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WP7 – Environmental Sustainability Assessment

Assessment of biodiversity of the pilot multi-use activities

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Abstract	A report on mitigation, restoration and creation solutions for OWF-LTA as analysed within the scientific literature. Culminating in the development of an environmental impact assessment framework with which to assess restoration solutions whilst keeping structural and functional biodiversity in mind.
Keywords	Offshore Wind Farms, North Sea, Baltic Sea, Mitigation, Restoration, Creation, Assessment framework

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Acronyms and abbreviations

AR: Artificial reef(s)

BESE: Biodegradable EcoSystem restoration Elements

BPNS: Belgian part of the North Sea

C: Carbon

CO_2: Carbon dioxide

DPNS: Dutch part of the North Sea

EC: European Commission

EEC: European Economic Commission

EIA: Environmental impact assessment(s)

EIRA: Environmental risk assessment

ESS: Ecosystem services

EU: European Union

GES: Good environmental status

HTA: High-trophic aquaculture

IMTA: Integrated multi-trophic aquaculture

IR: Impact risk

IUCN: The International Union for Conservation of Nature

LTA: Low-trophic aquaculture

LTA-MU: Low-trophic aquaculture ocean multi-use

LTAP: Low-trophic aquaculture pilot(s)

MPA: Marine protected area(s)

MSFD: Marine Strategy Framework Directive

MU: Multi-use

N: Nitrogen

NBS: Nature-based solutions

NID: Nature-inclusive design

OSPAR: Oslo and Paris Conventions/The Convention for the Protection of the Marine Environment of the North-East Atlantic

OWF: Offshore wind farm(s)

OWF-LTA: Offshore wind farm(s) – low-trophic aquaculture

P: Phosphorous

Risk-based management: (Ecological) Risk-based management

SCAIRM: Spatially explicit cumulative impact assessment method

SDGs: Sustainable development goals

UNEP: United Nations Environment Program

UNGA: United Nations General Assembly

ULTFARMS: Project name

UNITED: Multi-**U**se offshore platforms demo**N**strators for boost**I**ng cost-effec**T**ive and **E**co-friendly pro**D**uction in sustainable marine activities.

Executive summary

There are growing concerns regarding the sustainability and long-term viability of several existing food production systems, especially in light of a rising global population with ever-increasing food demands. Anthropogenic needs for dietary protein cannot be sustained solely by reliance on an increased production of high-trophic aquaculture (HTA) and livestock on land, the detrimental impacts of which range from waste generation to excessive or improper use of chemicals and even habitat destruction. To minimise these impacts, **low-trophic aquaculture** (LTA) and **ocean multi-use** (MU) can contribute to the mitigation of climate and other environmental change by promoting a shift in people's diet from terrestrial animal-based proteins to seafood with a lower carbon footprint and thus a lower likelihood for detriment to the environment. The added value of MU is severalfold including economic, social, and environmental benefits. Therefore, the advocacy of LTA as a means with which to support anthropogenic dietary demands has high potential for success on the basis that these areas are both properly assessed and managed.

One form of strategic ocean MU is the combination of LTA with **offshore wind farms** (OWF) i.e., LTA-MU and is the focus of ULTFARMS. This report presents a state-of-the art of the scientific literature focusing on LTA in the North and Baltic Sea, alongside the results of consultation with expert stakeholders from industry partners such as Jan De Nul NV, Impact-9 Energy and Marine Limited, Bantry Marine Research Station, Hortimare, Nordic SeaFarm, and Parkwind.

This report summarises the state-of-the-art on LTA-MU in the North Sea and the Baltic Sea using scientific literature, constrained by parameters such as environment type and location (section 2.1–2.2). A method of scoring criteria for environmental friendliness was developed in order to assess each of the topics: mitigation, restoration and creation (Section 3.4). Subsequently, within this report we present an environmental impact assessment (EIA) framework. For the assessment framework, two aspects of biodiversity were at the core of this exercise: structural and functional biodiversity (section 3). Three over-arching thematic areas are discussed, i.e., mitigation, restoration, and creation summarising measures and solutions which have been modelled and/or deployed as part of scientific case studies as tools with which to support strategic ocean LTA-MU.

Please note, that this deliverable (7.1) focuses on the biological and ecological aspects of mitigation, restoration and creation measures. It does not delve into the technical feasibilities of these measures in relation to constituent pilot projects within ULTFARMS which will be outlined as part of deliverable 7.2 (Nature-inclusive (NID) and regenerative designing of offshore aquaculture).

Based on the results on this **stakeholder consultation**, we present here a framework based on ecological and economic assessment criteria which has been subdivided into effectiveness and efficiency parameters. Mitigation and creation measures have been researched and summarised, however, based on the availability of data within the literature, we present our **assessment framework** for restoration measures only as this is where the breadth of information for the North Sea and Baltic Sea were available. Our results indicate that of the nine restoration studies containing restoration measures analysed in detail, the application of the assessment framework found five restoration measures to be of high feasibility, with a further three restoration measures also scoring well on the basis of their cost-efficiency.

The best solutions resulting from the outcome of this exercise will be used to inform ULTFARMS deliverable 7.2 when these measures are applied to the individual ULTFARMS constituent pilot projects, and may also be fed into the co-designing phase of WP3. Furthermore, these solutions may be assessed over the lifespan of the ULTFARMS project and assessed in close collaboration with WP4 and WP6. Therefore, this report contributes towards evidence-based planning and policy decisions.

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1. General introduction

1.1. Expected impacts of offshore wind farms

Global demand for renewable energy is increasing. As such, the revised Renewable Energy Directive (EU/2023/2413, European Union, 2023) sets an overall renewable energy target of at least 42.5% by 2030. This target is guided by the six pillars of concerted action outlined in the recent EU Wind Power Action Plan (COM/2023/669, Council of the European Union, 2023). OWF have the potential to contribute significantly to renewable energy initiatives of several governing bodies. Consequently, there has been a rapid global increase and expansion of turbine technology enabling development in previously inaccessible offshore areas (Bento and Fontes, 2019).

Scientific data on the potential effects of OWF on the function of marine biodiversity (Thompson et al., 2013; Goodale and Milman, 2019; Virtanen et al., 2022) and ecosystem functioning (Degraer et al., 2020a) are improving, driven by the necessity to close knowledge gaps which are hindering marine spatial planning efforts. As a result, studies on the effects of OWF have undergone a rapid maturation with the bulk of knowledge being determined in the last twenty years (Bergström et al., 2014).

OWF have both direct and indirect, and both positive and negative impacts on biodiversity during the construction, operational, and decommissioning phases. OWF pose a threat and/or opportunity to birds, fish, marine mammals, and bats. Such threats include, but are not limited to, mortality by collision, displacement from breeding or nesting areas, disruption of migration corridors, barrier effects on movement through avoidance behaviour, changes to food supply, and habitat degradation. A synthesis study outlines that the main pressures most frequently cited in literature include acoustic disturbances, increased sediment dispersal, and

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for the operational phase, habitat gain, fisheries exclusion, acoustic disturbance, and generation of electromagnetic fields (Bergström et al., 2014).

Negative general impacts of OWF are reported more frequently (albeit still low) in the literature (up to 10% of the scientific findings). These negative impacts tend to focus on birds, marine mammals, and ecosystem structure. In comparison, positive general effects of OWF are less reported (up to 1% of scientific findings), relating mostly to fish and macroinvertebrates (Galparsoro et al., 2022). These effects are well-categorised in a synthesis study by Thaxter et al. (2017) and further constrained by the most representative indicators of ecosystem elements, e.g., by type i.e., positive/negative and by magnitude i.e., high-low in a recent review study by Galparsoro et al. (2022) (Figure 1).

Figure 1. The most frequently reported environmental impacts of wind energy devices on the most representative indicators of ecosystem elements, by type (positive/negative) and magnitude (high to low). Source: Galparsoro et al., 2022.

Despite the synthesis studies, to date, there is a paucity of studies on the cumulative impacts and long-term effects on the food web arising from OWF. Cumulative impacts are highly relevant as the impacts of multiple turbines and wind energy facilities have the potential to cause population declines, especially over time (Goodale and Milman, 2016). Furthermore, as space is at a premium in the North and Baltic Sea, conflicts of interest over ocean use continue to arise, yet there are few studies outlining the potential combined effects with other industries e.g., fisheries (Bergström et al., 2014).

The EU strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030 advocate: "*promoting the development of … aquaculture systems with lower environmental impact … diversification to lower-trophic species (mollusks and other invertebrates and algae and herbivore fish)*" (COM/2021/236, EC, 2021, p.14), thus outlining that LTA is instrumental in making a significant contribution towards net-zero-carbon food systems. Although co-locating OWF with LTA may provide positive effects, such as generation of emission-free energy, nutritious seafood for human consumption, CO_2 capture and balancing of excess nutrients, and recapture especially in eutrophic areas i.e., restorative ecosystem services (Maar et al., 2023), there may also be negative impacts to consider. This poses new challenges regarding co-use, food safety, and marine governance.

However, whilst there is a decent coverage of studies outlining the impacts of OWF, there are fewer studies which address this very specific niche of OWF-LTA (Buck et al., 2018; van den Burg et al., 2019, 2020; Maar et al., 2023). This provides an opportunity to focus on strategic ocean MU, especially as seaweed and shellfish farms are expected to play a greater role in sustainable food production. Therefore, for the purposes of this report we constrain our discussion of impacts to OWF as they relate to low-trophic aquaculture ocean multi-use (LTA-MU). As such, to effectively assess the impacts we must first clearly

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define impacts on the functional and structural biodiversity (Croll et al., 2022) (section 3) by building on knowledge ascertained from preceding projects.

1.2. The UNITED project

The UNITED project was a precursor of the ULTFARMS project and ran from 2020-2023. In UNITED, five different forms of multi-use (MU) were tested in five different countries in Greece, Belgium, the Netherlands, Germany, and Denmark (UNITED Project, *in prep*).

As part of the project, cumulative environmental impacts were predicted for each pilot and multi-use combination, using an environmental impact risk assessment (EIRA), adapted from a spatial cumulative assessment of impact risk for management (SCAIRM), developed by Wageningen University and Research, a partner of the project (Piet et al., 2023, Van Gerven et al., 2023a).

The EIRA is a linkage framework, linking activities to actions, actions to pressures, and pressures to ecosystem components. To complement this method, a literature review was conducted to identify broader environmental impacts, and especially benefits of MU and the environmental policies that may be facilitated by this approach (Van Gerven et al., 2023a; 2023b).

The primary findings of this application of the extended EIRA were that considerable reductions in impact risk (IR) can be achieved through MU (compared to single-use), in the pilots combining LTA and OWF. Highest reductions were of approximately 40% for fish and mammals in the installation phase of the Belgian and Dutch pilots, approximately 15% for fish and mammals in the operational phase of the Dutch pilot and approximately 20% for seabed habitats in the decommissioning phase of the Belgian pilot (Van Gerven et al., 2023a). The full description of the methodology can be found in UNITED D4.4 section 2.1.4 (UNITED final report, *in prep*).

The analysis was conducted by factoring in the current context in which multi-use might be implemented, including technical and regulatory challenges limiting the extent to which actions from different activities can be combined. Yet the future may yield significant changes that will improve and optimise combinations of marine use, such as infrastructure developed especially for MU, less stringent safety regulations, innovative business models, or cheaper and more permitting insurance measures. With these possibilities in mind, MU scenarios were developed, in which (under the assumption that technical and other challenges were resolved) activities were optimally combined. The application of the EIRA to evaluate these scenarios indicates that MU projects could provide a potential two-fold reduction in environmental impact risk (Van Gerven et al., 2023a) (Figure 2).

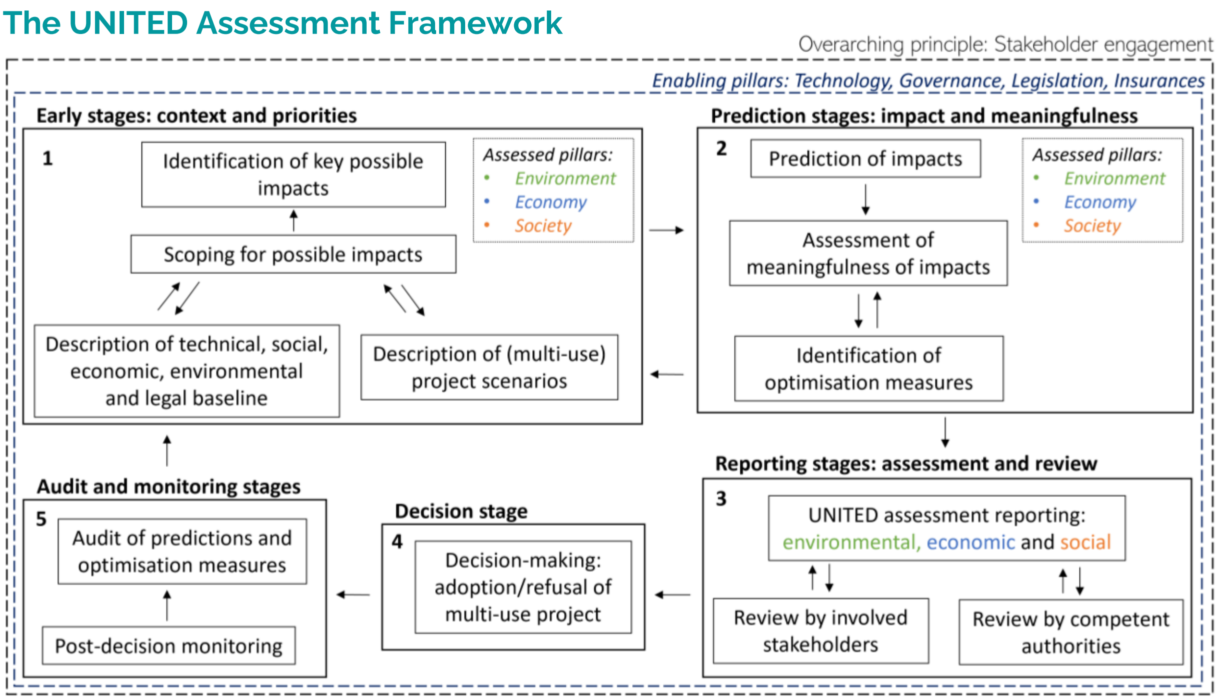

Figure 2: The assessment framework developed within the UNITED project. This framework and project were the precursor for ULTFARMS. Source: van Gerven et al., *in prep*.

Adapting the EIRA to small-scale scenarios proved complex because the spatially explicit cumulative impact assessment method (SCAIRM) was originally developed to assess direct impacts at a sea-basin level. Whilst great advancements have been made, not all impacts could be accounted for. Such wider consequences of MU on the marine environment were therefore described based on expert knowledge and information gathered through scientific review of the literature. As a result, Van Gerven et al. (*in prep*) identified the following examples for potential added value for the marine environment:

i. The possibility to incorporate habitat restoration (specifically biogenic reefs in the North Sea) in OWF-LTA multi-use combinations.

ii. Biodiversity increases as a result of strong fisheries exclusions and artificial reef effect in the multi-use area, although not equivalent to a natural reef.

iii. A potential increase in the abundance of commercially important adult fish species if the project is well designed and well protected.

iv. Increased nutrient cycling and carbon sequestration in the case of multi-use including LTA.

v. Sustainable food production and increased social acceptance of offshore wind production and aquaculture.

vi. More space for conservation and reduction of conflicts over space use at sea.

In addition, optimisation measures were identified to promote the environmental benefits of multi-use projects. These measures specifically target means with which to render OWF and aquaculture more suitable for multi-use, and to enhance the positive impact on the marine environment. They include nature-inclusive design (NID) of infrastructures at sea, rethinking the decommissioning of OWF, using an electrical fleet to operate at sea, and using biodegradable materials in aquaculture farms. Much of the work conducted within the UNITED project forms

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the foundation for ULTFARMS and in this report we focus particularly on the environmental pillar (Figure 2).

1.3. The ULTFARMS project

The European Commission strategic guidelines for aquaculture advocate for promoting the development of aquaculture systems with lower environmental impact (COM/2021/236, EC, 2021). The pioneering ULTFARMS project aims to move beyond the current application of LTA systems by utilising novel engineering, technical, ecological, and biological processes to optimise production in harsh offshore conditions and/or low salinity environments (Figure 3). The project furthermore promotes the integration of LTA within OWF, thus covering the whole value chain of food and energy production. In doing so, this project directly contributes to sustainable development goals (SDGs) 2, 13, and 14 (A/RES/70/1, UNGA, 2015).

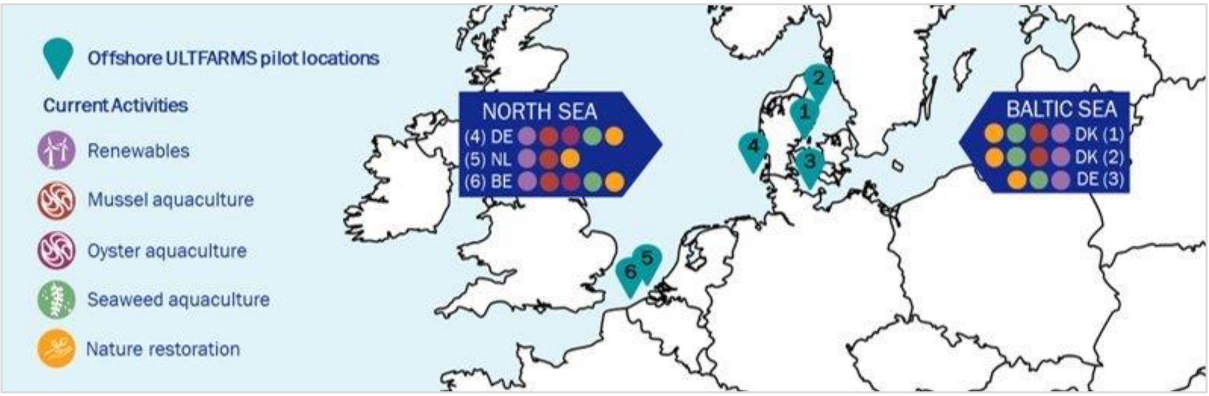

Figure 3: Overview of the six Low-Trophic Aquaculture (LTA) pilots within the ULTFARMS project. Source: (Submariner, *pers comm*).

The ULTFARMS project works with research and industry partners to develop and operate six innovative low-trophic aquaculture pilots (LTAP) in six different OWF locations across the North and Baltic Seas (Table 1).

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Table 1: Overview of the six Low-Trophic Aquaculture (LTA) pilots within the ULTFARMS project.

Member State	Name of Offshore Wind Farm	Low-Tropic Aquaculture production type
Belgium	Belwind	Seaweed-Mussels-Oysters
Denmark	Anholt	Seaweed-Mussels
Denmark	Samsø	Seaweed-Mussels
Germany	FINO2	Seaweed
Germany	FINO3	Seaweed-Mussels-Oysters
The Netherlands	Borssele	Mussels

1.4. Aims and objectives

This deliverable presents a method for assessment (section 3.4.) of mitigation, restoration, and creation solutions based on a framework of measurable indicators co-developed with the ULTFARMS consortium during internal progress meetings and finalised during the three-day General Assembly which took place in Brussels between 31.01.2024–02.02.2024. The fundamental aim of this deliverable is to consider what can be done as to make an MU project environmentally friendly and (hence environmentally licensable) in a quantitative manner (section 3.4.).

2. Methodology

2.1. Defining key concepts

Environmental impact assessment (EIA) has differing definitions. However, for the purposes of this report, this deliverable focuses on key aspects of mitigating the bad and promoting the good in the biophysical environment (Figure 4).

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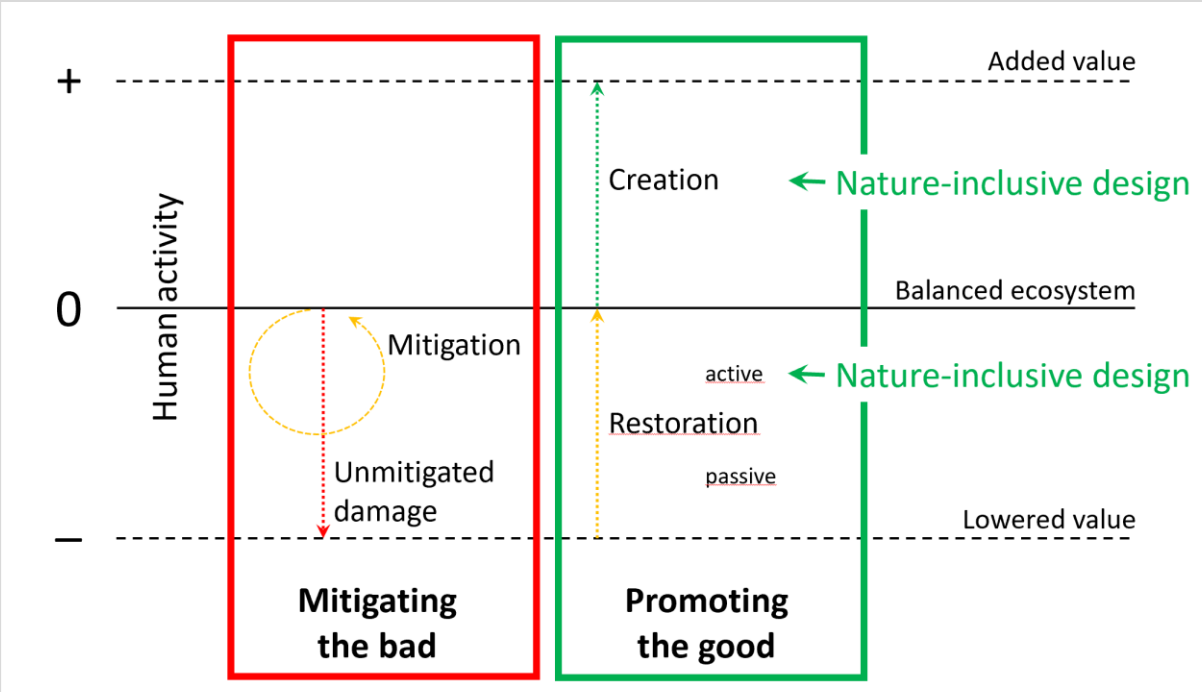

Figure 4: A schematic illustrating how best we can consider the impacts of human activities on biodiversity. There are two primary subtypes of nature-inclusive design (NID). Namely, restorative and creative NID. Source: modified from Degraer et al., 2020b.

In addition, the ULTFARMS consortium has collectively developed accepted definitions for the primary concepts discussed in this report (Table 2).

Table 2: Overview of the key concepts and principles used throughout this report with definitions stipulated and peer-reviewed by the ULTFARMS consortium.

Key concept	Definition	Example
Mitigation	Measures taken to reduce or minimise the negative impact of a human activity on the ecosystem. In the case of aquaculture, this can include reducing the risk of introducing diseases, invasive species, the risk of over-exploitation of the	Offsetting

	area, or mitigating anchoring effects.	
Restoration	Nature restoration is the re-establishment of lost habitats where they had known occurrence, or of lost species in their natural historical range and densities. It is thus defined as an action that recreates/restores natural habitats, hydrological processes, biological mechanisms, and/or sustainable occurrences of species. Please note, that restoration, rehabilitation and regeneration are used synonymously in this report.	Translocation
(Habitat) creation	The development or establishment of (parts of) an ecosystem in areas where it was not historically present. This is a key differentiation factor between creation and restoration.	Introduction of hard substrate

Restoration in the context of this report is defined as the process of returning an ecosystem as closely as possible to its original, pre-disturbance conditions. To minimise risk and respect the ecosystem's natural functioning, species should only be reintroduced in areas within their natural and historical habitat. Hence a distinction is made between habitat creation and habitat restoration. Therefore, not all wind farms are suitable to host species and/or habitat restoration.

According to the ULTFARMS consortium, NID refers to options that can be integrated in or added to the design of an infrastructure to create optimised

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artificial habitat for native species (or communities) whose natural habitat has been degraded or reduced. Inherently, it creates an optimised artificial habitat with which to boost biodiversity. Underlying key measures for NID include approaches with which to offset the promote the good i.e., the positive effects of OWF-LTA. In principle, there should be an overarching trend towards regeneration and efficiency, i.e., producing more at a lesser cost. This may be achieved by strategic self-reinforcing feedback loops to accelerate the process (Figure 5).

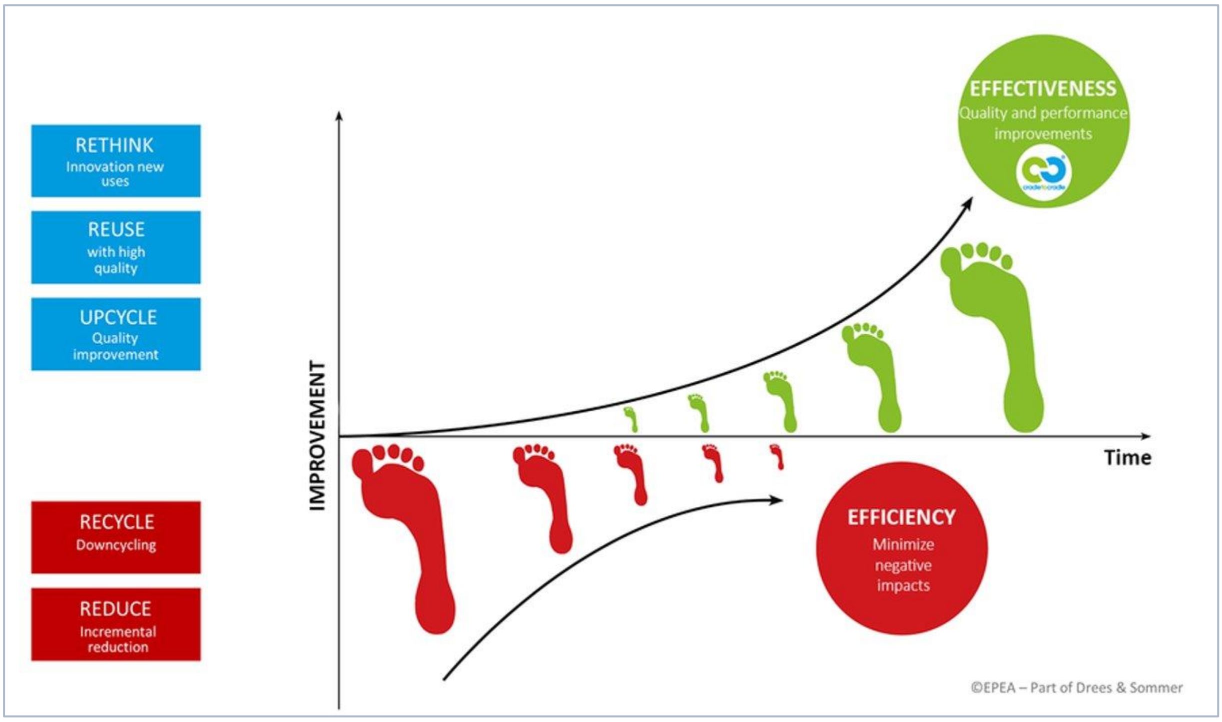

Figure 5: Design principles for nature-inclusive design (NID). Source: EPEA GmbH, 2024.

2.2. Compilation of the literature review

This report compiles the state-of-the-art at the time of publication and utilises this library as a foundation for the development of the assessment framework (section 3.4.). The state-of-the-art was constrained by scientific literature and government publications relating to the North and Baltic Seas only, and with a date of issue or ISBN of within ten years of the time of publication. Reputable databases were used to search for A1, peer-reviewed studies i.e., Google Scholar, Web of Science, ResearchGate. We have considered experimental approaches and case studies, review papers, and definition papers from the literature. In this stepwise approach, we excluded global analyses or US-focused papers as the environmental conditions in these regions are vastly different to the North and Baltic Seas.

The search also disregarded unintentional reef creation. For the North Sea, the search returned 859 unique results from Google Scholar, 13 results from Scopus, 24 from Web of Science. For the Baltic Sea, the search returned 381 results from Google Scholar, 1 result from Scopus, 1 from Web of Science. Studies were screened by title, then by abstract and finally by full text, and studies that were not relevant to the topic of solutions for restoration were discarded. The total number of items in the joint library is218. An example of this methodology is shown in Table 3. For a full list of keywords please refer to Table S1 in the supplementary information.

Table 3: An overview of the keyword search methodology employed to build the library of literature for mitigation, restoration, and creation measures in the North Sea and the Baltic Sea.

	Keywords
North Sea	*"Mitigation + wind farm + North Sea"*
	"Restoration + biogenic reefs + North Sea"
	"Artificial reefs + North Sea (+OWF)"
	"Habitat creation"
Baltic Sea	*"Mitigation + wind farm + Baltic Sea"*
	"Restoration + biogenic reefs + Baltic Sea"
	"Nature enhancement offshore wind"
	"Offshore wind + Biodiversity"
	"Reef creation"

Part of the studies were definition studies providing the general guidelines and conceptual framework for restoration, e.g., habitat classification, criteria and principles for restoration projects, and design considerations. Other studies provided empirical evidence or practical examples of restoration interventions, such as field experiments, pilot projects, or case studies. The latter are compiled for each measure and used as a basis for the assessment of the effectiveness of the solutions and presented in (please refer to supplement S1 and S2).

2.3. Development of the assessment framework with expert consultation

The measurable indicators were subdivided into two categories, namely "effectiveness criteria" and "efficiency criteria," on which the scoring system is based. Additional relevant criteria not used for the scoring system were included as "certainty criteria". Examples of certainty criteria include whether the solution was field-tested or not. Table S1 and S2 shows that the assessment framework is a culmination of three scoring elements (effectiveness criteria, costs and feasibility). Based on a customised script in the R computing environment (v. 2023.12.1) developed by RBINS, ecologically-relevant "effectiveness" criteria are depicted as bubbles in Figure 11. Intuitively, the larger the bubble the higher the effectiveness score.

To assess the feasibility, the efficiency criteria were used to assess the difficulty of implementing the measure. This is depicted as a percentage whereby a higher percentage is equivalent to higher overall feasibility. The feasibility is subdivided as follows: high- (> 66.66%), mid- (33.33–66.66%) and low-feasibility (< 33.33%).

To assess the cost, three classes were selected based on technical reports from Seafood Technical Services Bord Iascaigh Mhara (BIM) (McElligott et al., 2023), EMBRC (*pers comm*) and Noordzeeoverleg (Hermans et al., 2024). Costs are based on best-available estimations and subcategorised as follows: low- (< €50,000), mid- (€50,000–100,000) and high-cost (> €100,000). Figure 11 therefore summarises the effectiveness of a solution as a function of cost and feasibility. The figure is a proof-of-concept designed to be scalable, i.e., with the future addition

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of extra effectiveness and efficiency criteria, the format of data presentation is still viable.

3. Results I: Redefining structural and functional biodiversity

As biodiversity enhancement initiatives gain traction, formulating explicit objectives for functional and structural biodiversity and defining measurable metrics for successful reef creation will be crucial. Driven by sustainable use, the Marine Strategy Framework Directive (MSFD) and allied regulatory frameworks at national level advocate for an ever-increasing focus on ecosystem-based management. So too, should ecosystem-based management drive our assessments of LTA-MU.

However, there is an inherent need to untangle the Gordian knot about the selection of indicators informing ecosystem services. A key issue that persists is that, when assessed, impacts on biodiversity focus primarily on structural indicators. This focus comes at the cost of a robust understanding of the link between the structural indicator of the ecosystem functions to the overall ecosystem services. Thus, the link to ecosystem services being unclear (among other reasons) is why functional indicators are hardly applied to ecosystem quality assessments by the industry.

Ecosystem processes are complicated and context dependent; therefore, it is challenging to use structural indicators as proxies for ecosystem functioning. Ecological risk-based management (RBM) advises that monitoring should be underpinned by scientific questions. Science-based integration needs to be able to assess functional quality, however there is no single approach which is suitable in such a context.

A potential solution under development by Hunter et al. (*in prep*) proposes a parachute diagram representing a framework for functional indicator selection (Figure 6). Each indicator is strategically arranged including the position of biological traits, so the directional flow is towards ecosystem function and thus ecosystem services. Thus, this diagram helps one to choose response variables or indicators that are informative as much as possible to ecosystem services.

Since this framework (Figure 6) has a clear focus on informing on the choice of indicators for ecosystem services, it does not consider spatial and temporal scale as indicators, but attributes them as cross-cutting considerations about scales in space and time, i.e., scales at which the data for the measurable variables have to be collected. Each box represents an ecosystem feature or measurable variable. For instance, within the ecosystem feature "biomass" we may consider parameters such as total wet weight as a measurable indicator. Furthermore, under "activity" we may consider the burrowing activity of benthic organisms. Moreover, under "density" we may consider the relative density of a species group, and finally under "function" we may consider the import/export of organic matter.

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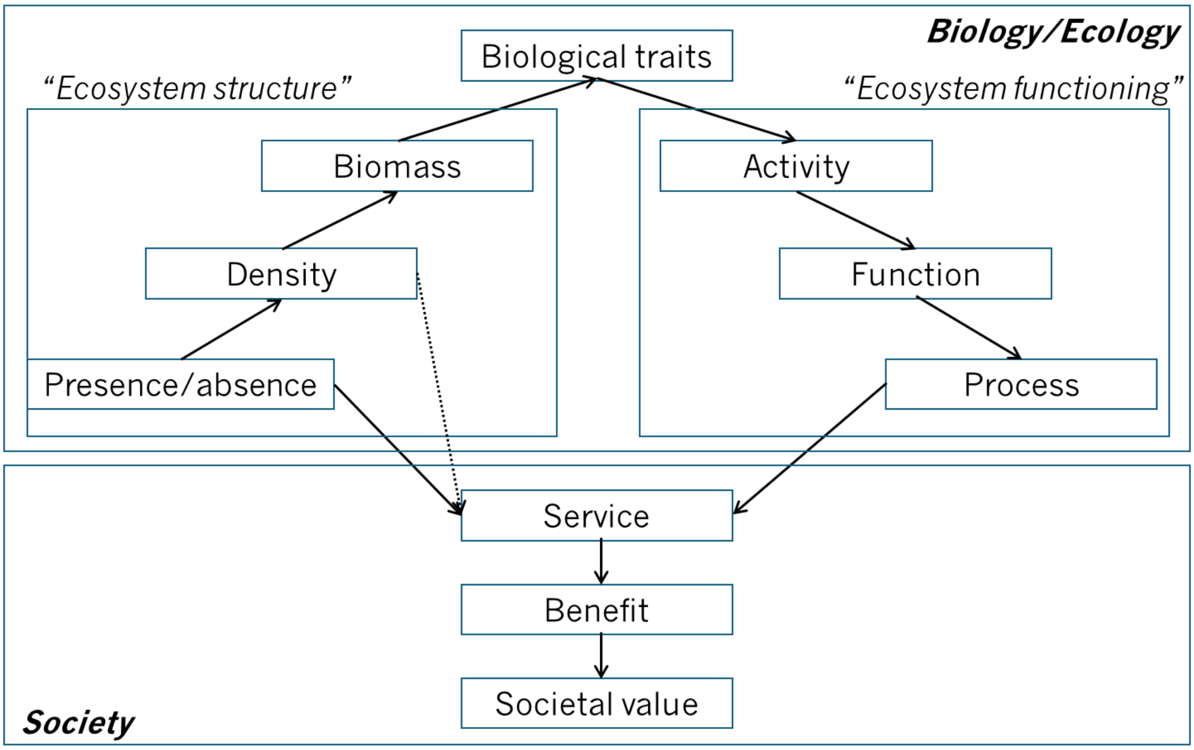

Figure 6: An innovative framework for functional indicator selection. Source: Hunter et al., *in prep*.

Within this report, we utilise this process (Figure 6) as the groundwork and develop it further in the context of LTA-MU. Such a framework is instrumental to the empirical assessment of [good] environmental status (GES).

Furthermore, we present the following revised definitions for both structural and functional biodiversity. Structural biodiversity refers to the variation in the composition and distribution of life forms within an ecosystem, such as the number of species present, their relative abundance and biomass, and their spatial configuration. Structural biodiversity can be measured at different levels ranging from taxonomic and genetic species up to populations and communities. On the other hand, functional biodiversity refers to the different types of activities, processes, and functions that organisms perform within a community or ecosystem e.g., bioturbation, filtration, habitat creation, carbon burial, nutrient cycling, etc.

Within each type of biodiversity i.e., structural or functional, a framework of indicators may be defined (Table S1). Structural and functional indicators may rely on either the precautionary- or the ecosystem-informed principles.

A prevailing issue is that when trying to measure net changes in primary production, and fractional changes in biomass around windfarms, there is significant spatial variability and regional heterogeneity. This is also reflected by environmental differences between the two key areas within this report, where for example, in the brackish Baltic Sea, the growth of many aquaculture species is hampered due to low salinity. Therefore, it is important to note that in differing environments the future threshold values set will also be inherently different for both the North and Baltic Sea.

3.1. Results II: Literature review

In this section we present the results of the state-of-the-art, namely, how mitigation, restoration, and creation measures may be implemented to intervene in LTA-MU environments.

3.1.1. The mitigation hierarchy

In addition to the definition given in section 2, the term "mitigation" is used in this report to mean "*measures envisaged in order to avoid, reduce and, if possible, remedy significant adverse effects*" as defined according to the EC Directive 97/11 (Council of the European Union, 1997, p.3).

It is imperative to gather data on the vulnerability of populations by estimating with demographic modelling or species distribution models the degree to which they may be displaced or subject to or at increased risk of disturbance (Best and Halpin, 2019). Mitigation measures are commonly required by financial institutions and regulatory frameworks to aid the environmental licensing of industrial projects (Niner et al., 2018). Thus, mitigation is a key tool in environmental management utilised during the EIA process to assist with lowering the environmental impacts wherever possible (Figure 7).

Mitigation measures may be subdivided into four primary areas, ranked in order of suggested execution, thus forming a mitigation hierarchy:

i. Avoidance/abandon.
ii. Minimisation.
iii. Restoration/repair/rehabilitation (please refer to section 3.3).
iv. Offsetting/remediation.

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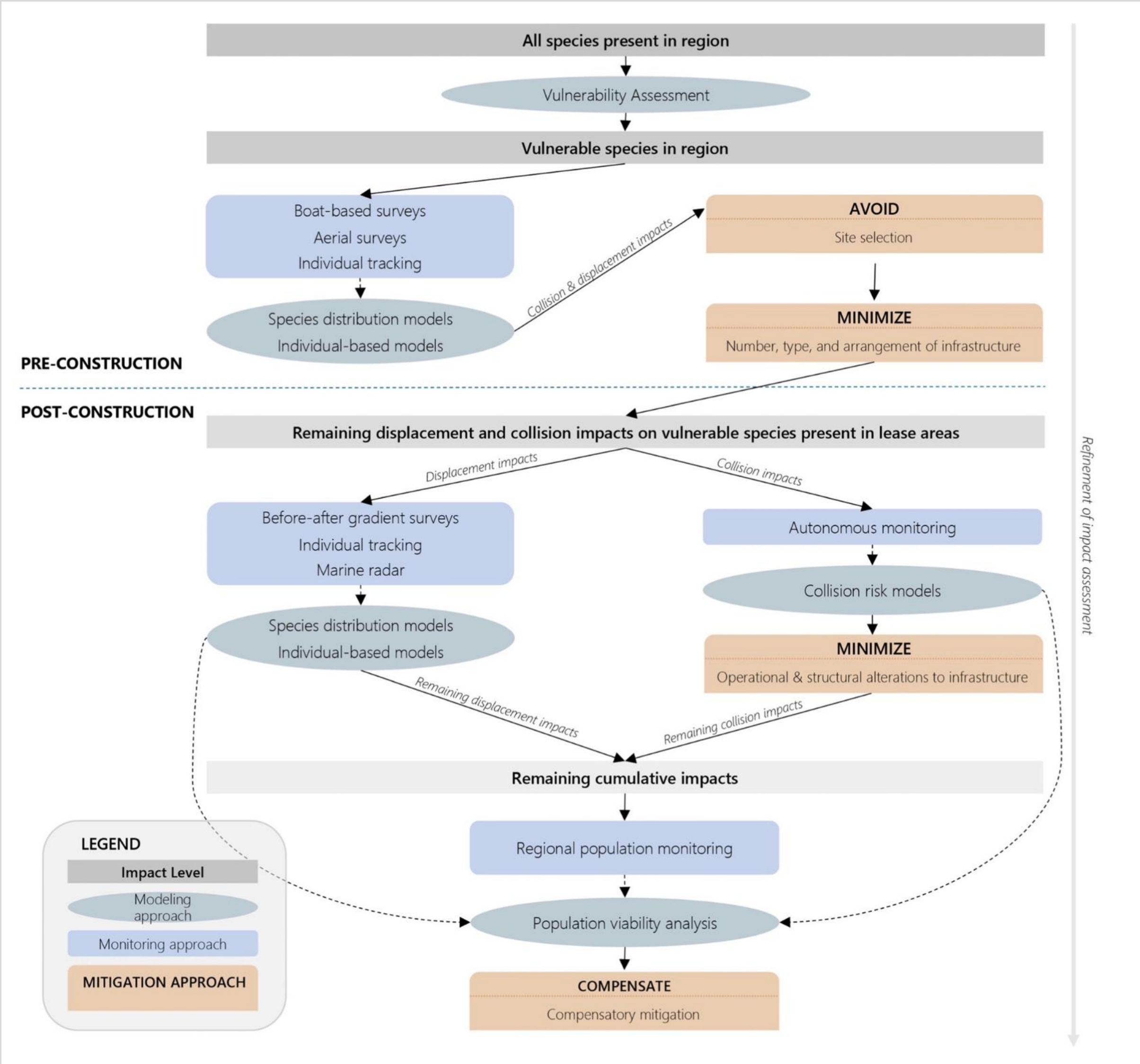

Figure 7: A flowchart of approaches for assessment and mitigation of impacts for marine birds in a region under consideration for and/or following development of offshore wind energy infrastructure. Dotted lines indicate where outputs inform subsequent modelling and mitigation approaches included (e.g., the efficacy of impact minimisation via operational alterations to wind turbines is not yet well tested in the marine environment). Source: Croll et al., 2022.

In the first step of the mitigation hierarchy, avoidance at the risk source or the receptor (e.g., marine animals, habitats, and ecosystems processes) reduces the impact footprint of activities by leaving the environment and associated fauna undisturbed. This can be accomplished for example, by considering and measuring species ranges (e.g., distribution maps), habitat and/or ecoregion mapping. This strategy is defined as both precautionary and adaptive (Niner et al., 2018).

In the second tier of the mitigation hierarchy, minimisation could constitute steps taken to reduce chemical discharges, light, and extended noise pollution. These are primarily accomplished by investing in engineering design, equipment, and spatial planning tools which minimise the overall potential for damage to biodiversity.

Minimisation could be supplemented by establishing biological corridors , areas that may provide shelter and protection from predation, and supporting these areas with sufficient regulation

Furthermore, mitigation requires consideration of 1) structural design, layout, and operational schedule, 2) the behaviour of vulnerable species, and 3) environmental conditions during encounters (Arnett and May, 2016).

In the third tier of the mitigation hierarchy, the definition for restoration according to the ULTFARMS consortium is given in Table 2. Finally, offsetting refers to measures which are which are designed to compensate for the impacts on biodiversity arising from LTA.

3.1.2. Mitigating the bad, promoting the good at a multi-use level

Sustainable development of the blue economy requires area-efficient use of marine space and implementation of innovative solutions demonstrating net emission capture, thereby contributing to mitigating eutrophication and climate change. In eutrophic, low saline areas (such as the Baltic Sea), LTA-MU can be used as a tool to remove nutrients (referred to as **mitigation culture**) rather than production for direct consumption. For example, mussel mitigation culture involves a higher mussel density, and the mussels are typically smaller and more variable in size compared to those commercially produced for human consumption. CO_2 is built into mussel shells, whereas organic carbon (C) and nutrients are incorporated into the tissue of mussels through filtration of suspended particulate organic matter. Hence, harvesting of bivalves and seaweeds removes nitrogen (N) and phosphorous (P) from the sea, leading to improved water quality (Figure 8), in essence **mitigating the bad** (Figure 4).

Aside from the ULTFARMS pilots (Table 1), at the time of writing, there is only one project actively collecting data on seaweed, co-located with offshore wind farms in the North Sea (North Sea Farmers, 2024). However, at the time of writing, the data from this case study were not yet available.

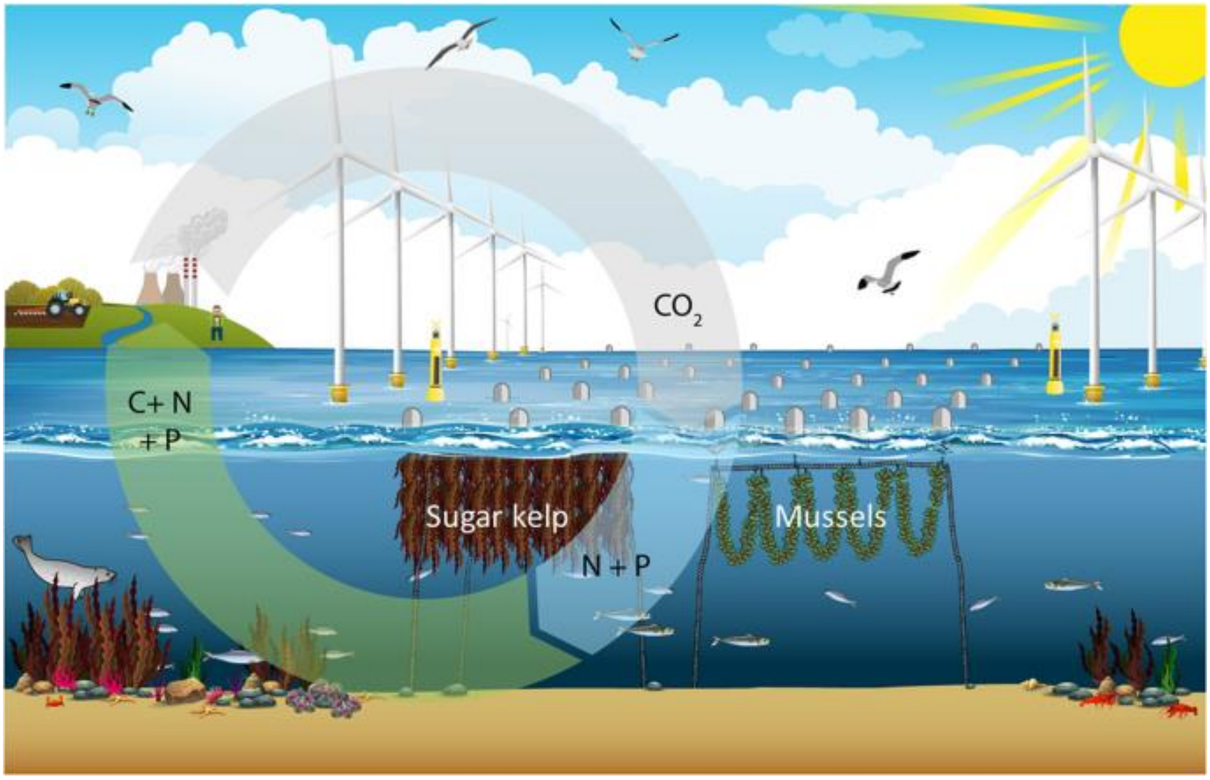

Figure 8: Multi-use in offshore wind farms with farming of blue mussels and sugar kelp can deliver emission-free energy, nutritious seafood, and positive ecosystem services through emission (CO_2 and nutrients) capture and utilisation. Source: Maar et al., 2022.

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Another method by which the impacts of OWF-LTA may be mitigated is by employing step two of the mitigation hierarchy, i.e., by minimising the loss of the original habitat, soft-sediment communities and their services (Dafforn et al., 2015).

As a first measure, the main threats to reef formation, primarily anthropogenic disturbances such as trawling, building infrastructure, etc., should be **minimised.** In situations where hard structures cannot be avoided, such as when used to prevent scouring around the foundation of a wind turbine in offshore wind farms, there is the potential for eco-engineering to mitigate the impacts of these structures and to maximise potential ecological outcomes (ter Hofstede et al., 2023). Increasingly, attention is directed towards Nature-Inclusive Design (NID) in offshore wind farms, particularly in the North Sea, aligning with the growing discourse surrounding nature-based solutions (NBS). In principle, NID may be applied to elements such as scour protection and cable protections (Groen, 2019; Coolen et al., 2020; Bos et al., 2021). Although scour protection is a field of rocks surrounding a turbine intended to ensure its stability, use of natural rocks, boulders of varying sizes and shapes, the inclusion of rock piles, concrete tubes, shell-filled nets, diverse grading widths, and increased edge length and vertical variability in scour protection design has been proposed to foster habitat diversity (ter Hofstede et al., 2022).

For example, the scour protection can be engineered to enhance biodiversity through the addition of complexity and microhabitats. This can be achieved by small adaptations in material use, texture, and shape i.e., factors which can improve the conditions for settlement and growth by a variety of marine life. For example, this scour protection around turbines provides area with hard substrate for oyster settlement. If successful, oyster presence at the scour protection of wind turbines will affect the connection of rocks and thereby its stability, especially in the case of smaller rocks which may benefit from this "binding effect" (Domisse, 2020) in essence, **promoting the good**. Thus, Glarou et al. (2020) also suggest that

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more attention should be paid to the choice of scour protection material as well as the optimal rock size that provides suitable habitat.

Groen et. al (2019) use four indicator species, *Gadus morhua* (Atlantic cod), *Homarus gammarus* (European lobster), *Ostrea edulis* (European flat oyster), and *Sabellaria spinulosa* (Ross worm) to, the authors describe changes to scour protection design, additional elements that improve the habitats for these species, and associated costs and benefits. It has been suggested that when adding additional elements to the scour protection such as piles of rock, concrete tubes, and shell filled nets as well as by incorporating a variety of grading widths in the scour protection itself, these measures provide a range of hole sizes suitable for different species. In addition, the length of the edges of the scour protection and vertical variability can also be increased to create additional different habitats (Groen, 2019). Thus, although scour protection is discussed here as a minimisation measure, it may also be considered as a creation measure.

Additionally, aquatic farming of seaweeds is a growing sector that may provide a new form of **offsetting** in the oceans, particularly in targeting carbon sequestration at a regional scale. The extractive species of LTA take up nutrients and store and sequester carbon from the water column. For example, CO_2 and dissolved nutrients are built into seaweed biomass through photosynthesis, uptake, and growth, sometimes referred to as "charismatic carbon". Seaweed photosynthesis contributes to increased pH and oxygen, effectively mitigating local ocean acidification and de-oxygenation.

However, seaweed aquaculture in a multi-use setting is still a hypothetical construct. Thus, offsetting by sequestration is not feasible at the pilot scales as this process is presently hindered by the high costs as calculated by economic modelling scenarios in the North Sea (Table 4) (van den Burg et al., 2016; Froehlich et al., 2019). The feasibility of seaweed aquaculture at a scale at which CO_2 may be sequestered was considered by authors as low and/or unfeasible in the case of

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human consumption, animal feed additive, and biofuel end-use cases. The cost-ineffectiveness was exacerbated by the fact that the seaweed is not able to be harvested multiple times per year and that much of this fiscal data is not publicly available as this is sensitive data of the single companies and partners.

Table 4: General cost estimates for seaweed farming in the North Sea. Authors explored high and low-cost investment scenarios. For both scenarios they assume: a 10-year lifespan for investment in systems, capital costs are excluded, and a yield of 20 (dry) tonnes ha^{-1}. Calculations do not attempt to control for inflation since 2013. Based on this analysis, it would cost an estimated $1,291–$1,924 to sequester per tonne of CO_2. Source: Froehlich et al., 2019 and references therein e.g., van den Burg et al., 2016.

Investment scenario	Harvest cost (USD/dry tonne)	Cost (USD/ per tonne CO_2)
Low	1,162	1,291
High	1,732	1,924

In the final tier of the mitigation hierarchy, offsets are designed to compensate with either the no net loss or even a net gain of biodiversity principle (IUCN, 2014; ten Kate and Crowe 2014). However, offsetting measures have been criticised for being *post-hoc*, rather than being built into the EIA process during its early phases for example with incentive-based regulations. Offsetting measures could be economic in nature. Economic offset examples in North Sea and Baltic Sea include **carbon credits** with which to add value to and to decarbonise the seaweed aquaculture supply chain as in the case of Swedish mussel farmers, wherein farmers received credits to offset nutrient C, N, and P discharges (e.g., from sewage outfalls) (Jansen, 2023). These incentives may also take the form of compensation funds and/or payment for ecosystem services (Gómez-Baggethun et al., 2010).

However, to date, there are several drawbacks to consider when upscaling seaweed aquaculture for restoration and emission abatement purposes. These offset calculations require a novel approach. Hurd et al. (2022) have proposed a Forensic Carbon Accounting approach, in which a thorough analysis of carbon flows between the atmosphere and ocean, and into and out of seaweeds would be undertaken, for assessing the magnitude of CO_2 removal and robust attribution of carbon sequestration to seaweeds.

3.1.3. Integrated multi-trophic aquaculture

Since the North Sea is an intensely used sea, aquaculture activities should also fit with other end-user functions (Jansen et al., 2016). In addition to the levels described in the mitigation hierarchy (section 3.1.1.), spatial-scale dependency plays at all levels of mitigation. Due to this, mitigation measures may be applied at the individual pilot levels. Thus, minimisation of impacts has been proposed in the North Sea via **co-location** of activities (Table 5). Co-locating OWF with low-trophic aquaculture (Figure 8) may minimise environmental impacts by providing emission-free energy, nutritious seafood, and restorative ecosystem services (ESS). This may be achieved through capture and utilisation of emissions such as CO_2 and other nutrients, thus mitigating the total impact footprint of activities at sea (this particularly by reducing the spatial footprint of the activities).

Moreover, co-location may also reduce impacts through combining antagonistic impacts at the same place and at the same time. This is the concept behind **integrated multi-trophic aquaculture** (IMTA) (Buck et al., 2018), and has been proposed to be used in conjunction with OWF (McVey and Buck, 2008).

3.1.4. Summary of mitigation measures

A summary of commonly used mitigation measures is presented in Table 5.

Table 5: A summary of mitigation measures and a statement on their outcome.

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Type of Approach	Description	Outcome	Reference
Co-location	Physical	26-fold expansion potential for LTA in the study area (Danish Fisheries Agency database).	Maar et al. (2022) and North Sea Farmers, (2024)
		Data not available at the time of writing.	
Mitigation culture of blue mussels (minimisation i.e., level 2)	Biological	Removed excess nutrients and also become feed ingredients for fish, pigs, or poultry substituting fish meal or providing spat for mussel culture elsewhere.	Maar et al. (2022) and references therein.
Reduce anthropogenic activities e.g., trawling, building to aid restoration (minimisation i.e., level 2)	Integrated	IMTA proposed as a tool with which to combine fish, shellfish and seaweed aquaculture and integrate it with offshore wind farms. No full data available at the time of writing.	Buck et al. (2018); McVey and Buck (2008)
Sequestration of carbon by seaweed (offsetting i.e., level 4)	Biological	It is estimated that 11% of the C fixed during primary production is lost as dissolved or particulate C and exported to deeper waters, where it can be considered sequestered.	Maar et al. (2022) and references therein.; van den Burg et al., 2016, and Froehlich et al., 2019
Scour protection (minimisation of erosion i.e., level 2)	Biological	Vertical variability in, and inclusion of smaller rocks increased habitat creation	Groen, (2019); Coolen et al. (2020); Bos et al. (2021).
Carbon credits, compensation funds, legal liability (economic offsetting i.e., level 4)	Physical	Could decarbonise the supply chain. However, no reliable estimations available at the time of writing. Very challenging to upscale from Pilot level.	Gómez-Baggethun et al., 2010; Hurd et al. (2022); Jansen, (2023)

3.2. Restoration measures at the multi-use level

It is important to review the opportunities and the challenges of marine habitat restoration in the North and Baltic Seas if we are to aim for an eventual implementation of the overall best measures. Measures for maintaining or restoring a favourable conservation status of protected species and habitats are mandatory according to the EU Habitats Directive (Council Directive 92/43/EEC, (The Council of the European Union, 1992).

Restoration measures can be focused on different aspects such as habitat classification, intervention methods, and overall project design. Some common elements and best solutions for biogenic reef restoration emerge across the studies reviewed. In this section, we report on the best solutions for restoration in terms of natural substrates, materials, timing, location, as well as species and genetic considerations.

The most commonly applied restoration measure is the implementation of biogenic reefs. Biogenic reefs are hard structures built by living organisms that account for several important ecosystem functions. Biogenic reefs can be made up of a variety of organisms, and in the North and Baltic Seas the most common are bivalves such as oysters and mussels, and polychaetes such as *Sabellaria spinulosa* (Ross worm) and *Lanice conchilega* (sand mason worm).

Biogenic reefs provide multiple ecological benefits, such as habitat creation, food, and shelter for a number of species, thus enhancing biodiversity. They also provide protection for the shoreline by promoting sedimentation thereby reducing water velocities. Moreover, biogenic reefs play a role in filtration, and carbon removal and thus in the regulation of biogeochemical fluxes.

Despite their importance, these ecosystems have been degraded or lost due to human activities such as dredging, trawling, fishing, and pollution over the last few

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centuries (Pogoda et al., 2019). Additionally, human-induced large-scale transfers of oysters (e.g., within Europe, but also to and from the US, Africa, Australia, and Asia) as an effort to stabilise dwindling fisheries has now resulted in the introduction of invasive species and in the wide spreading of diseases induced e.g., by the protozoan parasite *Bonamia ostreae*. This finding was corroborated by Beck et al. (2011) who reported that the overall condition of native oyster reefs was poor in most ecoregions. For these reasons, there have been increased efforts towards their restoration.

Native European oysters vanished almost completely approximately 70 years ago and with them the memory of their existence and ecological relevance was lost (Pogoda et al., 2019). Interestingly, the European oyster is a reef-building species with extensive historical occurrence in the area and should therefore be considered as a key ecological player in the North Sea ecosystem (Pogoda, 2019). Therefore, the decline of native oyster beds in the North Sea exemplifies a loss of vital ecological baseline knowledge. To remedy this, by estimating the oyster reef abundance and condition across many bays and ecoregions in the North Sea researchers can establish a new baseline from which to set much needed realistic and achievable goals for oyster reef restoration, conservation, and continued evaluation. **Restoring oyster beds** in a **OWF** area can reinstate a habitat that may have deteriorated due to former fisheries activities and is hence, an example of how OWF can positively contribute to restoration. In light of this, one such suitable site may be the Natura 2000 area Borkum Reef Ground which has been identified as a suitable site for oyster restoration (Pogoda et al., 2020). Additionally, two areas at the Frisian Front are considered suitable for European flat oyster restoration, with the northern half of both locations being more suitable than the southern half (Kamermans et al., 2022). It was hypothesised during the UNITED project that If aquaculture and restoration prove to be feasible in offshore wind farms, a new time of prosperity might start for flat oyster (UNITED Project, *in prep*).

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A report by Sas et al. (2023) discusses the biogenic reef species and their potential for biogenic reef enhancement or restoration in the DPNS. It was proposed that restoration efforts should minimise human intervention as much as possible i.e., to let nature run its course. As discussed in section 3.1.2., anthropogenic disturbances such as trawling and building of infrastructure could be minimised in a bid to aid restoration. Advocation for this action was echoed by Rabaut et al. (2008) who argues that the BPNS should be recognised as a sandbank habitat type, which is commonly associated with the reef-habitat type that is formed by the tube-dwelling polychaete *Lanice conchilega. L. conchilega* has significant ecological implications as a reef builder and thus as an ecosystem engineer. Therefore, Rabaut et al. (2008) also suggest that bottom fisheries should be better regulated in the BPNS as an effort with which to achieve ecological restoration and protection of this habitat type in line with the EU Habitats Directive (Council Directive 92/43/EEC, The Council of the European Union, 1992).

Van Duren et al. (2017) reviewed the habitats of various natural reef-building species native to the Dutch continental shelf and proposed a set of criteria for restoration projects. These criteria focus on native species and structures outlining the measures that reduce disruptive activities thereby tackling firstly disturbance before moving onto active restoration. Certain measures such as the deliberate placement of settlement tiles comprised of quartzite have also been attributed to the successful settlement of reef-forming species such as *Serpula vermicularis* (Cook et al., 2021). In some cases, the optimum timing of the deployment i.e., seasonality and location of restoration measures can affect its overall success. Indeed, Cook et al. (2021) found that the settlement of *S. vermicularis* was three-fold higher in July. Similarly, a mussel reef could be established with a hard substrate and under a suspended mussel longline but only during summer months (Goedefroo et al., 2022).

It is only if spontaneous reef formation cannot be expected within at least five years, additional interventions such as providing natural or artificial substrate, or importing of live organisms, should be considered. Any intervention should conform to the natural habitat of the reef species, and avoid adding hard substrate to naturally soft sediment, unless they were once present but disappeared due to human activity. Sas et al. (2023) recommend that if hard substrate is needed, this should be comprised of either natural shells and/or rocks that are of similar composition to those that were historically present in the area, or be temporary structures which are preferably biodegradable. For oysters, most common substrates include porcelain, concrete, limestone, non-calcium stone, non-oyster shell, dredged shell, and engineered reefs, further reviewed in Goelz et al. (2020). Other substrates are mixed materials such as bivalve shells (e.g., scallop shells, surf clams), crushed limestone or rock, and 3D-printed sandstone reefs (Pineda-Metz et al., 2023). In some cases (where species distributions overlap), native oyster restoration may even be facilitated by novel substrate provided by the invasive oyster *Crassostrea gigas* (Christiansen et al., 2018).

Although most restoration projects have to date targeted oyster species, reefs comprised of other species such as *Mytilus edulis* (blue mussel) also form biodiversity hotspots and can increase fish production in the Baltic Sea (Orfanidis et al., 2021). The authors suggest that if the environmental goal is to support commercially important fish species such as *Gadus morhua* (Atlantic cod) and flatfish, mussel reef restoration projects should target low current areas.

A review of key design considerations for restoration (albeit specific to oysters) stresses the importance of early identification of project goals, budget, and overall timeline. These parameters should be used to guide site and material selection (Howie and Bishop, 2021). For example, substrate should only be provided in areas where the natural substrate is lacking, limited or inappropriately configured and therefore is unlikely to attain the desired environmental goal(s) without intervention.

Different structural considerations are needed contingent on the targeted ecosystem service. For instance, habitat provision requires a substrate containing more structural complexity, whereas for coastal defence a high vertical relief is more appropriate. Seeding reefs would only be needed when there are inadequate or no remaining live oysters. For example, small, hatchery-produced seed oysters can support sustainable and successful restoration efforts even in sublittoral offshore waters, with high survival and growth over a 2-year experiment (Merk et al., 2020).

Translocation of oysters may also be considered as a restoration measure in the context of LTA-MU. Bos et al. (2023) translocated adult oysters from Ireland, Norway, and the Netherlands in five pilot projects and observed good oyster performance for both foreign sourced and local oysters. However, if the end-habitat is deemed suitable for translocation, particular attention should be paid to controlling the biosecurity risks associated with translocating oysters from another estuary or system as well as to their susceptibility to disease and/or predation once translocated.

Therefore, active restoration measures may be summarised as the following:

i. Minimising the use of non-native material.

ii. Formulating clear objectives and evaluation methods.

iii. Reducing the risk of introducing non-native species and/or diseases.

Whilst the focus of this review has been on biogenic reefs, a recent study has proposed an innovative conceptual framework of multi-habitat restoration. Liversage (2020) suggests that multi-habitat restoration can improve the planning, objectives, and outcomes of reef restoration projects. For example, two or more co-occurring and ecologically related habitat types such as shellfish reefs and boulder reefs could be restored in tandem to enhance their conservation and recovery. Potential benefits of multi-habitat restoration of shellfish reefs and boulder reefs can be measured via an increase in recruitment, survival, diversity, and functioning of both habitats.

A holistic understanding of created reef systems and the avoidance of undesirable results necessitate a focus on environmental and ecological drivers behind abundance and richness data, adopting a systems ecology approach (Coolen et al., 2019). In principle, metrics for monitoring and assessing AR success range from fish density, biomass, richness, and diversity to comparisons with surrounding natural reefs. In addition, the temporal and geographic scales of these metrics must be considered. The approaches ideally include studies on larval and other connectivity between installations, the impact of reefs on the broader food web, and ecosystem dynamics. For example, a fast and inexpensive molecular tool to identify *Ostrea edulis* larvae and distinguish them from those of *Crassostrea gigas* and *Mytilus edulis*, has been recently proposed (Benkens et al., 2021). This tool can facilitate the confirmation of restoration progress and inform site selection by considering larval occurrence in a site.

Ultimately, when considering the feasibility of these restoration measures at the MU level, it is imperative that the feasibility of their execution is also explored by developing measurable indices. When taken together, these metrics may form the basis for the assessment framework posited in section 3.4. In this review, when considering mitigation (section 3.1.1.–3.1.4.), restoration (3.2.–3.2.1.), and creation (section 3.3.–3.3.7.) and measures, there have been differing methods by which the relative success of each has been analysed in the literature. It is only by combining this breadth of data along with expert consultation and input from the ULTFARMS consortium alongside industry input, that the following section provides a criteria-based solution analysis (section 3.4.). This framework (Table S1, S2, Figure 11) may be applied to evaluate the measures outlined in the literature, but also to serve as a basis with which to evaluate measures implemented in the ULTFARMS pilots in future deliverables.

3.2.1. Summary of restoration measures

Restoration measures may be summarised into four types.

i. Physical restoration: this involves providing a substrate or physical structure that can support the recruitment growth and development of the reef. For example, this could involve placing rocks or other materials on the seafloor to provide a base for coral or oyster growth.

ii. Biological approaches: this involves reintroducing individuals to a degraded or destroyed reef. For example, this could involve transplanting oysters from a healthy reef to a degraded one.

iii. Chemical and environmental modifications: this involves altering water chemistry or other environmental factors to make conditions more favourable for reef growth (e.g., acoustic enhancement) (Gordon et al., 2019).

iv. Integrated approaches: this involves combining multiple techniques, such as providing a substrate whilst also reintroducing individuals.

Table 7: Summary and comparison of these practical restoration measures and statements on their outcome.

Type of approach	Description	Outcome	Reference
Physical	Biodegradable EcoSystem restoration Elements structures (e.g., BESE sheets, made of potato starch) were used to stimulate settlement	Structures with addition of fibrous ropes facilitated the growth of mussels, whereas the growth of oysters was	Temmink et al. (2021)

	and post-settlement survival by reducing predation.	facilitated by hard substrates only.	
Physical	General intervention measure to aid restoration such as adding shells, or historically present rock types.	Theoretical approach only.	Sas et al. (2023)
Biological	Seed oysters were deployed in cages in offshore field experiments.	High survival and growth reported over two years. Present-day environmental conditions and small, hatchery-produced seed oysters are suitable for supporting sustainable and successful restoration efforts even in sublittoral offshore waters.	Merk et al. (2020)
Biological	Adult oysters from Ireland, Norway, and the Netherlands were translocated in five pilot projects	Good oyster performance was reported for both foreign and local oysters. Growth rate was explained by origin and average water temperature, to a lesser extent by number of months, location and salinity, and not to other environmental factors such as pH and O_2.	Bos et al. (2023)
Integrated (biological and physical)	Nylon bags (filled with stones or empty mussel shells) were dropped on	A mussel reef could be established under the dropper line	Goedefroo et al. (2022)

	the seafloor to create a hard substrate, and a suspended longline containing mussels was added to allow the mussels to fall to the bottom instead of being harvested.	structure but only during summer months.	
Integrated (biological and physical)	Installing a reef base (limestone boulders and shell material) and live oysters (spat-on-shell, single juvenile and adult seed oysters), also on 3D-printed sandstone reefs.	Increase in biodiversity after one year, but still lower than historical records.	Pineda-Metz et al. (2023)
Integrated (biological and physical)	Restoration experiments using tiles allowed settlement of a rare biogenic reef forming species (*Serpula vernicularis*). The settlement tiles were 10 cm × 10 cm tiles, were made from quartzite and attached vertically in pairs to canes. At each site, the canes were pushed into the sediment at random points	Settlement on deployed materials was three times higher in July than other months.	Cook et al. (2021)
Integrated	As part of the "*Rich North Sea*" program, at the "Gemini" Wind park an oyster bank of 5 ha is being constructed (of historically present oysters in 1883) to study growth, survival, reproduction, and settlement.	No results were available at the time of writing.	*Link to report on "Gemini" Wind park* (The Rich North Sea, 2024a)

3.3. Creation measures at the multi-use level

Soft-engineering measures can provide a range of solutions for different OWF-LTA scenarios. For example, the addition of structures or elements either at the design phase or implemented once they are already in the water can provide effective biodiversity benefits. This can potentially be achieved by designing structures that provide important ecosystem services, including pollution reduction, habitat provision for target species, recreation, and education (Dafforn et al., 2015) at differing physical and biological scales (Figure 9).

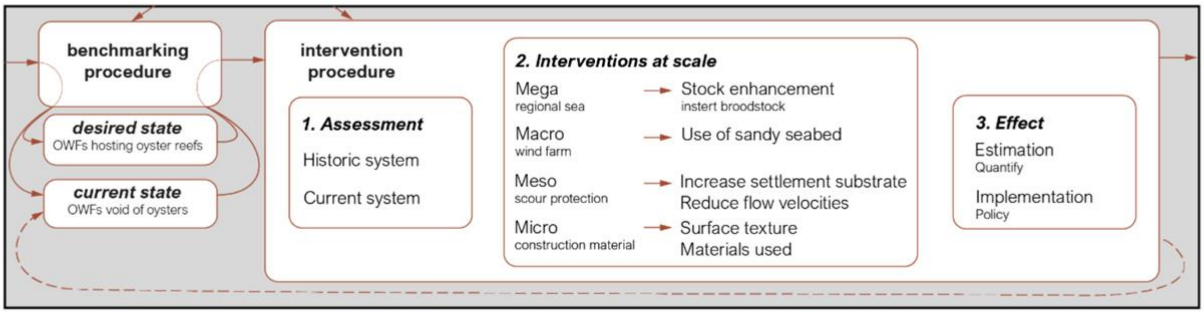

Figure 9: A stepwise procedure with which to assess the potential effects of interventions at differing scales on oyster reef development in an offshore wind farm, i.e., bringing a wind farm that is void of oysters towards one that is hosting oyster reefs. Source: ter Hofstede et al., 2023.

3.3.1. Artificial reef definition and subtypes

One such soft-engineering measure is the creation of (an) artificial reef(s) (AR). The United Nations Environment Program (UNEP) Regional Seas Convention published in 2009 its guidelines for the placement of AR (UNEP, 2009). These guidelines provide a more restrictive definition of AR, i.e., one that excludes structures that are not intentionally and specifically intended to mimic natural reefs. The definition stipulates that "*An artificial reef is a submerged structure deliberately constructed or placed on the seabed to emulate some functions of a natural reef such as protecting, regenerating, concentrating, and/or enhancing populations of living marine resources. Objectives of an artificial reef may also include the protection, restoration and regeneration of aquatic habitats, and the promotion of research, recreational* *opportunities, and educational use of the area. The term does not include submerged structures deliberately placed to perform functions not related to those of a natural reef - such as breakwaters, mooring, cables, pipelines, marine research devices or platforms - even if they incidentally imitate some functions of a natural reef.*" (UNEP, 2009, p.2). More recently, as defined by the OSPAR Convention, an artificial reef is a "…*submerged structure placed on the seabed deliberately, to mimic some of the characteristics of a natural reef*" (OSPAR, 2010, p.1).

An AR may serve five primary purposes as proposed by Reis et al. (2021), based on a previous categorisation made by Fabi et al. (2015): i) management and restoration, ii) protection and conservation of habitats/coastal areas/(endangered) species, iii) production, iv) research and scientific innovation, and v) recreation (e.g., diving and recreational fishing sites) (Ramm et., 2021; Reis et al., 2021).

These structures offer opportunities for colonisation by sessile biota, habitat provision and shelter for all types of organisms, and also food as they have the potential to influence water currents, leading to localised upwelling of nutrient-rich waters (Ramm et al., 2021). AR also provide ecosystem functions, such as nutrient cycling through the increase in organic matter which is ingested by filter-feeding organisms.

Whilst often portrayed as having positive impacts on marine ecosystems, AR remain a topic of controversy. Frequently, their primary objective is to boost (commercial) fish populations, either via a general enhancement to the local ecology or by creating areas where fishing yields are more substantial i.e., fish stock enhancement. This is achieved as the increase in fish abundance and/or diversity significantly boosts the overall productivity and economic viability of said fisheries (Ramm et al., 2021). In some cases, the utilisation of AR can potentially encourage intensified fishing practices and therefore the overexploitation of marine resources. This trade-off comes at the expense of more critical conservation measures such as maintaining of fishing quotas, restrictions, and the establishment of marine protected areas (MPAs) (Reis et al., 2021). Figure 10 provides an overview of the artificial reef effect, based on the multi-use scenarios that were envisaged in the UNITED project (section 1.2.).

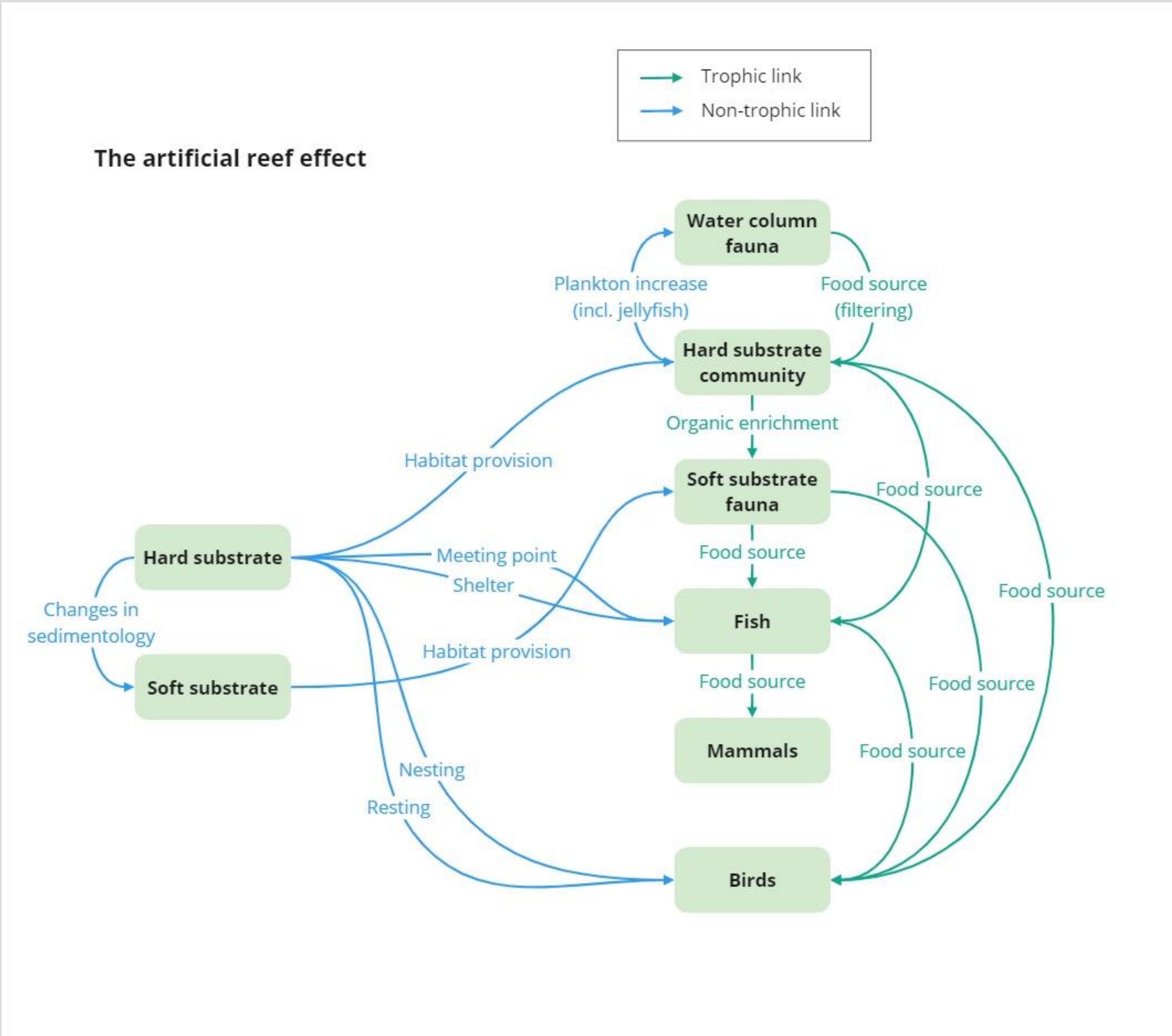

Figure 10: Simplified representation of the artificial reef effect in the context of the UNITED ocean MU scenarios. Source: modified after Van Gerven et al., 2023.

According to Ramm et al. (2021) the creation of artificial reefs may be subcategorised into three types:

i. Accidental deployment (e.g., shipwrecks).

ii. Intentional deployment but unintentional artificial reef creation (e.g., oil and gas platform, offshore wind farms, jetties, etc.).

iii. Intentional deployment.

Intentional deployment but unintentional reefs are generally partially toppled or left *in situ* former oil and gas platforms. In the USA, the conversion of oil and gas platforms into AR was common practice until the late 1980s. Whereas in Europe this practice was partially prevented by banning the conversion of "*Rigs-to-Reefs*" in a bid to minimise deepwater disposal of non-virgin materials by the OSPAR Commission (OSPAR, 1998; Smyth et al., 2015; Ramm et al., 2021). Type ii deployments are mostly found in the USA, North Sea (UK) and Australia and were therefore not the focus of this report.

Moreover, it has already been documented that type ii installations do not achieve the desired complexity or diversity sought with which to enhance biodiversity (Degraer et al., 2020; 2023). This is because unintentional reef creation is not sufficient for significant biodiversity creation because it does not specifically promote strong foundations for structurally and functionally diverse ecosystems. This outcome requires the presence of specific species i.e., target species.

The North Sea in particular was formerly covered by oyster beds that provided the foundation for complex ecosystems but is less so at the time of writing. Thus, at the time of writing, candidates which may serve as possible target species as natural reef builders in the North Sea include the flat oyster (*Ostrea edulis*), the Ross worm (*Sabellaria spinulosa*), the Northern horse mussel (*Modiolus modiolus*), the sand mason worm (*Lanice conchilega*), cold water coral (*Lophelia pertusa*), and the honeycomb worm (*Sabellaria alveolata*), amongst others which vary between locations (van Duren et al., 2017).

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A positive ecological outcome also requires use of appropriate materials. Historically, AR were constructed using readily available and inexpensive materials, with little consideration for their broader ecological consequences. For instance, many reefs were made from objects of opportunity, such as rubber tires which released toxic substances, including heavy metals, that and were later detected in filter-feeding organisms (Reis et al., 2021).

In recent years, as environmental awareness has risen and policies have become more stringent, the use of more natural materials such as seashells has been favoured. The UNEP (2009) mandate stipulated that most intentional reefs be made of concrete mixed with natural rock or seashells, as it is a cheap material, easy to shape and effectively colonised by fouling organisms owing to its porous structure. Indeed, Kamermans and Saurel (2022) advocate for the presence of shells on the seabed is positive as it provides a potential settlement substrate for shellfish larvae, particularly when coupled with a low silt content (20–40%). This effect is especially enhanced when combined with the implementation of pH balanced marine-grade mixtures (Ramm et al., 2021). For example, the use of concrete or "reefcrete" (Dennis et al., 2018) which is standard concrete (e.g., oyster castles) mixed with various additives often aimed at lowering pH or resource consumption during manufacture (e.g., "ECOncrete") (Sella et al., 2018). Other environmental parameters to consider regarding flat oyster development may be that areas with bed shear stress between < 0.3 N/m^{-2} (Bennema et al., 2020) and < 0.6 N/m^{-2} (Kamermans et al., 2018) seem suitable for flat oyster development.

Thus, unlike deployment types i and ii which are predominantly comprised of steel and concrete materials, materials used in deployment type iii, i.e., intentional reef creation, may be more variable in nature. Although deployment type i and ii are excluded by UNEP (UNEP, in the context of OWF areas it is imperative that they are considered. Regardless of whether the structures at sea are AR (*sensu stricto*) many will have similar effects which can be strengthened with targeted NID measures, particularly when linked with OWF.

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3.3.2. Offshore wind farms as artificial reefs

OWF can facilitate the establishment of AR processes via their capacity to enhance connectivity on a significant scale. This enhancement occurs through the generation and distribution of larvae to and from various regions, effectively serving as "stepping stones" which boost the connectivity within ecological communities (Molen et al., 2018; Degraer et al., 2020; Tidbury et al., 2020).

Overall, OWF are known to increase biodiversity for two major reasons. Firstly, via the introduction of added artificial hard substrate that serve as the scour protection around the monopiles (see also section 3.1.2.). Once installed, these added hard substrates rapidly attract fauna such as fish leading to an increased density of e.g., large decapods (Andersson and Ohman, 2010; Dannheim et al., 2020).

Therefore, the fishing exclusions mandate coupled with the interdiction of bottom-disturbing activities in all OWF for safety reasons can lead to positive ecological outcomes. This finding was consistent with results presented by Glarou et al. (2020) who report that in comparison to reference areas, OWF contained higher abundances and diversity of species commonly affiliated with hard substrates. However, in the BPNS, artificial reefs unintentionally created by offshore wind farms were measured to be poorer in complexity than natural reefs, as they were dominated by mussels and anemones from six years post-implementation onwards (Degraer et al., 2020).

Although accidental deployments are the most common in Europe (e.g., from copious sunken battleships), for the aforementioned reasons deployment type iii is considered to be the most ecologically sound method. Therefore, this report only presents a review on **intentional NID** and **intentional reef creation** (section 3.3.3.).

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3.3.3. Intentional artificial reefs

Deployment type iii (section 3.3.2.), intentional AR, can be most frequently found in the USA, Japan, South Korea, Australia, the Philippines, France and Brazil. Efforts for intentional creation of biodiversity surrounding offshore wind installations can be further subcategorised into the following:

i. Primary artificial reefs (structures installed to serve as reefs).

ii. Secondary artificial reefs (structures not installed to serve as reefs but do so regardless).

3.3.3.1. Primary intentional artificial reefs

The scientific literature found using the methods outlined in section 3 concerning the implementation of AR structures with the explicit purpose of biodiversity promotion, especially within the North and Baltic Seas, is notably limited. Thus, when looking further afield, globally intentional AR installations predominantly focus on fisheries enhancement, in turn unfortunately relegating the enhancement of biodiversity to a secondary benefit (Reis et al., 2021). In recent years, there has been an increased interest amongst developers to foster biodiversity and ecological restoration in OWF. At the time of writing, these initiatives were still in their infancy and thus data was limited (Table 6).

3.3.3.2. Secondary intentional artificial reefs

In light of the limited literature on primary AR installations in the North and Baltic Seas, this review focuses on secondary AR efforts. Secondary AR installations involve the purposeful modification or re-design of existing structures which were originally designated for fisheries or biodiversity enhancement (Reis et al., 2021).

3.3.4. Nature-inclusive design strategies

There are several reviews and reports that outline some general categories of nature-inclusive design (NID) in OWF. A positive ecological outcome may be reached by the implementation of either physical measures (section 3.2.4.1.) such as strategic placement or modification of offshore structures as well as by biological measures (section 3.2.4.2.) such as testing of breeding lines and other reef-building techniques (van Duren et al., 2019).

3.3.5. Physical nature-inclusive design strategies

It is important to consider both reef location and design when creating a new reef. Some successful physical design trends have been identified (Reis et al., 2021). These include but are not limited to use of structures with a higher vertical relief to enhance larval settlement and shelter for pelagic fish, and incorporation of cavities for benthic species. Coolen et al. (2020) also include depth as a key driver of species presence on reefs. Van der Stap et al. (2016), Schutter et al. (2019), and Todd et al. (2018) also explain that distinct communities at different depths develop on offshore platforms because of the depth zonation of flora and fauna.

With regards to the shape of the artificial reef, the design typically seeks to reproduce natural shapes and/or shapes more appropriate for a specific species. Overall, smaller structures may be better for foraging volume and food provision whereas larger ones may also act as refugia. In principle, a structure that is generally high in complexity necessitates the provision of suitable substrates and habitats catering to diverse life stages of target species. These concrete structures can result in a higher attraction of species richness and biomass, in some case even rivalling the success of natural reefs (Reis et al., 2021). For example, in the North Atlantic, cubic and irregular shaped structures were positively correlated with vertebrate i.e., fish richness (Reis et al., 2021).

In principle, depth and the spacing between structures emerge as key determinants in the efficacy of AR installations (Coolen et al., 2019; Glarou et al., 2020; ter Hofstede et al., 2023). However, ultimately, the location of the reef and its unique environmental conditions such as sediment type and existing biodiversity will play a crucial role in the successful recruitment, colonisation, and behaviour of target species (Baine, 2001). For example, in Australia, Komyakova (2019) found that AR location significantly influences fish abundances whereas AR design more significantly influences the diversity and community structure of target species.

This means it is important to choose depth depending on the goals of the AR structure. At secondary installations colonisation should be induced at the correct depth for the species of interest, not just that of the existing platform. This then has implications for choices made during decommissioning concerning the height at which structures are left in the water.

Whilst options for strategic location of AR within OWF may be limited, strategic design can be still instrumental in fostering biodiversity, for instance, via rock dumps or scour protection . Scour protection is primarily designed by engineers as a mitigation measure with which to minimise the impacts of erosion (section 3.1.2.), but can also be adjusted to help set up reef systems and protected habitats for juveniles of important reef-building or keystone species (Coolen et al., 2019). Thus, scour protection not only serves its engineered purpose but also functions as an AR by local habitat complexity therein providing shelter, nursery, reproduction, and feeding grounds for various fish species as well as settlement grounds for bivalves and macroalgae (Glarou et al., 2020). A comprehensive analysis of methods with which scour protection may be successfully physically augmented for nature enhancement can be found in Groen et al. (2019). In principle, combining oyster restoration with oyster culture is a viable option (i.e., larvae produced by off-bottom cultivation may settle on substrate placed on the bottom).

Effects of the choice of substrates for *Ostrea edulis* (flat oyster) settlement was explored in the "Borssele V" OWF whereby calciferous materials (beneficial to shellfish species) such as mussel shells, along with granite and granite-gravel, were considered based on factors such as cost-effectiveness and longevity (Tonk et al., 2020). The success of these measures is echoed in more recent studies such as in ter Hofstede et al. (2023) who also advocate for the integration of materials rich in calcium, such as shells or calciferous rock, to enhance habitat complexity as a measure with which to facilitate the settlement of target species.

Within a wind farm the size of a reef installation, the shape, and orientation towards natural reefs or other artificial reefs also have a considerable impact (Glarou et al., 2020). Therefore, it is imperative to consider whether the individual turbines or other placed structures will function more as primarily independent reefs or more as interconnected systems. The latter will affect optimal habitat utilisation and the overlapping of foraging areas (Glarou et al., 2020). Therefore, the measurable physical parameters which may be used to evaluate the success of AR are:

i. Configuration and design complexity of the reef.

ii. Materials of the reef i.e., structural integrity/stability.

iii. Size of the reef including volume and area.

A prevailing issue is that often NID does not identify target biodiversity assets and is thus, sub-optimally applied. It is therefore necessary to first identify what it is that ought to be promoted (and why), then subsequently choose the appropriate NID to achieve that goal. The physical design considerations outlined above must therefore also be tailored to specific ecosystems i.e., considering the unique requirements of target species and biological or integrated NID strategies. This ethos of **promoting the good** (Figure 4) will be discussed in following section 3.3.6.

3.3.6. Biological nature-inclusive design strategies

Biological NID measures adherence to ecological principles in reef creation and include reef-building techniques which are used to add additional substrate thereby creating additional (species-specific) habitat, and the human introduction of target species (Glarou et al., 2020; Bos et al., 2021; Lengeek et al., 2022; ter Hofstede et al., 2023) (see also section 4.2.1).

A report on the eco-friendly design of scour protection by Lengeek et al. (2017) recommends targeting umbrella species for which sufficient data exists, as well as fauna categorised as "overall native biodiversity" and/or "policy-relevant species". These umbrella species, determined through policy frameworks, such as Natura 2000 (The Council of the European Union, 1992; EC, 2009) and MSFD (Directive 2008/56/EC, MSFD, 2008), serve as focal points for the optimisation of scour protection and, more broadly, reef design. Promoting the development of an umbrella species such as *Gadus morhua* (Atlantic cod) and *Ostrea edulis* (European flat oyster) can provide knock-on benefits for a variety of species as well as for overall ecosystem functioning (Lengeek et al., 2017).

However, consideration of additional species beyond primary targets is essential for building a comprehensive reef community. Studies by Bergmark and Jørgenson (2014) on the deep-water coral *Lophelia pertusa* highlight the importance of mutualistic species such as the polychaete worm *Eunice norvegica* in augmenting the AR thus improving its eventual effectiveness. Therefore, these data advocate for the need to implement a holistic approach to species selection.

The human introduction of certain species, such as *Homarus gammarus* (European lobster) and *Ostrea edulis* (European flat oyster) is recommended by Groen et al. (2019) and ter Hofstede et al. (2023) as such introductions are hypothesised to mitigate the difficulties encountered in the natural development of an AR. In

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essence, these species can serve as a catalyst for laying the foundation for a self-sustaining population.

Introduction of target species can be *ex situ* induced either naturally via colonisation and artificially via transplantation, or *in situ* via cultivation measures (van Duren et al., 2017). For example, the "*Eneco Luchterduinen*" project released young oysters in 2018 and now observes that these oysters have matured, reproduced and in turn attracted other sea life towards the deployment area (van Duren et al., 2019). However, van Duren et al. (2019) also note that not all measures for their AR design were as yet optimised since their conclusions report that some designs were not suitable for particular conditions e.g., time of year or increased robustness as a result of laboratory cultivation. These designs will now be revised to include measures with which to improve the settlement conditions for reef-building tube worms.

Viable examples of biological NID and nature restoration in high replicates were reported off the coast of the Netherlands in the Dutch part of the North Sea (DPNS). For example, the analysis by Kamermans et al. (2018) shows that a number of wind farms in the DPNS are suitable for flat oyster bed development, although empirical tests (pilots) are still needed to verify actual suitability.

The success of these designs may be attributed to policies which were implemented by the Dutch government mandating that OWF developers integrate NID into leasing proposals (RLI, 2022). For example, the government-backed "*Rich North Sea*" program has collaborated with developers to initiate design measures with the sole aim to promote specific marine organisms around OWF installations. The targeted fauna include species such as sand and shell tubeworms, flat oysters, mussels, and cuttlefish.

AR will be most successful when acting as a source of individuals that survive to reproductive age and contribute to the metapopulation through their reproductive output (Komyokova et al., 2021). However, there is mixed evidence on which side of the "attraction – production" equation OWF farms fall on. Wilson et al. (2010) and Bergström et al. (2014) both found that the turbine foundation influences distribution more strongly than production, whilst others highlight the provision of nursery habitats near the foundations (Glarou et al., 2020).

The utilisation of OWF installations and their surrounding areas for the creation of new biodiversity and reef systems in the North and Baltic Seas is a relatively nascent strategy. However, the growing acknowledgment of the limitations of previously observed artificial reef effects in oil and gas platforms and OWF installations has spurred new initiatives by developers and governments to intentionally consider biodiversity creation. As these initiatives are implemented, it is imperative to establish clear objectives for both functional and structural biodiversity, accompanied by measurable metrics to define and monitor successful reef creation. However, many of these projects are in early stages, either newly implemented or still in planning as developers partner with research institutions and non-governmental organisations to add NID to wind farm plans (e.g., Ørsted and WWF 5-year partnership) and are therefore difficult to evaluate or score.

3.3.7. Summary of creation measures

A summary of the intentional creation measures implemented in the North Sea and the Baltic Sea which have been discussed in this review can be found in Table 6.

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Table 6: Non-exhaustive compilation of current efforts to boost biodiversity in the North Sea and Baltic Sea by offshore wind developers.

Type of Approach	Description	Outcome	Reference
Physical	Reef cubes and reef balls have been placed near the offshore substation jacket to investigate which structure works best for a range of species ("Hollandse Kust West VI" wind farm, Dutch Part of the North Sea).	No published results at the time of writing.	*Link to report on Hollandse Kust West VI* (Tennet, 2024)
Physical	Also at the "Hollandse Kust Zuid VI" wind farm as part of the "*Rich North Sea*" program, the effect of water refreshment holes in the hollow foundations of the wind turbines for use as shelter or habitat is being tested.	No published results at the time of writing.	*Link to report on Hollandse Kust Zuid VI* The Rich North Sea, (2024b).
Physical	Through a partnership with the World-Wide Fund for Nature Denmark, the energy company Ørsted has deployed twelve 3-D-printed artificial reef structures at the Anholt Offshore Wind Farm in the Danish part of the North Sea to increase the available cod habitat and help halt the decline of the species. The structures are made of natural materials, have a wedding-cake like appearance, provide hard surfaces and crevices for other organisms to settle as well as varying in size to imitate natural habitats. The 3-D-printed reef structures complement twenty-four existing boulder reefs which were already established in 2012 when the wind farm was constructed.	No reported outcomes for the 3-D-printed structures deployed in 2022, for the original boulder reefs. Whilst the energy company Ørsted reports that they are "teeming with life," no scientific literature or results are published at the time of writing.	*Link to statement by Ørsted* (Ørsted, (2024).

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Physical	As part of the "*Rich North Sea*" program, at the "Borssele I" and "Borssele II" wind farms foundations comprised of concrete have been strategically placed to provide shelter for *Gadus morhua* (Atlantic cod) as well as other species in addition to mixed-use of materials comprising shells and stones at some of the locations.	No published results at the time of writing.	*Link to article on the "Rich North Sea" program* (The Rich North Sea, 2024c).
Biological	As part of the "*Rich North Sea program*," oyster cages containing 2,400 *Ostrea edulis* (European flat oyster) were placed in Blauwind (Borssele III and IV) wind farm. Settlement of the scour protection at the base of the turbine is being tested rather than installation of artificial reef structures.	Initial recent results (2024) indicate successful settlement and reproduction of *Ostrea edulis* (European flat oyster)	*Link to Ostrea edulis translocation* (The Rich North Sea, 2024d). *Link to Ostrea edulis translocation* (The Rich North Sea, 2024e).
Integrated	The BOOST (Better Oyster Outplacing and Seeding Techniques) Consortium is working to restore oyster populations in the North Sea through the deployment of biodegradable reef tiles that are covered with juvenile oysters. These tiles can be applied to renewable energy projects and as the oysters grow and the reef tiles biodegrade the reef eventually expands naturally.	Research is still active. No published results at the time of writing.	*Link to BOOST project* (BlueLinked, 2024).

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Integrated	As part of the "Rich North Sea" program, at the "Eneco Luchterduinen" wind farm, young oysters were released with artificial reef cage systems to test their reproduction and survival. Settlement conditions for *Lanice* and *Sabellaria* (tubeworms) as well as placing oyster cages in the vicinity of tubeworm reefs which are also being investigated.	Results from July 2019 show that oysters had grown and reproduced; in turn attracted other species. Design data on the suitability of artificial reef cage systems was also collected	*Link to integrated measures on the "Eneco Luchterduinen" wind farm* (The Rich North Sea, 2024e).
Integrated (Nb: that some of this measure could be considered restoration (flat oyster and reef worms historically existed in the area)	From 2022–2026, a series of measures for nature-inclusive design of the "Ecowende" wind farm located on the Hollandse Kust West VI in the Dutch part of the North Sea will be tested and monitored. Measures include the following: testing three different ecological scour protection designs that include variation in size of stones and crevices, investigating use of water replenishment holes by fish species in the areas, protecting and stimulating reef-building *Sabellaria* worm, stimulating flat oyster larval dispersal, building flat oyster nursery rooms at cable crossings, and building circular and biodegradable reef structures from discarded fruit trees at cable crossings.	Wind farm to be commissioned in 2026. No published results at the time of writing.	*Link to scour protection designs implemented at "Ecowende"* (Ecowende, 2024).

It is important to keep in mind that the measures outlined in Table 6 are under development and whilst they are promising, regretfully published evidence for their capacity to maintain or restore natural assemblages still requires more data. However, ultimately the creation of new (hard substrate) habitats albeit important, does not offset the loss of soft-sediment communities, and the various services that they provide. Thus, efforts need to be made to not only understand how such losses can be minimised with the use of alternative techniques and practices, but also on the restoration of ecologically equivalent areas to those that have been lost (Dafforn et al., 2015).

3.4. Results III: Application of assessment framework

In this section, we present the assessment framework which comprises an effectiveness and efficiency criteria-based solution analysis. The solution analysis is based on nine restoration measures as compiled from the literature review (section 3.2.-3.2.1.). Figure 11 shows a (non-exhaustive) summary which studies were included in the analysis of restoration measure, and shows how each study was scored for its effectiveness, as a function of its feasibility and cost. A synthesis table with explanations may be found in supplement S1 with justification of the scoring matrix in S2.

Figure 11 shows that of the nine analysed restoration measures, five fell into the "high feasibility" classification. Within this classification, Pineda-Metz et al. (2023) scored the highest feasibility of 87.5%. Due to the differing scales of each study, cost was considered as a second order after feasibility. Of the five "high feasibility" measures, the best scores (9/10) for cost-efficiency were Liversage (2020), Goedefroo et al. (2022) and Bos et al. (2023) (Table 7).

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Figure 11: The assessment of restoration solution. Summarising the score of nine restoration measures based on effectiveness criteria (green bubbles). The larger the bubble, the higher the effectiveness score out of ten. The *x*-axis scores the cost according to three classes, low- (< €50,000), mid- (€50,000–100,000) and high-cost (> €100,000). The *y*=axis depicts the feasibility of each of the nine restoration measures and is subdivided as follows: high- (> 66.66%), mid- (33.33–66.66%) and low-feasibility (< 33.33%). This figure therefore summarises the effectiveness of a solution as a function of cost and feasibility. Measures are as follows: 1 = Hard substrate (HS) introduction: Fully biodegradable, Temmink et al. (2021); 2 = Hard substrate introduction: Historically present, Sas et al. (2023); 3 = Hard substrate introduction: Non-biodegradable, Cook et al. (2021); 4 = Multi-habitat restoration, Liversage (2020); 5 = Translocation (TL): Ex-situ oysters, Pineda-Metz et al. (2023); 6 = Translocation: Ex-situ oysters, Bos et al (2023); 7 = Translocation: Ex-situ oysters, Merk et al. (2020); 8 = Hard substrate introduction: Partially biodegradable, Goedefroo et al. (2022); 9 = Translocation: Ex-situ oysters, The rich North Sea, (2024a).

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Table 7: Summary of the studies which not only scored high in the depicted effectiveness criteria, but were also deemed high-feasibility and low-cost measures.

Measure/Study	Feasibility	Cost score	Measure type	Action taken
1: **Temmink et al. (2021)**	High (75%)	9/10	Physical	Hard-substrate introduction (fully biodegradable)
4: **Liversage (2020)**	High (75%)	9/10	Physical	Innovative multi-habitat/tandem restoration of shellfish reefs and boulder reefs
8: **Goedefroo et al. (2022)**	High (75%)	9/10	Integrated (biological and physical)	Translocation of mussels (*in-situ*) coupled with introduction of hard substrate (partially biodegradable)

4. Discussion

On the basis that the results of this deliverable are centred around restoration measures, so too is this discussion. When defining, assessing, and monitoring any given measure, there is a myriad of criteria encompassing ecological parameters such as species richness, species evenness, and reef complexity to consider. In principle, these parameters should be delineated early in the process to ensure the most effective measures for the desired objectives (van Duren et al., 2017; Bos et al., 2021). These objectives could also be further subcategorised into the strategic and the operational objective phases of a project (van Koningsveld et al., 2021). These criteria are inherently linked to policy objectives such as boosting the abundance of specific species.

Whilst the ideal scenario involves AR providing habitat of comparable quality to natural reefs, this metric proves challenging to measure. In this report, we have ascertained that there are numerous ecological or technical obstacles to mitigation, restoration, or creation of long-lasting reef systems. These challenges include successful colonisation of the hard substrate by appropriate reef building species, addressing competition between different target species, and the risk of invasive species (Lengeek et al., 2017; van Duren et al., 2017).

We have also demonstrated that there is no one "type" of restoration measure that scores the highest. In principle all four types of restoration measures, i.e., physical, biological, chemical, or integrated, may score high if both effectiveness and efficiency criteria are sufficiently considered.

Although not exhaustively explored in this report, key elements encompass challenges related to the objectives and targets of biodiversity enhancement initiatives. For example, Lengeek et al. (2017) posit that successfully increasing overall native biodiversity on scour protection is a strong indicator for successful optimised design. In line with this ethos, Komyokova et al. (2019) advocate for ARs needing to contribute to net population growth to be deemed successful, which is related to the "attraction – production" debate regarding AR efficacy. This debate is centred around the question of if AR increase biomass, production, or diversity, or they simply redistribute it or reconcentrate it in a different area (Glarou et al., 2020; Layman and Allgeier 2020).

In addition to the ecological challenges associated with establishing biodiverse and complex reef ecosystems, there are socioeconomic and policy challenges that merit consideration. There are numerous regional and European frameworks intended to guide conservation and biodiversity enhancement effort such as the environmental provisions of OSPAR (OSPAR, 1998), Natura 2000 (comprising the EU Habitat Directives (Council Directive 92/43/EEC, The Council of the European Union, 1992) and the European Birds Directive (Directive2009/147/EC, European

Commission, 2009), and the EU Marine Strategy Framework Directive (MSFD, 2008), as well as country-specific policies such as the , Dutch regulations to include NID in OWF projects. From these frameworks, definitions of "overall native biodiversity" and "policy-relevant species," which are targets for reef creation, can be shaped but may differ by area, country, or over time. These frameworks also suggest community characteristics of interest, such as high biodiversity and low invasive species (van Duren et al., 2017).

Coolen et al. (2020) presents a set of considerations to evaluate the added value of artificial reef systems in the North Sea. These questions include:

- Which organisms have colonised these artificial structures?
- What characteristics of these structures influence their community composition?
- What are the habitat preferences of the species currently found on these structures?
- Are the communities found similar to those on natural reefs?
- What habitats are particularly suitable for non-native species?"

The contentious nature of secondary AR installations within discussions on marine dumping, pollution, and decommissioning further complicates the policy landscape. The OSPAR Convention (OSPAR, 1998), which regulates environmental protection in the North Sea, stipulates the removal of structures when no longer in use, yet debates persist regarding the removal of structures that contribute positively to ecosystems as reefs after protracted periods in the water (Jørgenson, 2012; Fowler et al., 2020). Indeed, within Table S1 and S2, efficiency criteria wherein studies consistently scored low were those where decommissioning or end-use should be considered. In general, there are more studies outlining the impacts on biodiversity during the construction phase, in comparison to the operational or the decommissioning phases (Thaxter et al., 2017, Dannheim et al., 2019; Gall et al., 2021). Continued dialogue on end-of-life and decommissioning debates will be essential to determine which structures can and should be retained on the seabed (see Fowler et al., 2020, for a more detailed discussion on decommissioning).

Although the effectiveness criteria and feasibility derived from efficiency criteria within this framework are considered statistically sound, we are unable to accurately comment on the cost of each measure due to limited availability of data. Furthermore, it could be argued that a high-feasibility and mature study of a large scale, e.g., Pineda-Metz et al. (2023) scored poorly under the cost parameter due to the large scale and expense of their mature experimental design. Therefore, when applying this assessment framework in the future, it is important to "benchmark" the costs so that they are standardised by metrics such as geographical scale of the experimental design, i.e., square metre of deployment, and other relevant factors

5. Conclusions

The assessment framework presented in this report compels the end-user to consider the link between ecosystem services, structural and functional biodiversity indicators, and environmental goals and thus enables us to quantify adverse changes to ecosystem functioning. These measures, when implemented into the EIA process, provide measurable conservation outcomes resulting from actions which are designed to compensate for the impacts on biodiversity arising from OWF. The protocol developed in this deliverable may steer the user in the direction of society-informed threshold setting. The framework also elucidates prevailing knowledge gaps and hence research priorities both within the ULTFARMS pilots and future scientific studies.

In sum, our findings suggest that restoration measures which consider ecological parameters, i.e., effectiveness criteria in addition to efficiency criteria are best suited to be implemented as potential NID strategies both within the ULTFARMS pilots and when considering potential upscaling. However, at the time of writing, the practical upscaling of these pilots is hindered by the absence of clear management objectives and the lack of quantitative knowledge on the effect of technical interventions that are still required to stimulate for example, oyster reef development. Ultimately, which measures yield environmental and societal benefits and in which scenarios they may transpire will depend on the natural carrying capacity of the North Sea and Baltic Sea.

An overall outstanding question to apply to the ULTFARMS pilots is that of desired ecosystem function This requires consideration of what the ecosystem currently looks like and what is still needed.

6. Outlook and recommendations

Assessing the sustainability of LTA-MU may be contingent on several criteria, such as whether the activity exacerbates an existing environmental problem, whether it is long-lasting and/or places a burden on future generations, and whether it violates any existing environmental or societal standards. Deciding whether an impact arising from OWF-LTA is considered positive or negative will depend on the stakeholder's environmental goal and the outcome of the monitoring efforts.

We present here the following recommendations:

- Where measures are based on theoretical applications alone, follow-up studies should confirm whether the practical applications are aligned with theoretical approaches.

- Suitability modelling can help to identify the best sites in terms of biological and environmental factors and logistical feasibility.
- All measures should take into account habitat complexity, habitat variability, habitat stability, habitat durability, and source populations.
- Focus should be on practical and technical considerations for the effective establishment of reef systems, i.e., promoting the good and mitigating the negative impacts of invasive species, pathogens e.g., *Bonamia*.
- Both positive and negative impacts of mitigation, restoration, and creation measures should be monitored in the short- and long-term for location, spatial extent, and longevity.
- Detailed descriptions of suitable substrates, layouts, and materials should be devised, coupled with collaborative efforts with initiatives to identify desirable and feasible target species for restoration.
- Monitoring strategies should be designed around specific targets, particularly the umbrella and focal species representing overall native biodiversity and policy-relevant species whilst also monitoring invasive species.
- Monitoring the efficacy of all measures should be ongoing by the contractor long after the cessation of activities and evaluated and amended where necessary, forming part of an adaptive management approach.
- Where possible, ecological measures should be supported by genetic techniques, such as the application of eDNA, to preserve genetic diversity, identify larval presence and mitigate the impact of pathogens.

- In the interest of consistency, there is an inherent need to standardise data collection and analysis practices between countries and across all ULTFARMS pilots.

- There is at the time of writing an asymmetric focus on studies conducted in the North Sea versus the Baltic Sea which may be addressed with future experimental designs.

Given the timeline of the ULTFARMS project deliverables 7.1 and 7.2, i.e., summer 2024, the outlook of these best solutions as scored based on the literature review will not feasibly all be implemented as NID strategies within the six pilots. However, deliverable 7.1 may still be referred to as a "best practice" summary for the latter stages of ULTFARMS and as groundwork for WP10, i.e., upscaling. Furthermore, if the cost parameter of Figure 11 were able to be refined with the availability of data, it may be useful as a starting point for the latter business model work packages. In addition, solutions presented within 7.1 may be utilised as a basis for WP4, i.e., the implementation of systems at the pilot sites (T4.2), and WP6. Finally, the data presented in this deliverable may also be used to inform deliverable 3.3., i.e., the "design and implementation of mariculture structures," in order to ascertain which are the highest scoring measures that can be successfully deployed as NID in the design phase.

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Supplementary information

S1

The synthesis of the assessment framework data may be found as a table here.

S2

Table S2: An overview of how efficiency and effectiveness criteria scores for restoration measures in the North Sea and the Baltic Sea were justified based on scientific and industry literature.

Measure (short title)	**Measure type (Bio, physical etc)**	**Criteria**	**Scored Yes? (i.e., +1?)**	**Excerpt/Justification**	**Citation**
		Certainty criteria			
		Field-tested? (North Sea and Baltic Sea only)	+1	"[...] we carried out complementary experiments in intertidal soft-sediment systems in Florida and the Netherlands"	Temmink et al. (2021)

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				"From 2017 till 2020, a pilot project was set up where mussel reefs were established as a nature-based solution to mitigate coastal erosion off the Belgian Coast."	Goedefroo et al. (2022)
		Effectiveness criteria			
		Numerical and/or statistical model simulations?	+1	"A linear mixed-effects model (LMER) with Gaussian error distribution was used to assess main and interactive effects of structure and predator exclusion treatment (i.e., full cage or cage control) on mussel biomass"	Temmink et al. (2021)
			+1	"Generalised Linear Models (GLMs) were used to test for spatial, temporal effects on recruitment and post settlement survival	Cook et al. (2021)

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				and interactions with the most abundant species. Negative binomial regression models were fitted using the lme4 package (Bates et al., 2013)	
				"Different mixed models were chosen to analyse the effect of the reef site on the macrobenthos."	Goedefroo et al. (2022)
		Risk to biodiversity considered. Incl. Invasive species, Diseases	+1	Experiments considered the natural establishment of native C. virginica or native *I. recurvum* in Florida, and native *M. edulis*, native *O. edulis* or non-native *C. gigas* in the Netherlands	Temmink et al. (2021)
			+1	"[...], active reef enhancement using the introduction of live animals to 'seed' a population will be considered as a last resort. Firstly, importing living organisms from other areas always yields a risk of invasive species	Sas et al. (2023)

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				(Lee and Gordon, 2006). Secondly, importing organisms from elsewhere creates a risk of introducing animals with a different genetic make-up from those that are, or were, naturally occurring in the target environment (Grant et al., 2017)."	
			+1	"Ecological implications of changing habitats need to be considered. For example, habitat creation allows hard-substrata species to invade soft-sediment areas (Dugan et al., 2017) and open-coast species to invade sheltered bays (Davis et al., 2002). The important role specifically of hard substrata such as boulders in facilitating marine invasive species was highlighted by Ruiz et al. (2009). Close proximity to developed shorelines such as ports and marinas was suggested as increasing the probability of invasion, which should be considered when choosing locations for creation of any boulder-reef.	Liversage (2020)

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				These same implications need to be considered even when dead shells are added to soft-sediment (Table 1) unless shellfish-reefs are known with certainty to have historically occurred there and anthropogenic influence caused their decline, in which case the community changes would be considered as restoration rather than invasion."	
		Timescale, duration, longevity of impact considered?	+1	"Specifically, we constructed five replicate blocks in Florida in April 2017 and seven replicates in the Netherlands in April 2016. Following a 20- and 22-month period, we terminated the experiments in Florida and the Netherlands in November 2018 and February 2018, respectively."	Temmink et al. (2021)
			+1	Yes, consideration of temporary nature of used materials (if biodegradable or not)	Sas et al. (2023)

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			+1	"The effect of deployment timing was investigated by deploying ten tiles at the Main Site on each of 6 occasions. These deployments were conducted at 2 monthly intervals between January 2012 and November 2012; all tiles were then removed in November 2013. This gave deployment durations of between 12 and 22 months."	Cook et al. (2021)
			+1	Hypothesised relationships between ecological properties and time since restoration are proposed using conceptual inferences based on data in past shellfish/boulder studies.	Liversage (2020)
			+1	"Only during the summer months, a mussel reef could be established under the dropper line structure."	Goedefroo et al. (2022)

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		t0 (baseline) considered?	+1	Yes, as above	Temmink et al. (2021)
			+1	"If hard substrate needs to be supplied this ought to be either in keeping with the environment (e.g., natural shell material, or rocks of a composition similar to what could be found in historical times) or of a temporary nature (e.g., structures that are biodegradable over a few years' time)."	Sas et al. (2023)
			+1	Yes, initial baseline was considered	Cook et al. (2021)
			+1	Yes, see Figure 1 and legend ("Hypothetical restorations at time zero include equal surface-area of rocks (cobbles, small and large boulders), living shellfish (single species at carrying capacity), or both.")	Liversage (2020)

			+1	"To account for the repeated measures and dependency, time was used as a categorical random variable with five levels (T_0, T_1, T_2, T_3, T_4)."	Goedefroo et al. (2020)
		Spatial scale considered?	+1	"[...] we carried out a reef structure experiment (the trans-Atlantic experiment) in Florida US and the Netherlands [...]"	Temmink et al. (2021)
			+1	Consideration of spatial heterogeneity in the site, and of large-scale restoration to create self-sustaining flat oyster reefs	Sas et al. (2023)
			+1	"The main study site (Main Site) was located near the southern shore of Loch Creran in the lower basin (56° 31.371' N, 05° 19.989' W). An additional three sites were spaced around the	Cook et al. (2021)

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				lower basin with one further site in the upper basin"	
			+1	Yes, the extent of restored habitat patches is considered in the proposed conceptual relationships	Liversage (2020)
			+1	Yes, different reef sites and experimental control sites were considered	Goedefroo et al. (2020)
		Ecotoxicological effects considered? E.g., paint, heavy/trace metals	+1	"Any hazardous or non-natural material (such as plastic, metal, composites) are to be avoided for reef enhancement, even if such materials are used in wind farms as essential components of infrastructure. In addition, such artificial materials are an additional risk for the settlement of invasive species (Bracewell et al., 2012, 2013)."	Sas et al. (2023)

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		Primary production affected? E.g., Biomass of phytoplankton			
		Biological scale or life-stage considered?	+1	Experiments on facilitating larval settlement by providing suitable substrate and subsequent set of experiments to test whether post-settlement survival could be enhanced by reducing predation	Temmink et al. (2021)
			+1	"[...] hydrodynamic conditions near the sea floor are critical for flat oyster recruitment and subsequent reef restoration: currents and wave-induced turbulence in the North Sea may cause such dispersal of the start population and the larvae produced by it that no reef is formed"	Sas et al. (2023)

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				Focus on larval settlement and the presence/absence of existing reefs	Cook et al. (2021)
				"Larvae of many reef-forming species require hard substrata for settlement, including oysters (Michener and Kenny, 1991), mussels (Commito et al., 2014), tubeworms (Chapman et al., 2007) and sessile gastropods (Franzitta et al., 2016). This is often the accumulated shells or tubes of dead conspecifics (Chapman et al., 2007; Michener and Kenny, 1991). These may not be present in degraded habitats where reefs occurred historically. Shellfish-reef restoration methods can involve deployment of dead shells to reinstate recruitment. Methods of disturbing the sediment to resurface buried shells (harrowing) have proven ineffective (Bromley et al., 2016). Restored boulder reefs, or created artificial reefs that use boulders, can	Liversage (2020)

				be an alternative substratum for shellfish recruitment and maintenance of adults."	
			+1	Both larvae and adult stages are considered	
		Interactions between criteria considered?	+1	Effect of substrate and protection from predation considered	Temmink et al. (2021)
			+1	Interaction between hydrodynamics, larvae dispersal, bottom sediment mobility	Sas et al. (2023)
			+1	Yes, interaction between location and timing (seasonality) of restoration	Cook et al. (2021)
			+1	"By considering abiotic and biotic structural habitat components together, there is opportunity to enhance reef restoration, and	Liversage (2020)

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				maximise biological diversity and ecological functioning."	
		Success in reaching environmental goal measured i.e., rate of restoration?	+1	Bivalve biomass and survival (number of individuals) measured at end of experiments	Temmink et al. (2021)
			+1	"All tiles were stored in seawater and examined alive under a dissection microscope within 1 week of recovery. Serpulids were identified to species level and counted, small serpulids less than 2mm in length were recorded as *Serpulidae* spp."	Cook et al. (2021)
		Efficiency criteria			
		Safety and/or Risk considered? i.e. EIA/EIS, biosecurity			

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			+1	Implementation in intertidal settings, without vessels and/or divers, suggests a low-risk solution	Temmink et al. (2021)
			+1	"In addition, such artificial materials are an additional risk for the settlement of invasive species (Bracewell et al., 2012, 2013)"	Sas et al. (2023)
			-1	"Biosecurity issues mean that time-consuming quarantine procedures are required before movement of shells (and potentially live epibiota) between marine habitats (Brumbaugh and Coen, 2009)."	Liversage (2020)
			+1	Considerations of how well the structures would hold	Pineda-Metz et al. (2023)

			+1	"These findings are timely and of high importance as they address current biosecurity risks and limitations of seed oyster availability, as formulated in the Berlin Oyster Recommendation (Pogoda et al., 2019)."	Merk et al. (2020)
			+1	Considerations of operational and safety reasons for the approach and methods chosen	Goedefroo et al. (2022)
		Added environmental value considered?			
			+1	Focus on added value by habitat-forming organisms and ecosystem engineers	Temmink et al. (2021)
			+1	For each species, their ecosystem function and added value of restoration are described	Sas et al. (2023)

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			+1	"This loss in habitat forming organisms has led to the loss of ecosystem services such as carbon sequestration and a decline in biodiversity (Ulanowicz and Tuttle, 1992; Sebens, 1994; Cook et al., 2013; Lee et al., 2020)."	Cook et al. (2021)
			+1	"Here, I discuss concepts concerning five potential synergies: 1) boulders provide natural hard-substrata that initiates shellfish recruitment, 2) boulders produce beneficial hydrological heterogeneity, increasing recruitment of some shellfish species, 3) shellfish generate self-sustaining supplies of novel hard-substrata habitat used by boulder/cobble species thus expanding the original restoration site footprint, 4) large shellfish populations strengthen valuable ecological functions in boulder habitats, and 5) boulders and shells together increase	Liversage (2020)

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				overall diversity of available hard-substrata types, and thus of associated specialist species."	
			+1	"Due to their ecological value, Ostrea reefs are now a focus of European conservation measures aimed at protecting and restoring biogenic reef structures (BfN, 2020)."	Pineda-Metz et al. (2023)
			+1	"Flat oysters are sessile reef-building "ecosystem-engineers" (Smyth and Roberts, 2010; Rodriguez-Perez et al., 2019). Oysters provide key beneficial impacts to their surroundings (Cobacho et al., 2020). For instance, the physical characteristics of the oyster reef functions as a nursery for other species, which is a positive driver to the system's biodiversity (Smaal et al., 2015; Kerckhof et al., 2018). This not only enhances the primary productivity and ecological	Bos et al. (2023)

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				functioning of the habitat, but also has a beneficial impact to commercial fish stocks (Gilby et al., 2018; Bureau Waardenburg, 2020)"	
			+1	"Due to its ecological significance in terms of biodiversity and other ecosystem services, the species, and the habitat it provides, are defined as highly endangered by the OSPAR Convention" (OSPAR, 1998).	Merk et al. (2020)
			+1	"Mussel reefs have potential ecological effects on soft-sediment communities by altering the sediment characteristics, thus indirectly affecting infaunal communities (Ysebaert et al., 2009). The presence of mussel reefs can greatly increase bio-deposition rates compared to bare sediment areas and lead to a higher fraction of finer sediments and organic content (Kaspar et al.,	Goedefroo et al. (2022)

				1985; Kautskyand Evans, 1987). Changes in mud content and organic matter will directly affect infaunal community compositions (Dittmann, 1990; Kröncke, 1996)."	
		Food safety considered?			
		Upscaling considered?	+1	"[...] we calculated construction costs for four scenarios for bivalve ecosystems in which we upscale our specific experimental technique as an example"	Temmink et al. (2021)
			+1	Considerations of spatial scale of restoration (large-scale restoration to achieve self-sustaining reefs)	Sas et al. (2023)
			+1	"Existing reefs in the present study, therefore, might have provided a stronger settlement cue to the larvae at small spatial scales, such	Cook et al. (2021)

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				that a higher proportion settled on adjacent reefs rather than on other available near-by substrates such as tiles. Away from these reefs and/or as the larvae age, they may become less choosy and therefore more likely to settle on tiles."	
			+1	The hypothesized relationship between the extent of restored habitat patch and time since restoration is considered (e.g. Table 1)	Liversage (2020)
			+1	"The results of this study in combination with respective habitat suitability analysis (Pogoda et al., this issue) provide the necessary information to move forward and to realize upscaling operations. Following the strategies that have proven successful in the USA and in Australia, a reef established over a 2-ha area	Pineda-Metz et al. (2023)

				is recommended here, before scaling up to 10 ha (e.g., Gilles et al., 2018)."	
			+1	The study considers the future expansion in offshore farming in the Dutch North Sea by 2050, with potential sites suitable for oyster restoration. It suggests recommendations for future oyster restoration efforts.	Bos et al. (2023)
			+1	The results are used to draw conclusions on whether large-scale restoration measures can be implemented with hatchery-produced seed oysters	Merk et al. (2020)
			+1	Improvements in both the engineering and ecological monitoring aspects that need to be incorporated into future studies in order to scale up and make this new technique more	Goedefroo et al. (2022)

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				effective, are summarized in the article (see for instance Table 5).	
		Low maintenance?			
			+1	None of the studies mention the need for frequent (e.g. monthly) maintenance or replacement of parts	All case studies
		Legal aspects considered? E.g., Directives, MSFD, OSPAR			
			+1	Tables mentioning (inter)national legal and policy instruments and their applicability for shellfish	Sas et al. (2023)
				"European Habitats Directive," "EU Marine Strategy Framework Directive (Directive"	Pineda-Metz et al. (2023)

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				"[...] several European Union directives and initiatives have helped to foster flat oyster restoration efforts [...]"	Bos et al. (2023)
			+1	"Marine Strategy Framework Directive"	Merk et al. (2020)
		Remote monitoring possible? Y/N (divers, satellites, robots)			
			+1	For all studies, periodic monitoring can be carried out remotely (for instance, with divers, satellite, drones, robots)	All studies
		Decommissioning considered? (Biodegradable structures will not require decommissioning/test)			

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			+1	This study used biodegradable structures designed to facilitate bivalve reef recovery	Temmink et al. (2021)
			+1	Recommended choice of material is either natural or biodegradable one, to also be in line with current decommissioning guidelines for human infrastructure	Sas et al. (2023)
			+1	It is suggested that boulder reefs can be made of both biodegradable or non-biodegradable materials like concrete and brick	Liversage (2020)
			+1	Various biodegradable deployment methods were tested in this case study	Pineda-Metz et al. (2023)

			+1	Some of the materials for the dropper lines were biodegradable, and decommissioning took place at the end of the experiments	Goedefroo et al. (2022)