials since most of the current findings are based on short-term pilots, analogies with artificial reefs and expert judgement. Ecological performance also depends heavily on ERUS design parameters, which limits the generalisability of results across unit types. In addition, outcomes are strongly influenced by environmental regional conditions such as seabed type, hydrodynamics, and local species assemblages. This emphasises the need for site specific adaptation. Uncertainty around decommissioning further complicates interpretation, as current legal frameworks do not yet recognise ecological value in end-of-life scenarios. Future research should therefore focus on pilot deployments of ERUS across different settings, supported by standardised and long-term monitoring. Advancing this field with ERUS will require comparative in situ studies of ERUS and conventional armour rock, integration of ecological performance into regulatory and tendering processes, and the development of decommissioning policies that recognise ecological value.

WP4 demonstrated that scour protection should no longer be viewed as a purely technical infrastructure. Both conventional/traditional armour rock and ERUS offer ecological functions. However, ERUS provides an opportunity to intentionally incorporate biodiversity goals into the scour protection layer design. To further advance the development of ERUS, future efforts should focus on comparative in-situ studies against conventional armour rock to obtain more empirical proof, incorporate ecological performance into regulatory and tendering frameworks, and create decommissioning policies that acknowledge the ecological value of structures.

¹⁸ Factsheet on Rigs-to-Reef Program, [rigs-to-reefs-program-fact-sheet.pdf](#)

6 JIP – SPREE Conclusion and Recommendations

The SPREE project has provided a multi-dimensional evaluation of Engineered Reef Units (ERUS) demonstrating their potential to be used as an alternative to conventional armour rock for scour protection in Offshore Wind Farms (OWFs). Through the coordinated efforts across four Work Packages (WPs), the project has generated valuable insights into key technical aspects of installation and stability, production sustainability, and ecological value potential of ERUS, with implications for future offshore infrastructure design and policy.

Across all work packages, ERUS emerged as a promising innovation that aligns with the multiple goals of hydraulic stability, sustainable production and ecological enhancement. The physical testing showed that ERUS can be installed using existing technologies and performs comparatively to traditional rock-based scour protection with regards to hydraulic stability. The modularity and geometric adaptability of ERUS designs allows for tailored configurations that can meet site-specific conditions, including varying hydrodynamic loads and seabed compositions. The LCA (Life Cycle Assessment) revealed that armour rock and the representative ERUS are comparable in terms of ECI with differences in the order of magnitude of around 10% depending on the location and functional unit. Meanwhile, to gain a realistic comparative assessment, the LCA stages of maintenance and decommissioning will need to be evaluated in the future. LCA performance is also highly dependent on site-specific conditions (e.g. proximity of material sourcing, transport distances to OWFs, met-ocean conditions, fuel consumption of transport modes, scour layout requirements etc.), which will influence the comparative advantage of ERUS and rock and may even change the outcomes. The evaluation of the ecological enhancement potential of ERUS, emphasized the advantage of customization of ERUS in support of targeted marine biodiversity enhancement as well as the relatively larger surface area created by ERUS compared to rock which contribute to increased habitat creation especially for species living on or off hard substrates.

The JIP-SPREE demonstrated the strong interconnectedness across the technical, environmental and ecological performance objectives that can be pursued through the application of ERUS. The results emphasize the need to evaluate ERUS and rock in a comprehensive manner for individual use case, to arrive at a well-informed decision which option will be best suited as scour protection. Efforts are under way to test ERUS in offshore locations, monitor ecological effects and develop frameworks for comprehensive decommissioning decision making. The following recommendations and future research suggestions can support prioritizing efforts to advance optimizing technical, ecological and sustainability related designs of armour layers in OWF scour protection.

6.1 Recommendations and Future Research Suggestions

Based on the findings across all work packages, the following recommendations are proposed to guide future development, deployment, and policy integration of ERUS.

1. Hydraulic stability tests suggest that ERUS can be used as armour layer, though they show somewhat more deformation than rock. An initial estimate of the deformation can be obtained by using the existing deformation model for rock (HaSPro) with some modifications, and selecting the 90% non-exceedance prediction of the model.
2. Deformation characteristics necessitate that the thickness of armour layer using ERUS will need to be optimised for the specific ERUS size(s), specific location conditions, and armour layer configuration. Design specific properties such as level of interlocking, shape, openings' size, layout and element complexity should be considered in the process – data, both in the lab and at scale, is needed to fill existing knowledge gaps and investigate validity of adopted methods. A limited set of experiments on non-conventional scour protection layouts with different extent, height and overall structure

have shown promising results in terms of stability. ERUS scour protections may therefore present unique possibilities for optimization compared to conventional loose rock methods. It is recommended to further explore the possibilities for alternative layout possibilities to fully leverage positive design aspects that ERUS may bring to scour protection geometry in follow-up research.

3. The schematisation of ERUS as spheres (i.e. equivalent sphere approach) and application of HaSPro method for relative mobility calculation with modified bed roughness will need to be further investigated for various ERUS shapes that deviate from a cube. Moreover, the method itself should be improved by ERUS design-specific testing and research on threshold of motion and drivers for this behaviour for different ERUS designs, in order to achieve better understanding of how to design with ERUS (mobility, estimation of stability etc.) and how to better represent physical properties of ERUS.
4. To achieve comprehensive objective and realise optimal trade-offs across stability, environmental impact and ecosystem enhancement, designing with ERUS, should go beyond size and mass (which is what is most relevant for rock). The layer thickness and (experimental) designs should explicitly incorporate ecological performance criteria alongside hydraulic stability. This includes embedding features that support context and species-specific functions e.g. through hole sizes, variety in element size, material choices or experimental layouts to transition from hard to sandy substrate habitats.
5. Expert judgement suggests that conventional installation methods seem feasible to be used for ERUS as well. However, actual offshore tests would be required to substantiate these suggestions. They are also required to more accurately quantify losses, installation overheight, breakage during loading and installation. These parameters are key to developing optimised loading or alternative installation methods that can further sustainable production efforts. They are also important to understanding and quantifying the ecological enhancement potential based on surface area created. Conducting additional LCAs that assess a broad range of realistic operational and context specific parameters (e.g. sourcing and production sites, loading speeds, armour layer designs and required volumes etc.) will provide more insights into optimization potential. Similarly, LCAs analysing a larger variety of material uses, such as recycled concrete, innovative concrete mixes etc. can advance the reduction in environmental costs. To gain a comprehensive picture of environmental impacts, LCA assessments should also be extended to include comparative assessment methods of biodiversity (for relevant methods see (Damiani, et al. 2023)). Moreover, LCA research needs to be extended to maintenance and decommissioning scenarios to gain a more comprehensive picture of environmental costs and enable a more accurate comparison with conventional solutions.
6. Stakeholders generally suggested considering ERUS to remain after their end-of-life if they support ecosystem connectivity and native species and have safe materials and avoid promoting invasive species. To understand the ecological impact and potential value creation comparative in-situ studies against conventional armour rock are required to obtain more empirical proof. Thus, quantifiable ecological value development should also be reflected within decommissioning decision-making frameworks.
7. Long-term local monitoring pre, during, and post-installation is required to validate the ecological enhancement potential of ERUS in real-world conditions looking at biodiversity as well as structural integrity over time. At-scale monitoring data is required to better inform ERUS stability estimations, valuation of ecological impact and thus decommissioning decision-making as well as to better quantify trade-offs.

6.2 Outlook

The SPREE project's research has made some steps to inform the advancement of ERUS' TRL as integrated armour layer scour protection. The findings highlight promising directions to explore during operational readiness tests at scale in suitable offshore locations which should be pursued in a next phase.

The flexibility in designing and ERUS can offer unique opportunities for customization—such as interlocking and weight properties, material adaptations as well as surface porosity area—that can be tailored to enhance both hydraulic performance and ecological value. Pursuing some of the suggested research pathways in terms of design and layout refinement for stability, production optimization to further reduce environmental costs and long-term monitoring of ecological effects can advance ERUS designs as a comparable rock alternative as location-specific NID scour protection, especially in regions where suitable rock is scarce.

The SPREE consortium encourages stakeholders—developers, regulators, and innovators—to engage with these findings and explore ERUS as a multifunctional scour protection solution. With continued research and collaboration, ERUS could become an enabler of more sustainable offshore wind infrastructure.

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