Technical report

AQUACULTURE in OFFSHORE WIND FARMS

in the Belgian part of the North Sea

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TABLE OF CONTENTS

GLOSSARY

Aquaculture longline: a rearing system in which the horizontal backbone is kept in the correct position in the water column with buoys and anchors.
BNS: Belgian part of the North Sea
CIA: Commercial and Industrial Activities
Dropperlines/droppers: ropes that hangs vertically in the water column
Dyneema rope: brand name of a strong, tear-resistant rope for winches and water sports, among other things
EMFAF: European Maritime, Fisheries and Aquaculture Fund
Epibionts: plant and/or animal organisms that grow on other plants or animals, but without causing any damage to the latter.
European Discard Ban: In 2014, the EU's landing obligation came into force with the aim of reducing discards and stimulating more selective fishing. It is part of the Common Fisheries Policy (CFP). It means that fishermen must keep their catches on board and land them, and that unwanted catches are deducted from the fishing quota.
FAO - Food and Agriculture Organization of the United Nations
Farm gate price: This is the market price of the product minus the sales costs (transport, marketing)
Fishing longline: A drifting longline is a fishing gear that consists of a mainline kept near the surface or at a certain depth by means of regularly spaced floats and with relatively long snoods with baited hooks, evenly spaced on the mainline. When using a set longline, the main line is set either horizontally on or near the bottom or less commonly near the surface.
IMTA: integrated multi-trophic aquaculture
IUCN - International Union for Conservation of Nature
IUCN status: indicates whether an animal or plant species is threatened with extinction in its natural habitat.
Juveniles: young animals or plants that are ready for cultivation to commercial size
Landing: seafood brought ashore by the Flemish fishing fleet (at the fish market (“vistrap”) in Ostend or fish auctions)
Lantern nets: closed net with several round platforms on top of each other, typical for the cultivation of scallops
Maripark: A maripark is a maritime business park at sea for which preconditions are created for shared use and sustainable entrepreneurship. Through shared use, wind farms can contribute to food production and nature development, in addition to renewable energy generation. The business park will be designed in such a way that local biodiversity and natural values are taken into account as much as possible. Management can be done by the private sector, the government or in private-public partnerships.
NID: Nature Inclusive Design
OSPAR Convention: Convention for the Protection of the Marine Environment of the North-East Atlantic
OWF: Offshore windfarm
Passive fisheries nets: the summary term for all fishing methods in which the net is stationary in the water. The fish has to swim in it voluntarily or is introduced with the current
PEZ: Princess Elisabeth zone, an offshore renewable energy development zone
Rederscentrale : federation that represents the Belgian fish industry
Screw anchor: a type of anchor that is drilled several meters deep into the ground
Sea food: is a general term for fish, crustaceans and shellfish
Suction anchor: a steel pole with a large diameter which is equipped with a lid at the top. With the help of submersible pumps, these are sucked into the bottom and serve as an anchoring point.
Sustainability: ecologically, economically and socially acceptable
UXO: unexploded ordnance

VAWT: vertical-axis wind turbine
VMS: Vessel Monitoring System is a satellite monitoring system that registers the activities of fishing vessels operating at sea.
WUR – Wageningen University & Research

LIST OF FIGURES

List of tables

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Global context

Europe's commitment to green energy remains a key objective. However, there is an emerging priority that demands immediate attention: food security (EC, 2021a; EC, 2021b; EC, 2022a; EC, 2022b; EC, 2023a; EC, 2023b; EFSCM, 2023; EFSCM, 2024a; EFSCM, 2024b; IPOL, 2023) and the need for a protein transition (EC, 2018; EC, 2020; Global Nutrition Report, 2021). Rapidly developing economies, particularly in Southeast Asia (such as China, Vietnam, South Korea, Indonesia, etc.), are driving changes in the import/export markets. For instance, China is not only the world's leading producer of shrimp (primarily from aquaculture) but also its largest importer. This has led to a decline in the availability of seafood exports to Europe, driving up prices (EU, 2023a; EC, 2023b). Given that Belgium's total self-sufficiency in seafood reached 16,932 tonnes in 2022 (https://landbouwcijfers.vlaanderen.be/visserij/totale-visserij/aanvoer-van-vis), while its seafood consumption that same year was a significant 97,000 tonnes (https://landbouwcijfers.vlaanderen.be/visserij/totale-visserij/consumptie-van-visproducten), it is clear that Belgium relies heavily on seafood imports. Therefore, increasing the local seafood production is crucial. This can be achieved by expanding commercial fishing, adopting aquaculture practices, and/or replenishing natural stocks that benefit both fisheries and aquaculture.

Context and objectives of the report

On 15 May 2023, the report "Vision development for Aquaculture in the Belgian part of the North Sea" (Van Maele et al., 2023a) was presented, outlining the results of the stakeholder process regarding options for aquaculture in the Belgian part of the North Sea. This initiative, spearheaded by former Deputy Prime Minister and Minister of Justice and North Sea, Vincent Van Quickenborne, was made possible through the Marine Environment Service of the FPS Public Health, Safety of the Food Chain, and Environment.

The aim of this process was to understand the perspectives of stakeholders concerning aquaculture, identify areas of agreement and disagreement, and provide recommendations for the development of aquaculture in the Belgian part of the North Sea based on these insights. Fundamental conditions for aquaculture in the Belgian part of the North Sea were proposed such as the use of native species and extractive farming methods. In addition, food production for human consumption was set as the primary goal. Regarding suitable locations for aquaculture in the Belgian part of the North Sea, the emphasis was placed on the importance of multiple-use of space.

As a follow-up to the stakeholder process, the authors of this report aim to present a comprehensive understanding of the aquaculture opportunities in the Belgian offshore wind farms. Specifically, this study addresses the following research questions:

- Which aquaculture species thrive in the Belgian wind farms, and are they candidate for commercial farming?
- What farming techniques can be employed for growing relevant aquaculture species in the Belgian wind farms?
- What modifications to the Belgian wind farms are necessary for the optimal integration of aquaculture, achieving a so-called Nature and Aquaculture Inclusive Design?

Strategy, basic knowledge and basic principles

This is not the first time a vision has been formulated to provide a clear direction for the development of marine aquaculture in the BNS. Various documents and initiatives have contributed to this effort, including different versions of the Marine Spatial Plan, the AquaValue project (9/2014 – 9/2015) (vliz.be/en/imis?module=project&proid=4518&printversion=1&dropIMIStitle=1), the National Aquaculture Strategic Plan under the European Maritime and Fisheries Fund (New National Aquaculture Strategic Plan NSPA 2021 – 2030 | Agriculture and Fisheries (vlaanderen.be)), and the vision document from the Blue Cluster (2023) (Vision on aquaculture in the Belgian North Sea | The Blue Cluster). These roadmaps have, either directly or indirectly, contributed to the initiation of several nearshore and offshore aquaculture projects in the BNS, such as Value@Sea (Anonymous, 2019), Edulis (Edulis: Offshore mussel culture in wind farms | BLUEGent (ugent.be)), Symapa (SYMAPA (Synergy between Mariculture & Passive Fisheries) | The Blue Cluster), UNITED (Home (h2020UNITED.eu)), and ULTFARMS (HOME | ULTFARMS). The insights gained from these projects serve as a crucial foundation for this study.

The marine ecosystem within the Belgian part of the North Sea faces immense pressure due to the high density of human activities. Therefore, the expansion of large-scale aquaculture must be approached in a regenerative or restorative manner. The objective is to foster the growth of a sustainable aquaculture sector. This aligns with the definition provided by The Nature Conservancy (IUCN), which describes offshore restorative aquaculture (ORA) as commercial or self-sustaining aquaculture that delivers direct ecological benefits, with the potential to achieve net positive environmental impacts (Restorative Aquaculture for Nature and Communities | TNC). The environmental footprint—both positive and negative—can be assessed across multiple domains, including water quality, CO2 emissions, and habitat loss. Additionally, the multi-functional use of space, combining energy and food production, fits well within this vision.

Within this study, the authors first examined the feasibility of integrating aquaculture activities into existing offshore wind farms (OWFs) or those already subject to tendering procedures. This "short-term" analysis identified several strict preconditions that significantly limit the deployment of commercial aquaculture activities. Looking ahead, modifications to OWF designs will likely be required to better accommodate aquaculture integration. This includes OWFs yet to be constructed without an established tender procedure, as well as those slated for repowering. According to the document

"Vision trajectory on decommissioning" (Van Maele et al., 2023b), the prevailing expectation is that repowered wind farms will be entirely dismantled.

A clear distinction was made between OWFs located within Natura 2000 areas and those outside, given the special protections afforded to these sites. This study, therefore, concentrates on opportunities for aquaculture development within wind farm zones, categorized into three groups (Table 1 & Figure 1).

Table 1 Classification of wind farms according to construction phase

	No tender procedure yet	Existing tender procedure[1]/ already built
Outside Natura 2000 Habitats Directive area	Category 1	Category 3
Applicable on (Royal Decree of 3 June 2024)	Repowering Eastern Zone Repowering PEZ I & PEZ II part 1	Eastern zone PEZ I & II part 1
Within Natura 2000 Habitats Directive area	Category 2	
Applicable on (Royal Decree of 3 June 2024)	Repowering PEZ II part 2 & III	PEZ II part 2 & III
implication	Co-design +/- Natura 2000 restrictions	Multiple use of space +/- Natura 2000 restrictions

In the short term, recommendations focus on OWFs that have already been built or those for which a tender procedure is in place. The aquaculture systems and species will be adapted to the existing layout and conditions of these OWFs (Cat. 3). Particularly in the short term, it appears advisable to first determine the most suitable techniques for application in OWFs before selecting the aquaculture species to be farmed, ensuring that environmental parameters are also favourable.

For OWFs that are yet to be constructed or repowered without an established tender procedure (Cat. 1), there is a strong emphasis on the principle of integral design or co-design. This approach considers the requirements for developing a profitable and sustainable aquaculture sector that contributes positively to the environment. It is crucial that the tender procedure incorporates preconditions for an integrated multi-use approach, facilitating the transition from co-location to full integration, with a strong focus on creating synergies.

[1] For the Princess Elisabeth zone, through the Royal Decree of 3 June 2024 establishing the competitive tender procedure, the conditions and the procedure for granting the domain concessions and the general conditions for the use of the plots for the construction and operation of an installation for the production of electricity from renewable energy sources in the sea areas under the jurisdiction of Belgium

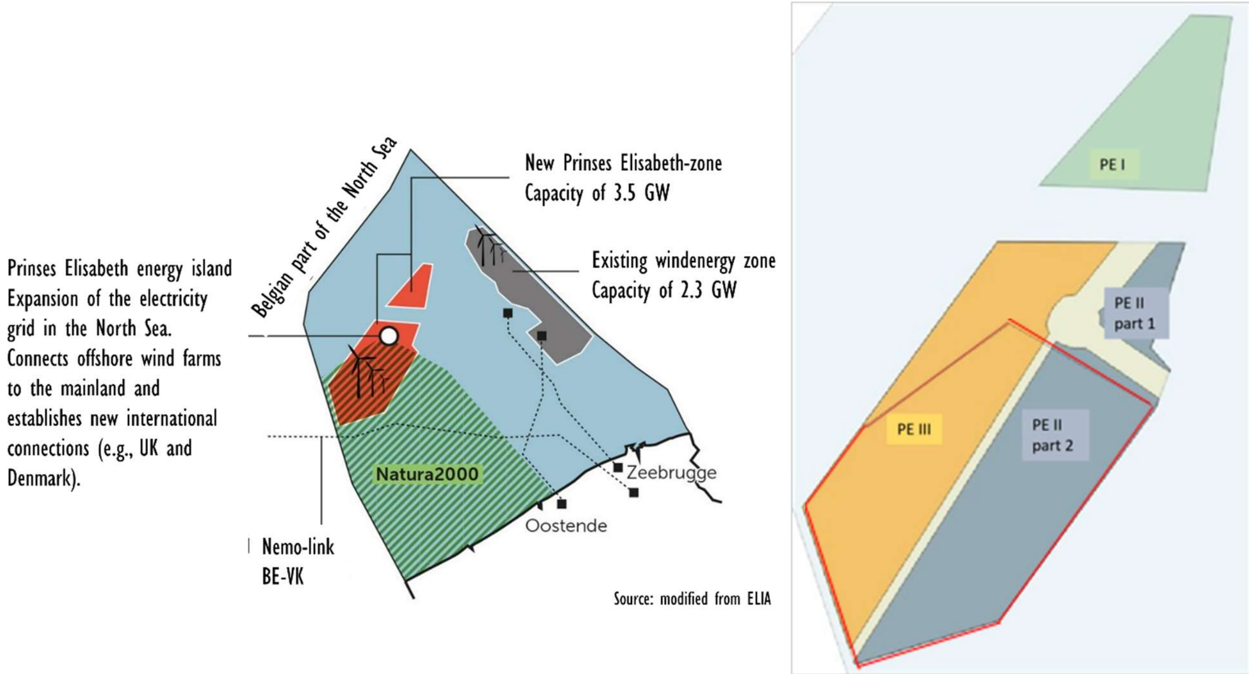


Fig. 1. Location of offshore wind farm zones (top, source: Belgian dredging companies Jan De Nul and DEME have been awarded permission to build 'energy islands' in the North Sea | De Morgen) in BNS and parcelling of the Princess Elisabeth zone (below, source: Identification of the sites for the construction of wind farms in the Belgian North Sea | FPS Economy (fgov.be)). The red line shows the overlap between the Natura 2000 area that coincides with PEZ.

PEZ II part 2 and PEZ III (Cat. 2) are partially located within a Natura 2000 zone (Fig. 1) and are subject to the specific condition that aquaculture activities may only take place if the areas maintain a favourable conservation status. Therefore, an assessment was conducted to determine how aquaculture could support the acceleration of achieving this favourable conservation status while ensuring compliance with the environmental permit and the Natura 2000 permit.

To ensure integration and accessibility for all entrepreneurs, it is essential that proposed plans receive broad support. Consequently, consultations were held with the Belgian Offshore Platform (BOP)(13/03/2023), Annex 7) and the Rederscentrale (18/03/2024, Annex 3).

Structure of the technical report

This study consists of six work packages, with the first three providing a broad yet detailed overview of existing aquaculture techniques (WP1), potentially suitable aquaculture species for the BNS (WP2), and the key preconditions that offshore aquaculture must meet within an OWF (WP3).

WP1 categorizes farming techniques into three main types: intensive systems, sea ranching, and population-support measures for commercial species. The integration of intensive cultivation systems into offshore wind farms can be approached in different ways: (1) as stand-alone systems, (2) using the turbine as an anchoring point, or (3) through full integration enabled by co-design. Where applicable, reference is made to Belgian experiences with these techniques in the North Sea.

WP2 presents an overview of all commercial seafood available at fish auctions (Belgian and European) and a list of seaweed species with aquaculture potential. From this selection, species are identified as candidates for offshore aquaculture based on factors such as market price, conservation status, native character, and ecological value.

WP3 outlines the key preconditions necessary for integrating aquaculture into wind farms, drawing from literature research and interviews with the BOP and the Rederscentrale. These preconditions are grouped into several categories: social acceptance, creation of positive environmental impact, economic viability, legal framework, and conditions imposed by OWFs.

The final three work packages (WP4 – WP6) develop integration scenarios for aquaculture and wind energy, depending on the construction phase of the later (Table 1). The integration process differs between OWFs with belonging to Category 3 (WP4) and those where tender procedures and park design have yet to begin (WP5). Additionally, aquaculture activities within OWFs located in Natura 2000 zones must meet additional specific requirements (WP6). These work packages define framework conditions, propose scenarios (matching systems with species), and offer recommendations to facilitate integration.

Given that a fully integrated design is not feasible for Category 3 OWFs, WP4 scenarios are based on cultivation techniques (WP1) that function independently of wind turbines, along with species that can be cultivated using these techniques (WP2). The proposed approaches are ranked from easiest to most complex to implement.

Solutions presented in WP4 are not repeated in WP5, as all options viable for Category 3 OWFs can also be applied to Category 1 OWFs. However, the range of potential aquaculture species is broader in WP5, as integrated designs offer more cultivation possibilities. While some innovative and relatively untested technologies remain long-term prospects, they hold promise for fully integrated systems.

WP6 focuses on the limited scope for aquaculture development within OWFs located in Natura 2000 areas (e.g., Fairy Banks). Strict environmental conditions apply, and aquaculture integration is only feasible if it actively contributes to maintaining a favourable conservation status for seabed habitats.
Recognizing the tender procedure as a crucial tool for mandating multi-use of offshore space, future tenders for OWFs (Category 1 & 2) should incorporate additional award criteria, such as food production through aquaculture and/or nature restoration, as well as relevant environmental permit conditions.

The report concludes with key reflections (Conclusion) distilled from stakeholder meetings organized by the Institute of Natural Sciences, consultations with the BOP and Rederscentrale, literature review, insights from national and international offshore aquaculture projects (whether combined with energy production or not), and the authors' own experiences from various Belgian and international initiatives.

WP1: Growing techniques for OWFs

1.1. General

Various methods are employed for cultivating commercial species in marine environments. This chapter outlines the breeding techniques, categorized into three main types for this study: intensive systems, sea ranching, and population-support measures (stock enhancement). Since seabed-disturbing fishing is prohibited in Belgian OWFs, passive fishing techniques must be utilized for the latter two aquaculture forms when harvesting animals within the wind farm. Outside the concession zone, harvesting is subject to standard fishing regulations.

In intensive systems, target species are farmed at high densities. Typically, mobile species like fish are cultivated in nets, baskets, and cages, while non-mobile species such as shellfish are grown on the seafloor or on structures designed to keep them in place. The choice of cultivation technique primarily depends on the species being farmed, as well as the surrounding environmental factors. Local conditions such as currents, nutrient levels, vegetation, sunlight, oxygen content, depth, and sediment type all influence the farming method.

Sea ranching, or herding fish (open sea farming), is a distinct form of aquaculture in which the farmer nurtures populations before harvesting them. Various techniques can enable sea ranching. For instance, juveniles may be introduced (“stock enhancement”) to bolster local populations. In the case of mobile species such as fish, the fingerlings are raised with the introduction of stimuli (such as sound, light, or smell) tied to feeding (Pavlovian conditioning). The farmed fingerlings are then released and conditioned through supplementary feeding (“treats”) to remain in the area. Since the fish primarily feed on natural prey, the nitrogen (N) and phosphorus (P) input from feed can be kept lower than the amount of N and P that is extracted when fishing the conditioned fish, resulting in a negative net nutrient balance (= extractive mariculture). Social facilitation amplifies the conditioning effect, where naïve (non-conditioned) fish join the trained individuals and learn through observation, increasing in this way the total conditioned biomass. Once the fish reach the minimum market size, they can be selectively harvested using the same luring methods. Sea ranching can also occur without introducing juveniles. In this case, locally present animals are conditioned by placing an artificial reef that provides both shelter and natural food. The stock is considered the property of the farmer or farmers’ organization. A notable example is the National Lobster Hatchery Cornwall in the United Kingdom, which farms, releases, and harvests lobsters (Ellis & Boothroyd, 2008).

In this study, population-support measures (stock enhancement) are also regarded as an aquaculture technique if the goal is to boost commercial stock species. This involves similar steps to sea ranching, where juveniles are introduced, and artificial structures may be installed. An intriguing alternative is the restoration of biogenic reefs, gravel beds, and their associated communities, which can provide nutrition, protection, shelter, and spawning grounds for the target species. However, in this scenario, the increased population is considered to belong to the community, rather than being the property of a single entrepreneur or group.

1.2. Intensive Cultivation Systems

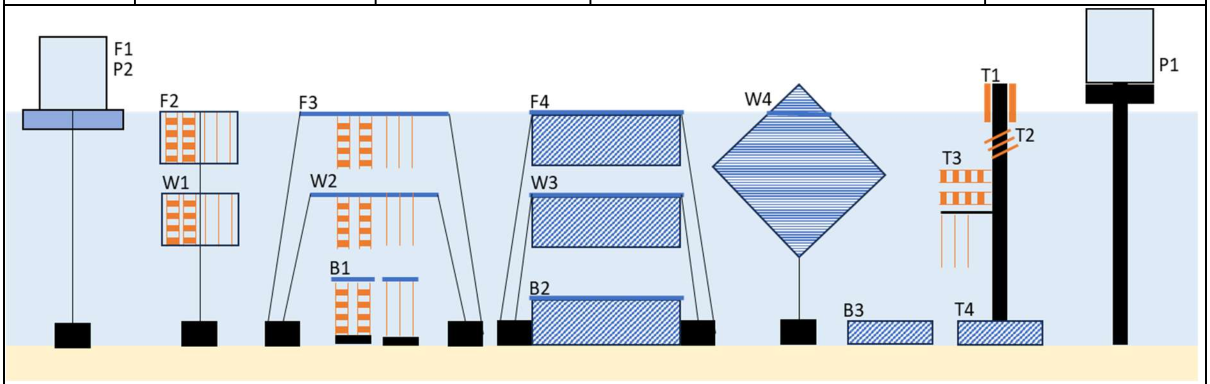
The integration of breeding systems within OWFs can be implemented in several ways, and for practical purposes, this study categorizes them into three types: (1) stand-alone systems, (2) systems using turbines as anchors, and (3) fully integrated systems (Table 2, Photos Annex 1). Intensive systems can be set up as independent units within wind farms. These systems can be placed between the wind turbines or within the 500m wide safety zone surrounding the concession area of an OWF. The anchoring of these systems can either be completely independent or utilize the existing infrastructure of the OWFs (such as turbine foundations or substations). While this dual-use approach is theoretically sensible, it would require a complete redesign of the turbines or substations to withstand the additional forces. The current OWF infrastructure is not designed for such use. For practical and innovative reasons, intensive aquaculture systems should be fully integrated with the offshore wind infrastructure during the wind farm's design phase and incorporated into its layout. Another possibility is the creation of multi-use platforms, which can serve for transshipment, energy production and storage, aquaculture, offshore personnel accommodation, and more. These platforms can be either fixed or floating. The latter option offers the greatest potential for developing aquaculture activities in synergy with offshore energy production.

1.2.1. Stand-alone systems

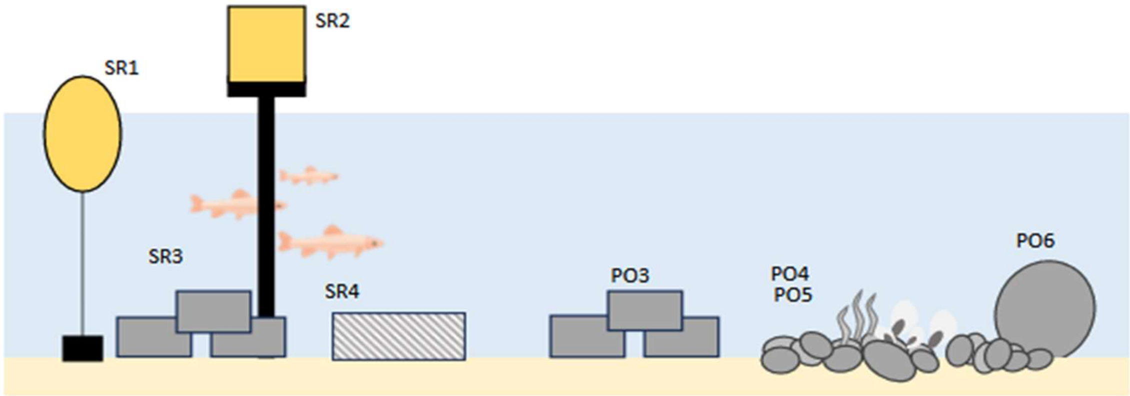
Intensive aquaculture systems typically consist of four components: the anchoring, an anchoring line, a farming system, and a floating device. The anchoring can be achieved using screw anchors, weight anchors, burrowing anchors, or post anchors. The choice of anchor type depends on factors such as depth, the composition of the seabed, and the forces acting on the anchor.

Table 2 List of potential intensive culture techniques, sea ranching and population-support measures

Code	Anchoring	Flotation device	Production system/technology	Target species
Intensive culture techniques				
Intensive stand-alone culture – Floating **(F)**				
F1	Single or multiple	Ship, Island, Raft	Tanks (recirculation systems, flow-through systems)	All
F2	Single	Raft, buoy	Ropes, sticks, baskets, nets	Bivalves, seaweeds
F3	Double	Buoys, floating backbone	Longline with droppers, baskets, sticks, nets	Bivalves, seaweeds
F4	Multiple	Buoys, floating tubes	Floating net cages	Fish
Intensive stand-alone culture - In the water column **(W)**				
W1	Single	Buoy	Shellfish towers, baskets	Bivalven
W2	Double	Tubes, submersible backbone	Longline with droppers, baskets, sticks, nets	Bivalven
W3	Superior	Buoys, tubes, submersible buoys	Net cages, submersible cages; metal cages	Fish
W4	Single	Floating tubes, submersible buoys	Net cages	fish
Intensive stand-alone culture – Bottom **(B)**				
B1	Single	Buoy	Standing ropes	Bivalven
B2	Double	Buoy	Standing wall netting	Bivalven
B3	None, anchor	None	Cages, pots, round cage nets, fence	Flatfish, bivalves, crustaceans
B4	None	None	None	Bivalven
Turbine as anchorage (T)				
T1	Turbine	None	Turbine itself	Mussels
T2	Turbine	None	Turbine with protection	Mussels
T3	Turbine	None	Ropes, baskets, droppers, nets	Bivalven, seaweeds
T4	Turbine	None	Cages	Flatfish, bivalves, crustaceans
Full integration (P)				
P1	Platform fixed	None	All, including tanks (recirculation systems, flow-through systems)	All
P2	Platform floating	Different	All, including tanks (recirculation systems, flow-through systems)	All



Sea ranching (SR)				
SR1	Single anchoring	Buoy	Feeding buoy	Fish, crustaceans
SR2	Platform fixed	All kinds	Feeding platform	Fish, crustaceans
SR3	Own weight	None	Artificial reefs (habitat, food supply, shelters, substrate)	All
SR4	Own weight	None	Demarcation on the bottom	Bivalven
Population-support measures (PO)				
PO1	None	None	Introducing juveniles	All
PO2	None	None	Introducing broodstock	All
PO3	Own weight	None	Artificial reefs	All
PO4	Own weight	None	Restoration biogenic reefs	All
PO5	Own weight	None	Creation of biogenic reefs	All
PO6	Own weight	None	Restore natural non-biogenic reefs (gravel, boulders)	All



Anchoring lines link the anchors to the cultivation system and can be made of chains or ropes. The *growing systems* are species- and location-specific, with a wide range of systems available commercially today. These can include floating fish cages, rafts, or longlines, from which various substrates or husbandry systems hang, such as ropes, nets, baskets, cages, and more. The *floating device* ensures that the culture system remains afloat or suspended in the water column and can consist of buoys, floating tubes, caissons (which are filled with water to sink), or floating platforms. This category also encompasses the use of self-propelled floating devices, such as aquaculture vessels. Photos of commercially available breeding systems are provided for reference in Annex 1. A list of various commercially available culture systems is also available in the MARIPAS report (Verhaeghe et al., 2011).

Experience in Belgium

Offshore aquaculture projects (both offshore and nearshore) in Belgium that utilize stand-alone systems are summarized in Annex 2. An overview of the techniques employed is provided, highlighting the main advantages and disadvantages experienced during pilot projects, as well as one commercial project. The Department of Marine Technology at UGent has developed expertise in calculating the forces acting on longline systems. This expertise is used to guide the design of longlines through an interactive process.

1.2.2. Turbines as anchors for mariculture systems

There are various techniques for integrating wind energy production with mariculture, where the turbines serve as anchoring points for the mariculture installations. For example, Buck et al. (2017a) provided several examples of breeding installations that could be attached to the turbines (Fig. 2). As the breeding species and biofouling increase in weight as they grow, the forces acting on such an installation become significant and must be absorbed at the anchor points. This means these forces will be transferred to one or more turbines, depending on the design. Currently, offshore wind farm designers do not consider this. However, if turbines are to be used as anchors for mariculture installations in the future, wind farm operators are advised to factor this into the turbine design phase to maximize the potential and achieve the most innovative results.

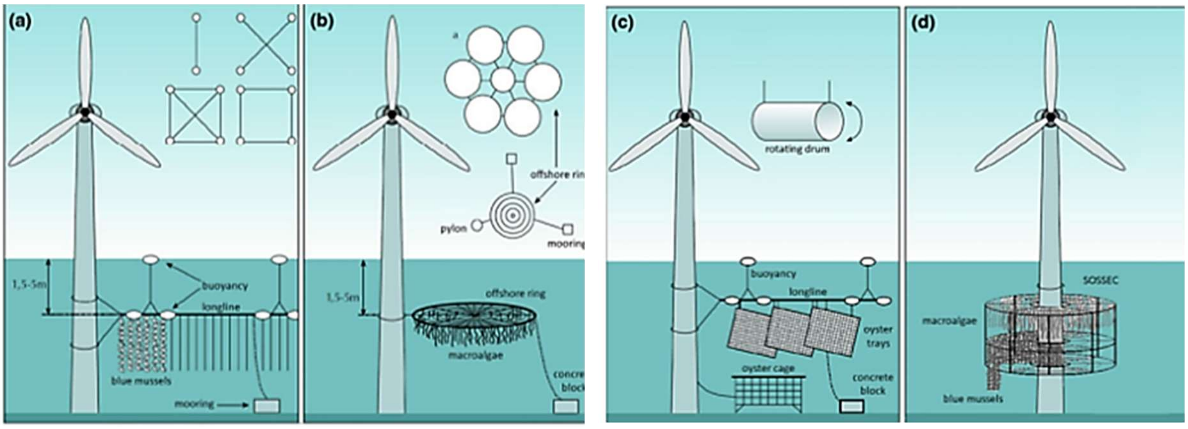


Fig. 2 Various designs of mariculture installations combined with offshore wind farms: a) A longline system for mussels or seaweed anchored to the turbine. At the top right an overview of longline constructions in a bird's eye view. The longline can have a length of 100 to 300 m; b) A ring construction for the cultivation of seaweed. At the top right a ring construction in a bird's eye view. The combined rings are fixed around the turbine and each anchored by attachment to the turbine and two anchorages (weight anchors); c) An oyster cage on the bottom attached to the turbine and a longline with oyster baskets. At the top right a rotating drum for oysters; d) SOSSEC (Submersible Offshore Shellfish and Seaweed Cage) design, which is underwater during cultivation and can be lifted to the surface for harvest. (Buck et al., 2017a; Images AWI/Prof. Dr. Bela H. Buck).

A significant amount of research is already underway to combine various forms of energy at sea, with several studies and pilot projects exploring the use of turbines to anchor systems that generate wave or tidal energy. These examples can serve as inspiration for the direct attachment of aquaculture systems to the turbines (Fig. 3).

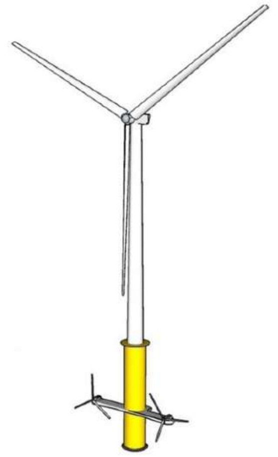
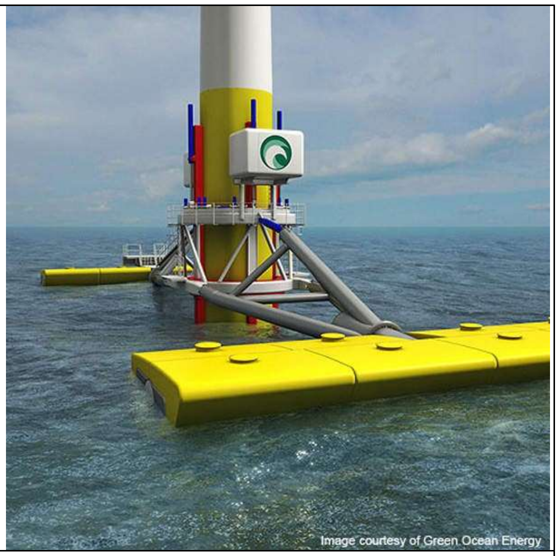
		
Nasab et al., 2022	Perez-Collazo et al., 2019	Green Ocean Energy Wave Treader - Renewable Technology (renewable-technology.com)

Fig. 3 Examples of attaching energy systems to wind turbines for inspiration

1.2.3. Total integration

Floating wind turbines (or, more broadly, floating energy platforms) offer greater potential for the full integration of energy with aquaculture. For example, several prototypes have been designed in China. In Fujian province, Longyuan Power Group and Shanghai Electric Wind Power Group (a subsidiary of Shanghai Electric) have completed the world’s first maritime renewable energy project combining floating offshore wind energy production with aquaculture (Fig.4). The platform consists of three semi-submersible columns, featuring a 4 MW turbine and flexible solar panels mounted on one of the columns. At full capacity, the platform can generate 96 MWh of electricity per day. In the centre, the platform includes a hexagonal space that can be utilized for fish farming. The platform operates in waters with a depth of 35 m (https://renewablesnow.com/news/longyuan-completes-maritime-floating-wind-plus-solar-project-in-china-838787/).

Fig. 4 Energy platform with integrated fish cage, designed by Longyuan Power Group and Shanghai Electric Wind Power Group (China) (https://renewablesnow.com/news/longyuan-completes-maritime-floating-wind-plus-solar-project-in-china-838787/)

Zheng et al. (2020) propose a floating platform that integrates wind energy (VAWT), solar energy, and fish farming (Fig. 5). The top of the fish cage serves as the foundation for the turbines and solar panels. The feasibility of such a platform has been demonstrated in the offshore conditions of the South China Sea (depths of 100-200m), where fish production significantly accelerates the payback period for the energy production systems.

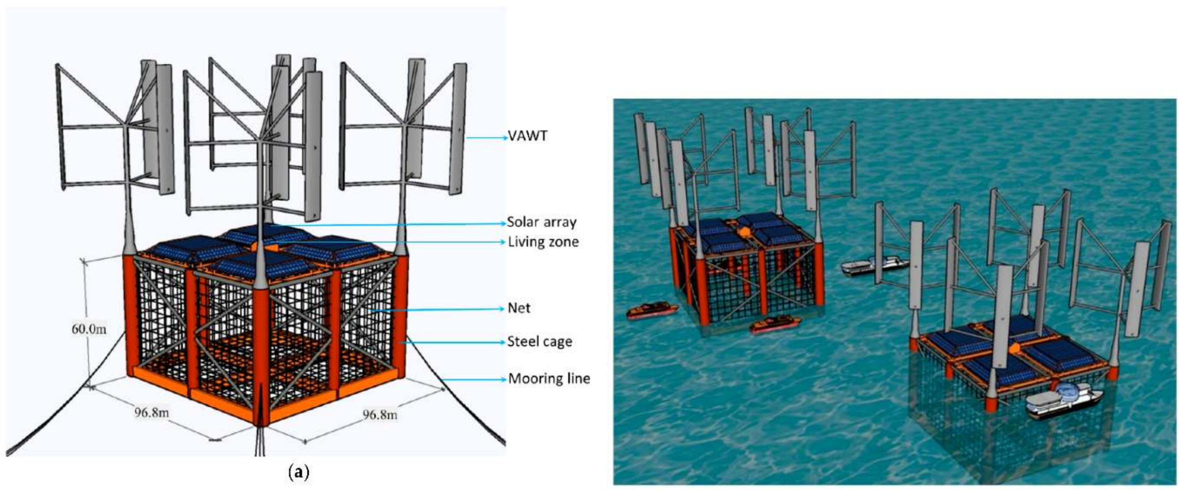


Fig. 5 Design fish cage integrated with floating energy platform with 4 windturbines (VAWT) and solar panels (Zheng et al., 2020)

Closer to home, there is the AQUAWIND project – an innovative multi-use prototype combining offshore renewable energy and aquaculture in the Atlantic Basin (2022-2025). The project aims to implement a fully integrated system featuring a floating energy platform paired with a fish cage. The W2Power floating energy platform prototype, equipped with a specially designed fish cage made from new net material, will be used for this. The project focuses on extensive digitization while the promotion of wide species diversity also features on the research agenda (Fig. 6).

Fig. 6 Left: Design of the W2Power floating energy platform with the fish cage in the centre; Right: The W2Power energy platform at the coast of the Canary Islands (https://cinea.ec.europa.eu/featured-projects/aquawind-innovative-multi-use-prototype-combining-offshore-renewable-energy-and-aquaculture-atlantic_en).

Floating wind turbines are more costly than monopiles, and in the BNS, connecting to the cable network presents challenges due to the wave regime (source: BOP consultation). An in-depth example of an integrated monopile with aquaculture systems is provided by Zhu et al. (2022). In this example, the turbine is equipped with a wave diffraction system, which is combined with a net cage system for fish farming (Fig. 7).

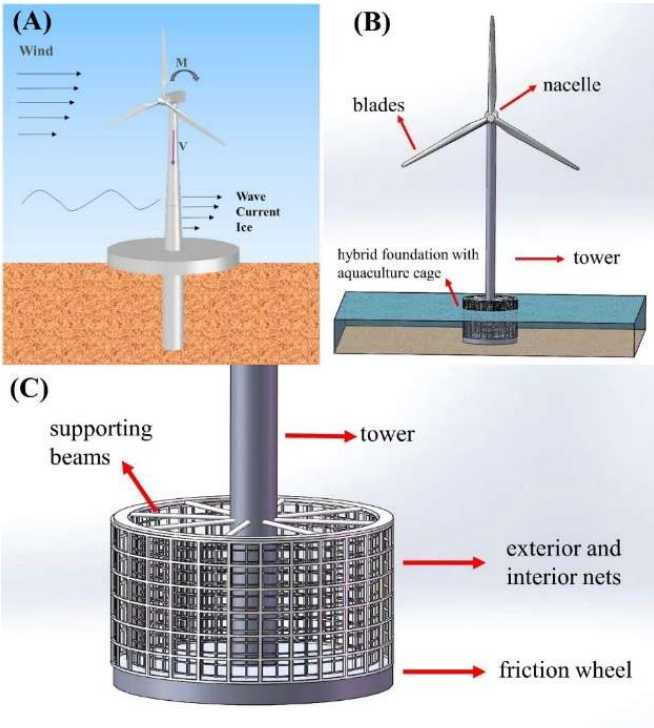


Fig. 7 Combination of a wave diffraction system with a net cage system for fish farming. A) Hybrid monopile foundation with a friction wheel (Wang et al., 2018); B) Hybrid monopile foundation with a double net cage structure; C) Details of the hybrid monopile foundation with a double net cage structure (Zhu et al., 2022).

1.3. Sea ranching

Sea ranching, or herding fish (open sea farming), is a unique form of aquaculture where the farmer supports populations before harvesting them. The stock is considered the property of the aquaculturist. Various techniques can be used: conditioned juveniles can be released to enhance local populations (stock enhancement), or artificial reefs can be installed to support or keep the target species in place. These artificial structures provide nutrition, protection, habitat, or reproductive opportunities. In cases without the introduction of juveniles, locally present mobile species can be conditioned by offering food (Pavlovian reflex), thus luring or keeping them on-site. The target species can then be harvested within the wind farm using passive fishing techniques or, using the luring stimuli, with traditional fishing methods outside the wind farm.

Sea ranching, or the open sea farm technique, has been practiced in several countries for many years, for both fish and shellfish. In Japan, as early as 1936, scallop seed (*Patinopecten yessoensis*) was sown on the bottom in Hokkaido Bay. Historically, sea ranching and bottom fishing in Hokkaido have contributed about 40 to 45% of Japan's total scallop production (approximately 120,000 tons/year). The steady landings of these shellfish are credited to sea ranching, where the spat is collected and then sown on the seabed, with young animals being protected against predation (274274.pdf; dfo-mpo.gc.ca). Japan has been exceptionally successful in recapturing the animals (34.5%), and the economic efficiency (the ratio of net income to the cost of restocking) is 460% (Kitada 2018 in Liu et al., 2022). The Japanese experience is invaluable and serves as a model for the rest of the world.

In Norway, tests were conducted with Atlantic cod (*Gadus morhua*), Atlantic salmon (*Salmo salar*), brook trout (*Salvelinus alpinus*), and European lobster (*Homarus gammarus*). Only sea ranching for lobster proved profitable. At the start of this century, the Institute for Marine Research also investigated the potential of growing scallops (*Pecten maximus*) in an open sea farm. However, predation from crabs turned out to be one of the major issues, so some form of protection, such as a "fence," was deemed necessary (HI presentation blue english; mote.org).

In Australia (Flinders Bay), new developments are underway for breeding abalone (*Haliotis laevigata*), where hatchery-bred juveniles are allowed to forage freely on the ocean floor for two years. However, the animals are kept in place by providing hard substrate in the form of artificial reefs, known as "Abitat" (A World First - Ocean Ranching - Rare Foods Australia) (Fig. 8).

Fig. 8 Introduction of the artificial reef "Abitat" keeps the released young abalones from the hatchery in place until harvest two years later (Flinders Bay, Australia) (A World First - Ocean Ranching - Rare Foods Australia)

In general, it can be said that predation pressure is often the biggest challenge, making the size of the juveniles at the time of release a crucial factor for their survival. The percentage of animals that are recaptured is often very low. In China, the recapture rate is 10% for crabs and only 1-2% for fish, jellyfish, and shrimp (Liu et al., 2022).

Table 3 Comparison between open sea farm, aquaculture in fish cages and fisheries (adapted from Muir, 1998)

	Open sea farm	Aquaculture/Cages	Fishery
		Production-related	
General expenses	High; farming or purchase of fry, conditioning equipment, monitoring, artificial reefs, fishing vessels, nets	High; farming or purchase of fry, cages, feeding systems, mooring jetties, maintenance vessels	Medium-high; fishing vessel, nets, peripheral equipment
Feed costs	Very low-low; enough to condition and as a supplement	High; food for a complete life cycle + high quality	None
Labour	Low; basic knowledge plus fishing techniques	Medium; depending on the automation	Variable; depending on the scale and type
Harvest complexity/cost	Low-medium; depending on the fish response	Low; harvesting cages	High; depending on the nature of the stocks
Risk of loss/damage	Low-medium; depending on the fish response	High: there are no fish cages that have yet been fully tested offshore in the North Sea	Low; occasional breakage at the net
		Product bound	
Reliability	Medium; depending on the variety, production and harvest, control is necessary	High; selective breeding with high quality and planned yield	Low; depending on the species and season
Growth and health	Medium-good; depending on the released fry	Medium to good; depending on food source and disease control	Variable; depending on selectivity,
Quality	Medium-high; depending on catch and handling	High-very high; provided that modern techniques are used	Variable; depending on the catch and handling
Number of species	Medium-high; depending on production, wild stocks	Low; a single species, no wild stocks	Medium-high; depending on the selectivity, usually wild stocks
		Environment-related	
Local species	Depending on the fry	No; usually selective breeding	Yes; Wilde Stocks
Bycatch/discards	Low-medium; depending on efficiency and selectivity	Not	Variable; depending on the selectivity and the fishing conditions
Biodiversity	Medium-high; depending on the fry and the environment	Low; Chance of damage when the stock escapes	Variable; depending on the fishing pressure
Visual disturbance	Low-medium; small and non-obstructive	Medium-high; very large structures, obstruction to shipping, continuous activity	Low; Traditional activity, frequent, widely accepted
Waste discharge	Low-medium; depending on the degree of supplementary feeding and aggregation	Medium-high; depending on spread and treatments	Low-fractional; possible boat and used waste
		Social/community bound	
Use of existing fisheries assets	Medium-high; depending on the fishing requirements	Low-medium; usually separate infrastructure	Variable; depending on future fishing activities and regulations
Control over resources	Medium-high; depending on the system used	Low-medium for local community	Variable; depending on the fishing regime, can be very low
Potential for community management	Medium-high; depending on the system used	Low; large companies, mostly multinationals	Variable; depending on the fisheries and traditions

Table 3 provides a comparison between the open sea farm, aquaculture in fish cages, and traditional fisheries. It shows that an open sea farm can offer certain advantages under specific conditions, particularly in terms of environmental impact and in locations where traditional fishing methods are difficult or impossible, such as within an offshore wind farm.

Experience in Belgium
The project "Aquavalue - A Roadmap for Sustainable Aquaculture in Flanders" concluded that sea ranching (Pilot 4) is one of two viable options for performing aquaculture within OWFs (alongside Pilot 3 - extractive aquaculture in OWFs) that are financially and economically feasible. By placing an artificial reef designed specifically for sea bass and considering the fact that bottom trawling within the OWFs is prohibited, the local production of sea bass can be increased. Passive fishermen, provided they have the appropriate license, can then fish very specifically for this target species. In the UNITED project, flat oyster farming was identified as a method for reintroducing flat oyster brooders and young flat oyster spat to the BNS to support the restoration of natural oyster reefs. Over the long term, the reef would produce oyster larvae that could be captured by the farmer. This approach would allow the sector to become independent of hatchery-produced spat, which would enhance the profitability of the business.

1.4. Population-support measures (*stock enhancement*)

1.4.1. What are population-support measures?

Population-supporting measures enhance the productivity of the ecosystem. On the one hand, target species can be bred or caught as juveniles, and once they are large enough to protect themselves from predation, they can be released. On the other hand, target species can be supported by providing substrates that offer protection, nutrition, and spawning opportunities, by restoring natural habitats, or by creating new habitats. Depending on the level of replenishment intended, this is referred to as restocking (the replenishment of a severely depleted, reproducing biomass) or stock enhancement (the strengthening of weak year classes or overfished stocks).

Restocking is very challenging in seas and oceans due to the low effective biomass (the portion of the fish stock that actually participates in reproduction), which is only a fraction of the total biomass (e.g., 0.01 – 0.001% for plaice in the North Sea) (Bell et al., 2006). This method is most useful for replenishing the spawning stock of fish species in low numbers, such as certain strains or subspecies of salmon, particularly in river systems.

The target species can be harvested using passive fishing techniques within the OWF or with traditional fishing methods outside the OWF (the so-called spill-over effect). Unlike sea ranching, the stock in this case belongs to the community. These population-support measures may be selective for a particular target species or may generally support ecosystems. Given the wide range of applications, we will now explore some of the techniques that can be used to support specific commercial species.

1.4.2. Stock enhancement via the introduction of juveniles

Species that qualify for stock enhancement are relatively limited in Europe, as only for a few species hatchery techniques can be scaled up to an industrial level: cod (*Gadus morhua*) (Svåsand et al., 2000, Støttrup et al., 2008a), sea bass (*Dicentrarchus labrax*), sea bream (*Sparus aurata*), catfish (*Anarchis lupus*), turbot (*Scophthalmus maximus*) (Støttrup & Sparrevohn 2010), halibut (*Hippoglossus hippoglosus*), sole (*Solea solea*), Senegalese sole (*Solea senegalensis*), plaice (*Pleuronectes platessa*), lobster (*Homarus homarus*), oysters (*Magallana gigas* and *Ostrea edulis*), scallops (*Pecten spp*. and *Chlamys spp*.), carpet shells (*Tapes* spp.) and mussels (*Mytilus* spp.).

Experience in Belgium

In 1998, ILVO conducted a stock enhancement experiment with **turbot** (*Scophthalmus maximus*) as part of the 5b project – 5BW/EOGFL29B/A.4.1. The primary goal of this project was to explore the possibilities of stock improvement for turbot within a national context. To achieve this, 3000 juveniles were purchased and kept until they reached a size suitable for adaptation to wild conditions. After conditioning with natural prey organisms (such as shrimps and gobies), about 1900 juveniles were tagged with a Petersen disc and released in June 1998 in an enclosed area on the Baland Bank near the Belgian coast. Buoys were placed to indicate that fishing was prohibited in this area. After a year and a half, the recapture rate was more than 15%. During this period, biological aspects related to migration, survival, and growth were assessed through the marks returned by the fishermen (together with the fish).

The spatial distribution showed that most individuals remained in the Belgian coastal waters until October of the release year. During winter, the turbot migrated to deeper waters in the Central North

Sea. In spring, a reverse migration occurred, with the turbot returning to the shallower coastal waters, particularly along the coasts of the Netherlands, France, Belgium, and the United Kingdom. Additionally, data from stomach analyses and growth patterns indicated that the released turbot adapted well to natural conditions, exhibiting similar growth and feeding patterns to the wild population (Delbare & De Clerck, 2000). In subsequent years, up to 30% of the released turbot were reported back, which closely matched the fishing mortality rate for the species in the area. This experiment clearly demonstrated the potential of stock enhancement or turbot restocking. The project was followed up by a PODO 1 initiative, which focused on improving juvenile turbot quality before release and assessing the technical and economic feasibility of establishing a turbot farm for stock enhancement purposes.

Between 2000 and 2001 (on 29/06/2000, 18/12/2000, and 18/06/2001), a total of 1222 farmed and tagged sole (*Solea solea*) were released in the same area, which was once again closed to commercial fishing for 3 months. The few recaptures showed that the released sole remained near the coast for the first two years before moving to deeper waters. The feedback rate was very low during the project, at only 0.9%. This low rate of recapture was explained only five years after the experiment. The coastal fishery community believed the experiment was a hidden study to determine how much young sole was being fished and would lead to restrictive measures. As a result, they decided not to report any recoveries. However, over the years, sole with ingrown marks or tags were landed, showing that some of the released animals did indeed survive.

As in the rest of Europe, there is significant interest in Belgium in reintroducing the flat oyster (*Ostrea edulis*) to the BNS after its decline due to overfishing in the last century (Kerckhof et al., 2018). Recently, research in Belgium has focused on using the remote setting technique to sow artificial substrates with oyster spat. The Belreefs project, launched by the Federal Public Service for Health, Food Chain Safety and Environment, aims to re-introduce an oysterreef in the Hinderbanken and is carried out by the consortium of Jan De Nul, KBIN, Mantis, and Shells & Valves.

1.4.3. Artificial structures to support target species

By constructing specific artificial reefs, it is possible to ensure that the target species remains nearby while also reproducing. The purpose of the artificial reef is to provide nutrition, protection, shelter, and/or reproduction opportunities, which helps increase the population of the target species. Grati et al. (2018) suggest adding artificial reefs, cod hotels, and other species-specific structures to the erosion protection layers of wind turbines, among other things, to promote egg deposition.

In contrast, Japan has a long history of using artificial reefs for stock enhancement of squid and shellfish (Fig. 9 & Fig. 10). Bamboo reefs were first documented as early as 1650, and since 1930, the Japanese government has been subsidizing the installation of artificial reefs. By 2004, 12% of Japan's coastal areas were occupied by artificial reefs, amounting to a total of 20 million cubic meters. The largest models reach up to 80 meters in height. There are 350 patented models, and these reefs have been installed at 20,000 sites (Thierry, 1988).

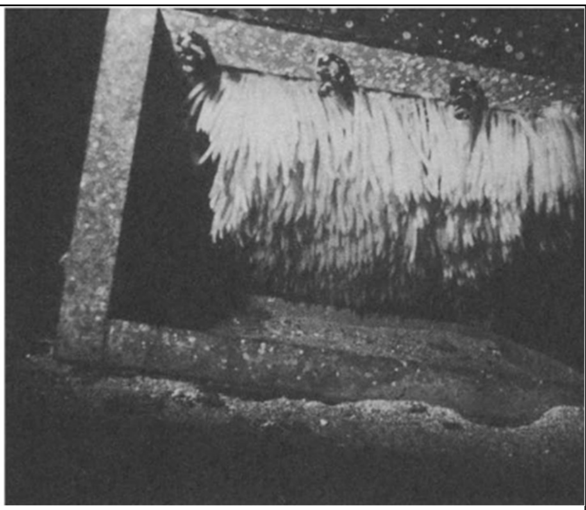


Fig. 9 A reproduction reef for squid, Niigata Prefecture, Japan (Thierry, 1988)

Fig. 10 An artificial reef to keep shellfish on sandy bottoms (Thierry, 1988)

As detailed in the literature, the scour protection layers around wind turbines, as well as the cable protection layers, provide a source of hard substrate that may attract certain targeted animal species and/or plants (Degraer et al., 2021). To date, the spill-over effect of these structures is still largely unknown, but a positive impact on plaice stocks has been demonstrated in Belgium (Buyse et al., 2022). The Before-After Control-Impact (BACI) monitoring method is effective in demonstrating impact effects, but for detecting a spill-over effect, a gradient design, where samples are taken at varying distances from the impact zone, is better suited (De Backer et al., 2022). In the southern North Sea, an increase in the biomass of target species such as North Sea crab (*Cancer pagurus*) and European lobster (*Homarus gammarus*) is expected due to the greater availability of hiding places and food (Ashley et al., 2014; Krone et al., 2017; Krone et al., 2013b). For example, the artificial reef structures formed by monopiles with erosion protection in the German Bight have resulted in a local biomass increase of North Sea crab by 320% (Krone et al., 2017).

Several studies have shown that increased habitat complexity leads to greater biodiversity. Therefore, it is recommended to use various stone sizes to create different-sized gaps between the stones for future erosion protection layers. According to Hermans et al. (2020), this substrate will serve even better as a nursery for Atlantic cod and the poor cod, a shelter for sharks such as the small-spotted catshark, North Sea crab, and European lobster, and as a spawning ground for rays and cuttlefish, such as squid. Furthermore, commercial products are available that enhance the bioreceptivity of artificial hard substrates. Seacrete® and Reefpaste® are coatings that can be applied to various marine installations, including metal, stone, or concrete, while Econcrete® is an additive for cement mixes that also increases bioreceptivity.

Experience in Belgium

Belgium has an extensive programme investigating the effects on the marine ecosystem of wind turbine construction, operation, and, in the future, decommissioning (Degraer, 2014; Degraer & Brabant, 2009; De Backer et al., 2020). This monitoring, as required by the environmental permit, is coordinated by OD Nature (KBIN). The programme is conducted in collaboration with INBO, ILVO, the Department of Marine Biology at Ghent University, and INTEC. The results are published annually in the *Memoirs on the Marine Environment* (MUMM; naturalsciences.be).

In Belgium, two artificial reefs were installed in 2013 within OWFs, one in Belwind and one in C-Power (Fig. 11). Each artificial reef consisted of a set of 33 reef balls.

Fig. 11 Reef balls (Source: Vliz, Karen Rappe, 2014)

The monitoring of both reefs is conducted by VLIZ. At the location of the artificial reef in the C-Power wind farm (Thornton Bank), a measuring buoy was installed with various monitoring equipment. In mid-March and early September 2014, scientific divers visited the artificial reef. Less than a year after installation, the reef was found to be well-colonized by various species, including crabs, anemones, starfish, and fish (such as pout and cod). Even North Sea lobsters had already discovered the reef. Unfortunately, it was later determined that both reefs had become significantly silted. Although the reefs are still present, they have not been monitored recently.

1.4.4. Habitat restoration to support target species

Habitat restoration, like habitat creation, can enhance the productivity of the ecosystem. Even habitats that lack a biological origin can be restored. This is also true for **biogenic habitats**—habitats created by living organisms—such as shellfish reefs, macroalgae forests, or reefs formed by other reef-building organisms like corals, worms, and sponges. It is generally believed that habitat restoration improves the ecosystem and increases species richness and biomass. In the medium term, the ecological functions of the newly restored reef play a significant role in its added value, including the boost in secondary production of fish, which can support fisheries. These benefits are considered ecosystem services. While habitat restoration may lead to increased populations of commercial target species, it is not inherently species-specific.

Beyond direct effects, such as increased habitat complexity and biodiversity among both sessile and mobile fauna, reefs serve additional functions. Complex, diverse habitats tend to be more stable and resilient against invasive species than simpler, less complex habitats (Alexander et al., in Van Duren et al., 2016). Other aspects influenced by habitat complexity and biodiversity include productivity and resilience—the ability of an ecosystem to recover from disturbances (Frid & Caswell in Van Duren et al., 2016).

A classic example of how biogenic habitat restoration can increase the production of commercial fish species is the restoration of oyster reefs (Grabowski & Peterson, 2007) (Fig. 12). Significant efforts are underway globally to restore oyster reefs, including in the USA (*Crassostrea virginica*), Australia (various species), and several European countries (*Ostrea edulis*). For instance, the species richness of the oyster beds in the Voordelta in the Netherlands is 60% higher than the surrounding sandy areas (Biodiversity of North Sea Native Oyster Reefs: Notes). Commercial species associated with these reefs include eel, Atlantic cod, sea bass, and plaice (Restoration of European flat oyster reefs in the North Sea and Wadden Sea - WUR).

Since oyster reefs are no longer found in the BNS due to the intense use of bottom trawling (Kerckhof et al., 2018), active measures must be taken to facilitate the return of the flat oyster. Simply protecting the area from bottom fishing is not enough, as no breeding populations remain (Stechele et al. 2023). Reintroducing animals is therefore essential, and this can be achieved through aquaculture. Bishop et al. (2023) also highlight that cultivating habitat-forming species can accelerate the recovery of biogenic reefs.

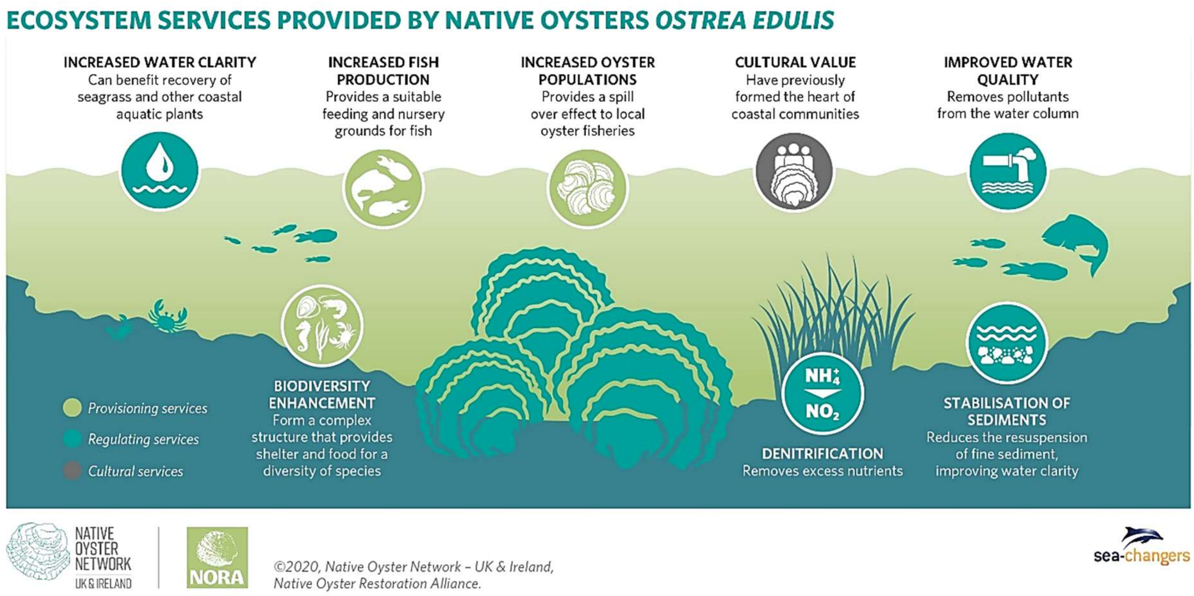


Fig. 12 Ecosystem services offered by flat oyster reefs (source: NORA Closes – NORA (noraeurope.eu)

The Native Oyster Restoration Alliance (NORA) coordinates European initiatives aimed at reintroducing native oysters and works to standardize protocols for hatchery production, cultivation to commercial size, biosecurity, and restoration practices. Several handbooks have been published and are available online for consultation (https://noraeurope.eu/).

Other species critical to forming biogenic reefs in the BNS (habitat type 'Reefs' - H1170) (Degraer et al., 2009) include the honeycomb worm *Sabellaria aveolata* and Ross worm *Sabellaria spinulosa*, as well as the sand mason worm *Lanice conchilega*. The *Sabellaria* worms form typical hummock formation of interconnected tubes. Sand mason worms trap sand between their tubes, forming microhabitats that attract other species. These worms are often referred to as "habitat engineers" because they significantly enhance local biodiversity. *Sole* is commonly associated with *Lanice* reefs (Ernst & Goerke, 1974). Such biogenic reefs typically form in areas exposed to strong currents, like tidal channels. While still present in the North Sea, extensive reefs have largely disappeared due to seabed-disturbing activities from the fishing industry.

In addition to biogenic reefs, the presence of natural hard substrates also contributes to increased biodiversity (Liversage, 2020). For the offshore areas in the BNS, gravel beds—composed of gravel and glacial boulders—are critical habitats with their own unique biodiversity. However, these areas have been significantly impacted by bottom-disturbing fishing practices, which destroy the fauna and flora of the gravel beds, and boulders have been largely removed through bottom trawling. A detailed description of these impacts can be found in Annex 3.

Experience in Belgium

The Coastbusters project conducted research into the construction of biogenic reefs to protect the coastline. These reefs can help stabilize the sandy bottom, preventing beach erosion. Three species were tested for this purpose: mussels, sand mason worms (*Lanice conchilega*), and sugarkelp (*Saccharina latissima*). The study found that mussel bed construction was easiest using aquaculture techniques, such as longlines with dropper lines. Building mussel beds on a larger scale, including at more exposed locations, was further explored in the Coastbusters 2.0 project. Within the Coastbusters project, ILVO developed a protocol for the artificial propagation of sand mason worms, although large-scale application in the field has not been possible so far because specific hydrodynamic conditions need to be fulfilled to enhance reef formation.

The UNITED project investigated the potential of turning the erosion protection layer of wind turbines into small oyster reefs by housing stones in cages with *Ostrea edulis* broodstock and placing these "restoration tables" on the erosion protection layer. While spatfall was observed, it occurred in very small numbers. A coating of lime around the stones did not prove effective, and many of the breeding animals did not survive the experiment, likely due to their Norwegian origins. These small-scale trials, however, provide a solid foundation for further research, particularly through the follow-up project ULTFARMS.

Interestingly, the presence of gravel and boulders is often associated with shellfish reefs. In some regions, boulders have been reintroduced on a large scale to restore shellfish reefs, particularly oysters. Notable examples of such restoration efforts have been carried out in the Australian regions of Victoria (Fitzsimons et al., Gillies et al., cited in Liversage 2020), South Australia (Colella et al., cited in Liversage 2020), and Western Australia (Thomson, cited in Liversage 2020).

WP2: Aquaculture species

2.1. List of potential species for aquaculture

Multiple sources were consulted to compile a list of potentially interesting species for aquaculture in the BNS (Table 4). This list was created based on the monthly reports of wild-caught species in Belgian fisheries, including their volume and farm gate price, as published in the monthly magazine of the Rederscentrale and available on their website (https://rederscentrale.be). Since Belgian fishermen frequently operate in foreign waters, the list also includes species that are not naturally found in the BNS. A notable example is monkfish, which inhabits hard substrates in the English Channel. However, it remains on the list as its habitat can be replicated using erosion protection layers, potentially attracting, supporting, or cultivating the species. Cod is also included due to its significance in Belgian fisheries. Whether it can be bred in the BNS requires further investigation, as the local waters may be too warm. Cod reproduces at temperatures between 0.5°C and 14.4°C and ceases feeding at 20°C (Bleil & Oeberst, 1998).

Additionally, certain species were identified based on the historical reference by Rappé (2008). This work highlights species that were once targeted by the Belgian fishing industry, such as herring and sprat, as well as species that appeared sporadically but held high market value, including tuna, sturgeon, and eel. These species are often too rare to be landed or auctioned and, as a result, are not included in the list of commercially significant species for the Flemish fisheries sector (2024-01; https://rederscentrale.be). Furthermore, the study by Quéméner et al. (2002) was also considered, as it identifies fish species with aquaculture potential along the Atlantic coast of France, the English Channel, and the southern North Sea. While some species—such as Atlantic bonito and albacore—may currently find Belgian waters too cold for production, future changes in environmental conditions could make their cultivation feasible.

The authors of this study advocate for sustainable aquaculture in the BNS using native species with the appropriate genetic background. In aquaculture, species selection is typically guided by traits such as disease resistance and rapid growth (domestication). This process relies on a limited number of parent specimens, leading to a reduction in genetic diversity in subsequent generations. To support populations facing intense fishing pressure, restocking with farmed fish is a potential strategy; however, maintaining high genetic diversity is crucial. This can be achieved through specialized breeding programs (Støttrup et al., 2008b). Ultimately, it will be essential to establish a clear causal link between the increase in commercial species and the reintroduction of farmed endangered species.

Support can also come from unintended but unavoidable escapees of farmed animals or the release of their gametes or larvae into the water column. For instance, the commercial cultivation of flat oysters can aid in the restoration of flat oyster reefs.

Species included in the list that hold ecological significance for the BNS were selected based on conservation objectives (Belgian State, 2021). As a result, breeding or other supportive measures for these species should contribute to achieving a favourable conservation status. A specific selection was also made for species essential to gravel bed ecosystems (Belgian State, 2023).

Consequently, this study diverges from the conventional criteria used to define a species as suitable for aquaculture. Le François et al. (2002) outlined these criteria as follows: the species should have a high reproductive potential; the necessary biological material (e.g., eggs, larvae, juveniles) must be available; breeding techniques should already be established; the breeding cycle (from egg to market-ready product) must be as short as possible; the market volume should exceed 1,000 tonnes per year, though higher-value niche products may have lower volumes; the species must have a high market value (unless produced in bulk); and it must be capable of being cultivated under local conditions (open systems).

Beyond fish, crustaceans, and shellfish, seaweed cultivation was also explored. The potential for seaweed farming in Europe is still under investigation (European Commission, 2022c). Interest in Flanders is growing, as evidenced by various projects (Seaconomy, Value@sea and United). The selection of macroalgae species for cultivation is based on a report by the European Commission (2022d). Species identified as having potential for Flanders by the Seaconomy project (2018) are highlighted in light blue, as well as oarweed, for being referenced in Wald (2010). According to Reith et al. (2005), the North Sea seaweed species with the highest potential as sustainable raw materials for animal feed and non-food applications include: *Laminaria digitata* (oarweed; brown seaweed), *Saccharina latissima* (sugar kelp; brown seaweed), *Palmaria palmata* (Dulse; red seaweed), and *Ulva lactuca* (sea lettuce; green seaweed).

Table 4 also presents the farm gate prices (in 2023) of these products. The Belgian market prices for the listed species are published annually in the information sheet of the Rederscentrale Additionally, the FAO releases annual reports on European market prices for farmed and wild-caught species. The prices provided correspond to whole (gutted) fish, rather than fillets or processed products.

Significant price differences are primarily linked to the size classes in which fish are sold. Additionally, prices are highly variable and experience considerable fluctuations each year. The prices of cultivated seaweeds also vary greatly depending on the species and are influenced by factors such as origin and condition (e.g., wet, dry or cut) (World Bank 2023). For instance, demand for dulse (*P. palmata*) is high, and this species is cultivated in Europe with a farm gate price of 160–250 €/kg. However, the same species is imported from Southeast Asia to Europe at just 6 €/kg. This stark difference is mainly due to the costs associated with cultivation systems and labour. Table 4 is based on the European reference prices available on the website of the AlgaProBanos project. However, prices were not available for all seaweed species.

In addition to the common name, scientific name, and price, the IUCN status of each species is also listed to highlight which species may be eligible for population-support measures. The species are categorized into fish, crustaceans, mollusks, seaweeds, and an additional category for nature restoration.

This study does not assess the economic feasibility of offshore aquaculture but enhances the likelihood of financial success by selecting a reference species (highlighted in green) for each category. The price of the reference species serves as a minimum threshold, above which a species in that category is considered economically suitable for aquaculture. The reference price for fish and mollusks corresponds to that of a species for which aquaculture is already an established sector in Europe (potentially even in offshore settings). For fish, farmed Atlantic salmon was chosen, with a reference price of 5.66 €/kg, while for mollusks, the blue mussel was selected, with a reference price of 1.8 €/kg. For crustaceans, the edible crab was chosen as a reference species due to the absence of an established (cold-water) crustacean aquaculture sector in Europe. The edible crab is frequently mentioned in literature as a promising species for offshore aquaculture and is highly valued in neighbouring countries. Its reference price is 4.92 €/kg. Since seaweed is not sold through fish auctions and no prices are set for species relevant to habitat restoration, no reference prices were established for these categories.
Potential species that could be cultivated profitably based on these criteria are highlighted in light blue.

*Table 4 List of potential aquaculture species for farming in the BNS including market prices and IUCN protection code. Blue : price equal to or higher than the price of reference species ; white : price lower than reference type price *Price for dried product (AlgaProBanos (http://vis4nlp.com/APB/ ; **No market value; +selection Seaconomy (2018) & Wald (2010)*

Common name	Scientific name	Price (€/kg), Belgium	Price (€/kg), EU	IUCN
FISH				
Atlantic salmon	*Salmo salar*	10,85	8,00	NT
Ref.Farmed Atlantic salmon	*Salmo salar*		5,66 – 11,40	NT
Anchovy	*Engraulis encrasicolus*		1,95 – 5,00	LC
Blonde ray	*Raja brachyura*	3,09		NT
European flounder	*Platichthys flesus*	1,19		LC
Spiny dogfish	*Squalus acanthias*	0,75		VU
Thinlip mullet	*Chelon ramada*	0,82		LC
Shad	*Alosa alosa*			LC
Red gurnard	*Chelidonichthys cuculus*	0,70		LC
Finely	*Alosa fallax*			LC
Spotted ray	*Raja montagui*	2,03		LC
Common smooth hound	*Mustelus mustelus*	0,21		IN
Undulate ray	*Raja undulata*	3,16		IN
Gilthead bream	*Sparus aurata*	1,41	4,00 – 10,64	LC
Golden grey mullet	*Chelon aurata*			LC
Brill	*Scophthalmus rhombus*	12,12	4,50 – 9,45	LC
Largehaed hairtail	*Trichiurus lepturus*			LC
Herring	*Clupea harengus*	0,42	3,20	LC
Hake	*Merluccius merluccius*	2,62	3,67 - 11,20	LC
Halibut	*Hippoglossus hippoglossus*	12,49		NT
Lesser-spotted dogfish	*Scyliorhinus canicula*	0,52		LC
Witch flounder	*Glyptocephalus cynoglossus*	1,26		VU
Cod	*Gadus morhua*	3,62	7,90 – 9,02	VU
Large-spotted dogfish	*Scyliorhinus stellaris*	0,58		VU
Conger eel	*Conger conger*	0,79		LC
Saithe	*Pollachius virens*	1,35		NE
Latour, porbeagle shark	*Lamna nasus*			VU
Leng	*Molva molva*	2,63	6,01 – 7,12	NE
Wrasse	*Labridae*	0,59		
Mackerel	*Scomber scombrus*	2,32	3,18 – 6,00	LC
May fish, mullet	*Mullus surmuletus*			LC
Striped red mullet	*Mullus surmuletus*	3,55		LC
Meagre	*Argyrosomus regius*		4,05-4,74	LC
Eel	*anguilla anguilla*	10,37	18,28	CR
Greater weever	*Trachinus draco*	2,42		LC
Plaice	*Pleuronectes platessa*	3,07	5,00-10,45	LC
Common scad	*Trachurus trachurus*		0,60 – 2,80	VU
Pollack	*Pollachius pollachius*	4,81		LC
Tub gurnard	*Chelidonichthys lucerna*	1,20		LC
Sardine	*Sardina pilchardus*	2,83	1,49-2,15	LC
Dab	*Limanda limanda*	0,74		LC

Common name	Scientific name	Price (€/kg), Belgium	Price (€/kg), EU	IUCN
Megrim	*Lepidorhombus whiffiagonis*	1,79		
Haddock	*Melanogrammus aeglefinus*	1,47	2,70 – 3,20	VU
Plaice	*Pleuronectes platessa*	3,07	5,00 – 10,45	LC
Musician, violin	*Squatina squatina*			CR
Siny dogfish	*Squalus acanthias*			VU
European smelt	*Osmerus eperlanus*			LC
Sprat	*Sprattus sprattus*	3,07		LC
Pout	*Trisopterus luscus*	0,73		NE
Thornback ray	*Raja clavata*	2,19	7,26 – 8,25	NT
Sturgeon	*Acipenser sturio*	6,01	7,50	CR
Turbot	*Psetta maxima*	15,68	9,85 – 15,88	LC
Sole	*Solea solea*	17,54		DD
Lemon sole	*Microstomus kitt*	4,64		LC
Tuna	*Thunnus thynus*		10,01-11,77	LC
Whiting	*Merlangus merlangus*	1,21		LC
Atlantic wreckfish	*Polyprion americanus*			DD
Sand sole	*Solea lascaris*	10,79	13,45– 31,00	LC
Sea bass	*Dicentrarchus labrax*	10,87	4,35 – 12,30	LC
Red mullet	*Mullus barbatus*			LC
Sea bream	*Pagellus acarne*	1,06		LC
Monkfish/lot	*Lophius piscator*	9,55		LC
Sea trout	*Salmo trutta*			LC
Sea carp	*Spondyliosoma cantharus*			LC
Atlantic wolffish	*Anarhichas lupus*	3,71		NE
John Dory/Peter's fish	*Zeus faber*	8,81	13,83– 23,50	DD
Grey gurnard	*Eutrigla gurnardus*	0,22		NE
CRUSTACEANS				
Brown shrimp	*Crangon crangon*	8,85		
Ref.Edible crab	*Cancer pagurus*	4,92	10-00 – 6,90	NE
European lobster	*Homarus gammarus*	13,84	25,93 – 44,00	LC
Red crayfish/Red lobster	*Palinurus elephas*	22,62	10,39 - 22,62	
Spinkrab	*Maja brachidactyla*	4-5		NE
Prawn	*Palaemonidae/pandalidae*			
Norwegian lobster	*Nephrops norvegicus*	10,39		
MOLLUSCS				
Razor shells	*Solenidae*		3,85-18,30	
Ref. Blue mussel	*Mytilus edulis*	1,8	1,70 – 6,27	LC
Octopus	*Eledone cirrhosa*	1,24	3,38 – 4,55	LC
European flat oyster	*Ostrea edulis*	7,2	11,40 – 18,60	NE
King scallop	*Pecten maximus*	2,58	4,35 – 5,35	NE
Queen scallop	*Aequipecten opercularis*			NE
Welck	*Buccinum undatum*	1,62		NE
Squid	*Loligo vulgaris*	7,42	8,15 – 15,07	NE
Cuttlefish	*Sepia officinalis*	3,18	3,07 – 4,50	NE
Sand gaper	*Mya arenaria*			NE
Cockle	*Cerastoderma*			

SEAWEEDS (wild + aquaculture)				
Sugar seaweed+	*Saccharina latissima*			
Sea lettuce+	*Ulva lactuca**		23,08	
Oarweed+	*Laminaria digitata*			
Dulse+	*Palmaria palmata**		165,87	
Toothed wrack+	*Fucus serratus*			
Bladderwrack+	*Fucus vesiculosus*			
Sea spaghetti	*Himanthalia elongata*			
Wing kelp/Atlantic wakame+	*Alaria esculenta* *		23,08	
Laver/nori+	*Porphyra umbilicalis*			
Irish moss+	*Chondrus crispus*			
Knotted wrack	*Ascophyllum nodosum*			
Button wrack	*Gracilaria* sp. *		12,2	
FOR NATURE RESTORATION**				
Ross worm	*Sabellaria spinulosa*			
Sand mason worm	*Lanice conchilega*			
European flat oyster	*Ostrea edulis*			
Keelworm/Christmas tree worm	*Pomatoceros (Spirobranchus) triqueter*			

2.2. Additional selection criteria for the right species

The selection of an appropriate location is one of the most critical factors for ensuring the success of aquaculture. Since the available areas for offshore commercial aquaculture in Belgium are restricted to the concession zones of wind farms and the five zones for commercial and industrial activities (CIAs) according to the current MRP 2020-2026 (this will change in the new MRP 2026-2034, currently being determined, cf. 5.2 Preconditions for long-term integration), it is essential to first assess the **biological and physico-chemical conditions** within the OWFs and determine whether they align with the requirements of the target species. Several tools can assist in making the right decisions regarding site selection, aquaculture species, and turbine foundation type. A Bayesian Network-based multi-attribute framework (BN approach) was used by Villaba (2022) to assess uncertain alternatives for co-located wind-aquaculture farms. OWFs and aquaculture were treated on equal footing and the approach worked very well when certain types of aquaculture were already established. For example, the study concluded that for Tasmania, the optimal choice was the combination of monopile foundations with production of Atlantic salmon, followed by seaweed farming, and thirdly by blue mussel cultivation.

Gimpel et al. (2015) developed a Geographic Information System (GIS) and a multi-criteria evaluation (MCE) technique to assess 13 potential aquaculture species (including seaweed, mollusks, crustaceans, and fish) in the German exclusive economic zone (EEZ). The study showed that several OWFs were suitable for farming certain species, such as *Laminaria digitata*, *Palmaria palmata*, *Saccharina latissima*, and haddock (*Melanogrammus aeglefinus*), even in an Integrated Multi-Trophic Aquaculture (IMTA) system (see below). The German project Offshore Site Selection – OSS added several species to the list, including European sea bass (*Dicentrarchus labrax*), Atlantic cod (*Gadus morhua*), *Laminaria hyperborea*, and *Delesseria sanguinea* (https://www.thuenen.de/en/institutes/sea-fisheries/projects/combination-of-offshore-wind-parks-and-marine-aquaculture-in-the-north-sea-a-realistic-scenario).

The concept of shared use of offshore aquaculture within wind farms is frequently proposed by policy (e.g., the Belgian MRP 2020-2026) and has been supported during vision processes by various stakeholders as the "way forward" for sustainable marine aquaculture development in the BNS. Specifically, the combination of OWFs with low-trophic aquaculture (LTA) species (those that feed on detritus, bacteria, phytoplankton, and zooplankton) is suggested as an efficient strategy to achieve multiple objectives, including emission-free energy production, nutritious seafood, and restorative ecosystem services, such as the extraction of emissions like CO2, nitrogen, and phosphorus compounds (Buck et al., 2018; Golden et al., 2021; Krause et al., 2022). Ecosystem services are defined as “services provided by ecosystems that contribute to human well-being, but differ from the goods and benefits humans actively derive with a clear purpose, such as seafood and salts” (Haines-Young & Potschin-Young, 2018). LTA provides food and animal feed with fewer resources required (e.g., freshwater) and has a smaller CO2 footprint compared to terrestrial protein production (Gephart, 2021; Filgueira et al., 2019); Hoegh-Guldberg, 2019). In the Belgian context, it is a minimum requirement that aquaculture does not contribute additional nutrients to the environment within the OWFs, making the choice of extractive species an obvious option (Belgian Official Gazette, 2014).

Experience in Belgium

Determining the selection criteria for the proposed breeding species was also considered essential during the Aquaculture Vision Trajectory for the BNS. The Flemish project AquaValue (desk study) previously conducted this exercise for extractive aquaculture, identifying the blue mussel, sugar kelp, and sea bass (in an open-sea farm) as the best candidates for offshore areas. Based on these results, follow-up projects (Value@Sea, Edulis, and SYMAPA) demonstrated that the blue mussel has significant potential for farming in the BNS, both biologically, technically, and economically. Additionally, a modified Dynamic Energy Budget (DEB) model was developed and can be utilized to predict the best production zones (Stechele et al., 2022).

The financial profitability of mussel farming within OWFs, however, is significantly hindered by factors such as the distance from the coast, the short time window for maintenance and harvesting, and the necessity to cover future liabilities and risks. The blue mussel is currently commercially cultivated in the Westdiep Sea Farm by the Colruyt Group. Last year, a first, albeit limited, production was marketed, and in the coming years, the number of longlines will be further expanded.

A second species tested in the BNS (through Value@Sea, SYMAPA, and UNITED) is the flat oyster (*Ostrea edulis*). This species also shows potential, but the growth of fouling on the baskets remains a significant challenge in making this cultivation financially viable. Within the same projects, experiments were conducted with the cultivation of sugar seaweed. The seaweed grew well, provided the correct sowing (presettlement of sporophytes on substrates) technique was used for the net material. As expected, good growth was confined to the surface layers.

2.3. Combinations of species in an integrated multitrophic aquaculture system (IMTA) and extractive farming in Belgium

An IMTA system refers to the cultivation of one species whose waste products can serve as food or fertilizer for another species. For example, mussels excrete ammonium, which can be utilized by seaweed as fertilizer. The AquaValue project conducted an extensive study of marine IMTA systems worldwide, but found limited opportunities for their implementation in the Belgian context due to various limitations, such as legal and biological constraints for fish farming, a lack of commercially interesting detrivores, and the strong hydrodynamic conditions of the North Sea (Anonymous, 2019). Within the projects Value@Sea (EMFF) and SYMAPA (DBC/VLAIO), various species, including mussels, flat oysters, scallops, and sugar kelp, were cultivated side by side. In these experiments, however, the dissolved nitrogen (N) and phosphorus (P)-containing products released by the shellfish could not be absorbed by the sugar kelp, as the production cycles of the different species were not synchronized. Mussels and flat oysters grow fastest at temperatures above 12°C, while sugar kelp must be sown and harvested at temperatures below 12°C. Even with the cultivation of a summer seaweed, such as sea lettuce (*Ulva sp.*), there would still be limited opportunity for the waste products from the mussels to directly serve as fertilizer for the sea lettuce due to the strong (tidal) currents in the BNS, which would result in rapid dispersal and dilution. The same goes for the use of detrivores, even if commercially interesting species were available, they could not be used at the same location because the strong (tidal) currents would disperse particulate material and dissolved nutrients.

To obtain concessions for the commercial production of blue mussels through suspended structures in four specific zones (D1 zone, radar tower Oostdyck, measuring pole Westhinder, and Thornton Bank/C-Power zone), an environmental impact assessment was submitted in 2005 by AG Port Oostende. BMM analysed the distribution of the (pseudo-)faeces of the farmed mussels (MUMM 2005). The study showed that due to the high current, the (pseudo-)faeces had little chance of accumulating beneath the suspended structures. Instead, they dispersed and settled over several kilometers to the northeast, near Zeebrugge, the Vlakte van de Raan, and near the Thornton Bank/C-Power zone in the Dutch part of the North Sea. The conclusion was that the (pseudo-)faeces from the mussels would not cause significant shifts in the composition of the infauna in the immediate vicinity of the suspended structures, due to the size of the dispersion zone. Therefore, it is difficult to implement IMTA systems in the BNS unless systems are chosen that are shielded from direct (tidal) current flow.

In the "Integrate" project by Sintef and NTNU (2007), the term "extensive integrated aquaculture" is used, modelling the distribution of nutrients in the water column from fish cages through the 3D hydrodynamic SINMOD model. The study identified areas of high primary production as a result of the fish farming, that could be located kilometers downstream and potentially suitable for shellfish farming (Næringssalter; www.sintef.no).

It is therefore possible to account for the nutrient uptake and the production of waste products (such as nitrogen and phosphorus) from each of the cultures and calculate the total nutrient balance to assess whether multiple cultures within a given area can be defined as extractive aquaculture or not.

WP3: General preconditions

3.1. Social support for aquaculture in the BNS

3.1.1. Social support for aquaculture

Social acceptance plays a crucial role in developing mariculture in the BNS due to the involvement of numerous stakeholders. The FAO guidelines assist countries in enhancing social acceptance of aquaculture (Table 5) (https://www.fao.org/3/cc2299en/cc2299en.pdf).

Table 5 Possible problems and proposed solutions to increase social acceptance of aquaculture in offshore wind farms (based on FAO guidelines to promote social acceptance of aquaculture)

Social problems	Proposed solution
Limited coordination between policy levels	Working group dedicated to legislation for integrated activities at sea (Government, NGOs, innovation clusters, representatives of activities)
Limited stakeholder participation during the initial phases	Inviting stakeholders during the start-up of the activity
	Communication with stakeholder groups in MRP evaluation, and more citizen participation in the OWF
Concerns about environmental impact	Communication about water quality
	Monitoring and reporting
	Labelling: information on the positive impact of aquaculture at sea
	Media attention, events, ect.
	Communication about initiatives that reduce the impact of aquaculture
	Strict regulations on environmental impact to prevent lowering social acceptance (regulations on preventing nesting of iconic species (seabirds, marine mammals, ect) in aquaculture infrastructure)
	Production for local consumption
	Production of species of local interest
	Production of species whose populations are under pressure
	Low Intensity Farming, Sea Ranching, Restorative Aquaculture, Passive Fishing
	Extractive culture
	IMTA
Concerns about product quality and food safety	Communication about the analyses of water quality & aquaculture products
	Product-labelling
	Media coverage of the health benefits of aquaculture products
	Strict regulation, monitoring a report
	Transparency
Concerns about economic impact	Local production
	Short chain initiatives
	Increasing local employment
	Reducing competition between fisheries and aquaculture
	Increasing synergies between fisheries and aquaculture
Limited knowledge about the benefits of aquaculture	Media attention, documentaries, etc.
	Social initiatives, festivals, collaboration with local restaurants, chefs, etc.

There are few examples that provide insight into the social support for mariculture in Belgium, apart from the production of blue mussels. Research into Belgian mussel cultivation began as early as 1997, with the first commercial mussels (Belgica mussels) from Reynaert-Versluys produced between 2007 and 2011 (Buck et al., 2017). More recently, mussels have once again been commercially farmed in BNS (Westdiep Sea Farm), with the first batch becoming available to consumers in the summer of 2023 (cf. Annex 2). The production of Belgian mussels is considered prestigious, as 'mussels with fries' is a well-known culinary classic in Belgium. However, this national dish relies entirely on imports, primarily from the Netherlands, but also from Germany and Denmark. Despite the numerous challenges (see below) that Belgian mussel production has faced, the sale of locally farmed mussels garners significant media attention and is often accompanied by rapid sales at high prices. This suggests that Belgian consumers have a strong interest in locally produced seafood.

Communication to the consumer is essential. It is striking that the "man/woman in the street" has little to no knowledge about breeding species, their cultivation processes, and their impact on the ecosystem. Knowledge institutions, government services, and the Colruyt Group frequently receive questions about mussel farming, such as how mussel seed is attached to ropes or what type of feed is required for mussels to grow properly. An NGO even inquired about which antibiotics are used in mussel cultivation in the high seas.

Providing objective information is therefore crucial, as aquaculture is often portrayed negatively in the media, typically focusing on outdated facts or isolated incidents—such as salmon lice infections in intensive salmon farming—that are indeed unacceptable. More efforts are needed to present a balanced view of the sector as it seeks to develop in Belgium. Positive initiatives, such as the TV program "Over Eten" (season 4, episode 6) on VRT.be, provide knowledge institutions like ILVO and UGent with a platform to educate a wider audience.

3.1.2. Social support for aquaculture specifically in wind farms

Aquaculture in wind farms is not an obvious choice, as it involves combining activities that present significant technological challenges and for which global experience remains limited. The brief overview presented by Nevejan et al. (2023) highlighted that such an evolution in Belgium would not have been possible without strong trust among the partners of pilot projects, the identification of mutual benefits, and the realization that multiple use of space is essential due to the rapid expansion of OWFs.

Belgium has been a pioneer in this field, notably through the development of one of the first MRPs that incorporated multiple use of space. Open communication and thorough risk management at every stage of the process fostered both trust and a willingness to test innovative systems (Fig. 13). As pilot projects proved successful, attitudes among other stakeholders, including the fishing industry, also evolved. Interest in aquaculture development within wind farm concessions grew, making offshore mariculture in OWFs a viable and negotiable concept.

Over the past two years, there has been increasing focus on co-design and the joint development of zones that would allow for activities such as passive fishing. This shift in mindset took place within just a few years, starting with the launch of the Edulis project—the first aquaculture initiative in collaboration with an OWF.

A concern that occasionally arises is ensuring the inclusiveness of offshore aquaculture for smaller players, such as SMEs (Van Maele et al., 2023b). Due to the high investment costs, there is a risk that only a few large companies will be able to establish themselves in the sector.

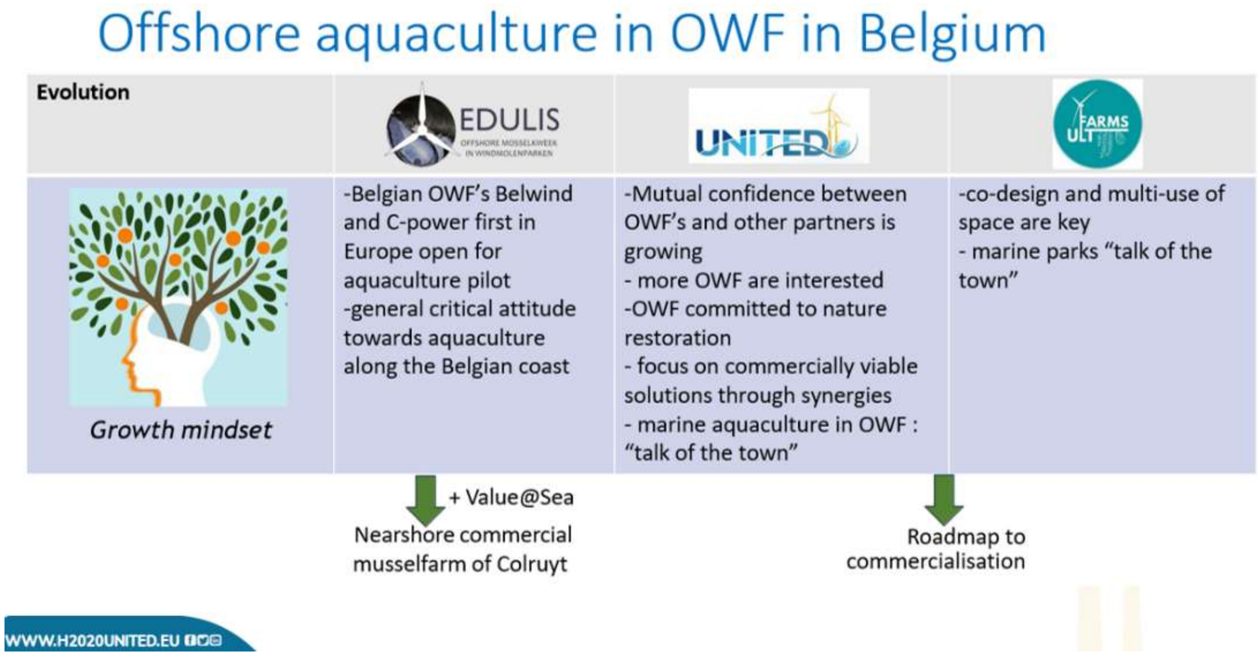


Fig. 13 From Edulis to ULTFARMS: a challenge for mind and craft. Presentatie n.a.v. closing event van UNITED, Gothenburg, Sweden, 15/11/2023 (Nevejan et al., 2023) [Nancy-Nevejan-offshore-wind-energy- UNITED.pdf (bluemissionbanos.eu)]

3.2. Ecological impact

Every human activity has an environmental impact, which can be categorized as positive or negative depending on predefined objectives. Whether an impact is considered positive or negative depends on the goals that have been set. Objectives for achieving a good ecological status are legally defined in regulations such as the Habitats Directive, particularly in Natura 2000 areas.

Aquaculture activities must adhere to legally established conditions regarding environmental impact. Additionally, they must contribute to achieving conservation objectives to maintain or restore the marine ecosystem to a favourable conservation status.

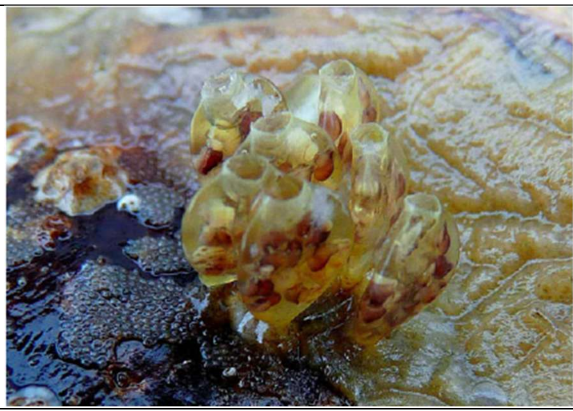
3.2.1. Negative impact on the environment (incl. mitigation techniques)

Most sustainable aquaculture developments today aim to minimize environmental impact, which is assessed through a robust environmental impact assessment. This assessment considers different spatial and temporal scales: environmental effects can occur at local, regional, and global levels (spatial) and can manifest in the short, medium, or long term (temporal). Various methodologies exist to evaluate the impact of aquaculture activities, closely linked to farming techniques and breeding species. Additionally, the impact largely depends on specific farming practices, such as vessel movements, feeding, and biofouling removal. Even minor adjustments to cultivation techniques or practices can significantly influence environmental impact (Stechele et al., 2023). Table 6 summarizes the negative ecological impact of mariculture and suggests solutions for ecological farming in the Belgian part of the North Sea.

A key environmental concern in mariculture is the potential genetic interaction between escaped cultured organisms and wild populations. The release of gametes during cultivation can also lead to genetic contamination. Two genetic processes play a role: outbreeding depression and inbreeding depression. Outbreeding depression can be mitigated by breeding individuals from local populations, while inbreeding depression cannot be prevented. Existing data indicate that genetic interactions between farmed and wild communities do impact wild populations, though further research is needed. The severity of these impacts largely depends on the species, particularly their level of domestication (Grigorakis & Rigos, 2011; Kitada, 2018).

Shellfish farming is often linked to the unintentional introduction of invasive species (Wolff & Reise, 2002). These may include macroscopic organisms that compete with native species for space and food, parasites, microscopic algae, and pathogens. For instance, the translocation of mussels and oysters introduces non-native species into the Eastern Scheldt each year, such as the sand horseshoe worm (*Phoronis psammophila*) in 2022 and the Big-horned flatworm (*Pseudoceros maximum*, Fig. 14) in 2023. A more severe case is the introduction of the Atlantic oyster drill (*Urosalpinx cinerea*, Fig. 15) and the Japanese oyster drill (*Ocinebrellus inornatus*) in the Netherlands, both of which primarily prey on hollow oysters and, to a lesser extent, flat oysters (van den Brink & Wijsman, 2010).

To mitigate these risks, biosecurity measures must be followed during translocations of broodstock, such as drumming oysters to remove vegetation, disinfecting animals, or using quarantine locations. In the Value@Sea and SYMAPA projects, flat oyster and scallop shells imported from France and the UK were brushed before restocking and then given a 10-minute freshwater bath to eliminate attached organisms. However, it remains impossible to guarantee that the animals are entirely free of "hitchhiking organisms." Therefore, the use of local species is strongly recommended.

	
Fig. 14 Big-horned flatworm (Pseudoceros maximum) must have been introduced to the Eastern Scheldt (the Netherlands) sometime in 2023 via the introduction of shellfish and is now found at various locations in the Eastern Scheldt and can reach a length of 10 cm (Photo: Marion Haarsma).	*Fig. 15 Egg capsules and juveniles of the Atlantic oyster drill (Urosalpinx cinerea) in Gorishoek, the Netherlands (Image: A.H.M.)*

In mariculture, disease transmission between farmed individuals and native species is inevitable, as intensive aquaculture in open waters leads to the aggregation of native species. Investigating the origins of disease outbreaks is challenging, and establishing causality is often impossible. Generally, diseases occurring in natural populations have minimal impact on aquaculture production, whereas diseases emerging from aquaculture operations can significantly affect wild populations (Grigorakis & Rigos, 2011). Disease prevention is a key area of research in fish farming and can be achieved through measures such as administering medication via feed, vaccination, stress-reducing treatments, and adjustments to farming techniques. However, for species like oysters and mussels, such preventive or remedial measures are not feasible. Therefore, limiting disease spread is crucial and can be achieved by breeding disease-free stock, respecting the ecosystem's carrying capacity, and maintaining low stocking densities (Grigorakis & Rigos, 2011).

The installation of aquaculture infrastructure impacts existing habitats. Anchoring, for example, can directly affect the seabed—not just from the anchors themselves but also from anchor chains dragging along the seafloor. Using adapted anchors, such as screw anchors or suction anchors, along with floating anchoring lines supported by buoys, can help minimize seabed disturbance. Screw anchors are preferable to gravity anchors in this context. In addition to intensive farming techniques, artificial reefs used for sea ranching or population-support can modify seabed habitats. Integrating aquaculture with offshore infrastructure, such as scour protection layers, can further reduce habitat degradation.

A significant ecological concern in intensive aquaculture is the localized enrichment of the environment with organic matter. In fish farming, uneaten feed pellets (1–38%), undigested feed (31% in sea bream farming), and excretion contribute to this issue (Grigorakis & Rigos, 2011). Even in extractive cultures such as bivalve farming, organic matter accumulation can occur, as plankton is converted into (pseudo-)fecal pellets. These can settle on the seabed near aquaculture installations, even in the dynamic conditions of the North Sea, as described by Mavraki et al. (2020), contradicting earlier findings (MUMM, 2005).

Beyond organic material, commercial feeds contain other pollutants, including metals, organochlorines, and pharmaceuticals, which can accumulate beneath mariculture infrastructure and contribute to environmental contamination. Additionally, material loss and wear from aquaculture structures contribute to plastic pollution on macro, micro, and nano scales.

Aquaculture operations also require raw material consumption, including energy, which is primarily sourced from fossil fuels. Energy is used in infrastructure construction, feed production, and processing and transporting aquaculture products. Moving aquaculture further offshore increases energy demands due to greater distances from shore and the need for more robust infrastructure to withstand harsher offshore conditions. Sea ranching, in contrast, requires less infrastructure and maintenance.

Similarly, passive fishing combined with nature-enhancing measures reduces raw material use for feed production but may increase resource use for harvesting.

Aquaculture activities influence interactions with natural wildlife. Predators, often protected species (Bath et al., 2023), are attracted to the high prey concentrations around aquaculture installations. These predators can become entangled in nets or be killed by aquaculture operators attempting to prevent stock losses or stress to farmed species. While switching to sea ranching can reduce direct predator mortality from aquaculture infrastructure, certain anti-predator measures may still be necessary to safeguard farmed stock. Passive fishing, when combined with nature-enhancing measures, does not directly threaten protected predators.

Table 6 Negative impact on the environment and possible mitigation techniques

Ecological problem	Impact occurs in:	Proposed approach to reducing impact
Genetic interactions	Intensive cultivation	Cultivation of local strains
		Production of juveniles with wild-caught breeding animals
		Avoiding growth based selection programs
		Catching local juveniles for rearing
Invasive species	Intensive cultivation	Cultivation of local strains
		Production of juveniles with wild-caught breeding animals
		Capture of local individuals for rearing
Spread of diseases	Intensive cultivation	Grow at low density
		Breeding with Specific Pathogen Free (SPF) animals
		No imports from areas with disease status
		Limiting the import of animals
		Strict biosecurity regulations and protocols to be followed
	Sea ranching	Releasing SPF animals
		No imports from areas with disease status
		Limiting the import of animals
		Strict biosecurity regulations and protocols to be followed
Habitat degradation	Intensive cultivation	Use of screw anchors or suction anchors
		Use of floating anchor lines instead of anchor chains
		Measures to reduce the accumulation of organic matter (see below)
	Passive fishing + recovery measures	Avoidance of trawl
		Integration of infrastructure with offshore wind infrastructure
Accumulation of organic matter	Intensive cultivation	Grow at low density
		Grow in locations with high flow rates
		Rotation of cultivation location
		Co-breeding with detritus feeders
	Sea ranching	Rotation in location of feeding
		Supplementary feeding or sweets that do not contribute to eutrophication.
Discharge of pollutants from feeding	Intensive cultivation	Breeding of low-trophic strains
		Feeding with locally available food sources
	Sea ranching	Supplementary feeding of low-trophic species

Ecological problem	Impact occurs in:	Proposed approach to reducing impact
		Feeding with locally available food sources
Use of raw materials (energy)	Intensive cultivation	Growing Strains that require less maintenance
		Automation
		Exploring synergies with the wind farm operators
		Switching to sea ranching (less maintenance)
		Ships on green energy
	Passive fishing + recovery measures	Use of infrastructure that does not require maintenance (reefs, deep water feeders)
		Ships on green energy sources
Use of raw materials (infrastructure)	Intensive cultivation	Submergeable structures ensures that the infrastructure is less subject to storms.
		Switching to sea ranching (less infrastructure required)
	Passive fishing + recovery measures	Use of submersed infrastructure
		NID, adapting offshore infrastructure to support target species
Use of raw materials (feeds)	Intensive cultivation	Grow with locally available food sources
		Use of high-quality feeds
	Sea ranching	Grow with locally available food sources
Wildlife interactions	Intensive cultivation	Use of innovative techniques to keep predators away
	Sea ranching	Use of innovative techniques to protect the target species from predators
	Passive fishing + population-support measures	Avoiding the use of nets for harvesting, to avoid entanglement

3.2.2. Positive impact on the environment

As indicated above, aquaculture activities can aim to reduce their environmental impact by adapting the breeding species, farming technique or farming method. The pursuit of (more) sustainable aquaculture development is mainly due to a reduced social acceptance of polluting aquaculture techniques (e.g. intensive salmon farming) and a stricter legal framework (through environmental impact assessment).

The positive environmental contributions of aquaculture are linked to the provision of ecosystem services, which can be classified into four categories *(*Gentry et al., 2020*;* TEEB, 2010*):*

- Provisioning Services (e.g., food supply, genetic resources
- Regulating Services (e.g., water quality improvement, erosion reduction, nutrient and pollution reduction, carbon and nitrogen sequestration)
- Supporting Services (e.g., habitat creation and biodiversity enhancement, supporting endangered populations, contributing to nutrient cycling)
- Cultural Services (e.g., Promoting tourism, recreation, and cultural activities)

All forms of aquaculture contribute to provisioning services, while cultural services can often be integrated into aquaculture-related activities. However, macroalgae and shellfish farming are particularly associated with regulatory and supporting services. These farming systems provide benefits such as climate regulation, storm protection, biogeochemical cycling, and habitat provision, supporting secondary production and enhancing fisheries. Habitat creation by extractive species is a critical ecological function that underpins biodiversity, ecosystem structure, and overall ecosystem function (Fig. 16). The ecosystem services provided by aquaculture align with several United Nations Sustainable Development Goals (SDGs), including:

- Promoting global health and well-being
- Ensuring economic growth and resilience in coastal communities
- Encouraging responsible consumption and production
- Enhancing marine ecosystems (Corrigan et al., 2022)

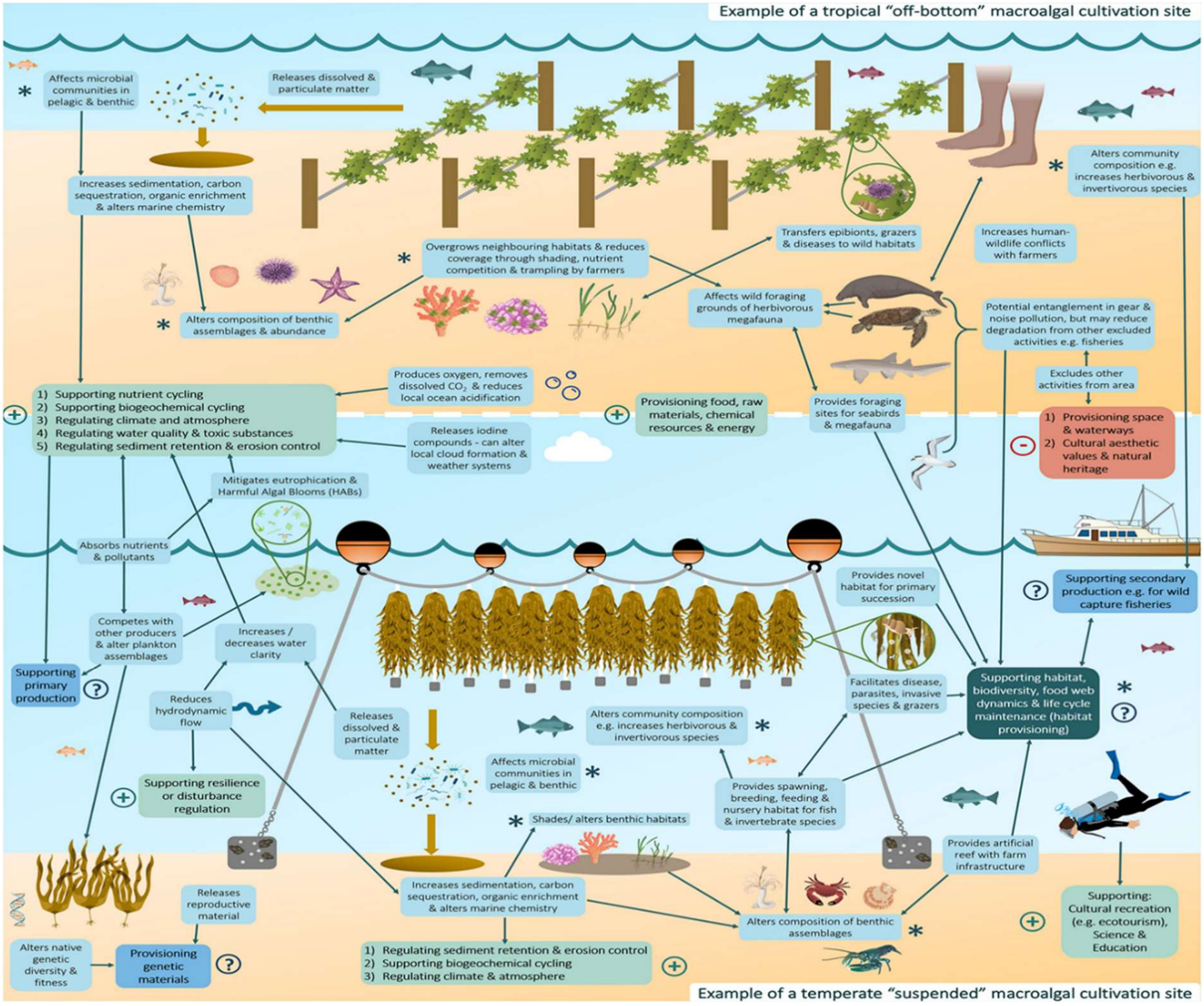


Fig. 16 Summary of the environmental impacts (light blue) and potential impacts on ecosystem services of a tropical 'off-bottom' macroalgae culture site (top) and a temperate climate 'hanging' macroalgae culture site (bottom). Potential effects on ecosystem services are indicated as positive (green (+)), negative (red (−)) and neutral or undetermined (blue (?)) and the habitat facility is marked (thunder blue-green). Some impacts related to habitat supply are indicated with an asterisk (*) for clarity (source: Integration and Application Network, University of Maruland Center for Environmental Science (http://ian.umces.edu/imagelibrary/) and BioRender (Biorender.com).

When aiming to increase or optimize ecosystem services, modifications can be made to cultivation methods (e.g., integrated multi-trophic aquaculture, offshore farming), cultivation systems (e.g., suspended culture, artificial reef structures) or Cultivated species (e.g., selecting native species or species with high ecological benefits). Table 7 outlines practical applications of these principles in aquaculture.

Table 7 Ecological services provided by aquaculture (based on the expertise of the authors)

Service	Species	Aquaculture practise
Provisioning services		
Food	Fish, molluscs, algae, crustaceans	Intensive cultvivation, sea ranching
Supporting wild populations	Fish, molluscs, algae, crustaceans,	Intensive cultivation with harvesting after breeding season
	Fish, algae, crustaceans,	Intensive breeding with controlled escapes
	Fish, crustaceans,	Sea ranching
	Fish, molluscs, algae, crustaceans,	Population-support measures
Regulatory services		
Storage of CO2	Algae	Intensive cultivation
	Bivalves (uncertain)	Co-cultivation with algae
Reducing acidification	Algae	Co-farming with shellfish
Erosion protection	Bivalves, algae	Cultivation in coastal areas
	Mussels	Creation of natural reefs under cultivation system
Nutrient removal	Lowtrophic fish species, bivalves, algae	Co-breeding
Increase water clarity	Lowtrophic fish species, bivalves, algae	Co-breeding
Habitat formation and biodiversity support		
Provision of artificial habitat	Fish, seaweed, bivalves	Intensive cultivation
Provision of natural habitat	Bivalves, seaweed, tube worms	Bottom culture; providing natural habitat
Cultural services		
Provision of employment	All	
Tourism	All	Allowing tourism activities linked to offshore wind and aquaculture

Although the net gain principle is gaining support, particularly within the aquaculture sector, there is still uncertainty regarding how it can be quantified. Is the goal for aquaculture to have a positive effect on all environmental aspects (reducing general pollution, reducing CO2, increasing biodiversity, creating habitat, etc.)? Or is it sufficient to adjust mariculture practices so that they result in a positive impact alongside a negative one? Certain types of aquaculture production (e.g., integrated multitrophic aquaculture) and the farming of extractive species (such as algae and bivalves) consistently generate a direct positive environmental impact, as they help mitigate excess nutrients (Stechele, 2023).

3.3. Economic framework conditions

A key question often raised in the development of offshore aquaculture is its economic feasibility. It is evident that the harsh offshore conditions of the Belgian North Sea and the considerable distance from the coast result in significant costs, both operational (OPEX) and in terms of investment (CAPEX). In the Belgian context, however, the MRP 2020-2026 stipulates that commercial cultivation can only occur in an OWF and in five zones designated for commercial and industrial activities. According to the draft version of the new MRP (2026-2034, kb_publieksraadpleging_nlfr_0.pdf (belgium.be)), this approach will be significantly revised, allowing aquaculture outside OFPs (among other changes), but this study cannot anticipate this.

Estimating the production costs of offshore farming is challenging without access to the economic data of a specific sea farm. John Holmyard of Offshore Shellfish, United Kingdom (Cultured Mussel Farm In Brixham I Offshore Shellfish Ltd), who farms offshore mussels (outside of OWF, though), confirms (pers. comm.) that production costs fluctuate significantly over time, between locations, and with the size of the sea farm. According to Holmyard, the most significant costs are labor, fuel, and the capital invested (CAPEX). These costs are highly location-dependent: the further out to sea, the higher the fuel and personnel costs. Investment costs are also elevated, as offshore conditions necessitate specialized equipment. Furthermore, material can be lost, and this loss can cause damage to other parts of the infrastructure, such as when a mussel line becomes detached and gets caught in the propeller of a service vessel. Tracker systems may offer a solution by enabling quick responses to detect and recover detached components.

When aquaculture is conducted in OWFs, there is also a hefty insurance premium for damage to third parties. Growers must insure against millions of potential damages to OWFs, leading to high premiums for a sector focused on primary production (Edulis, United projects). For example, Dutch fishing vessels operating passively in the OWF Borssele II are insured for a minimum of 500 million euros (Neitzel et al., 2023).

For offshore mussel farming, several calculations have been made based on demonstration pilots or available literature (Buck et al., 2008; van den Burg et al., 2017). However, the profitability predictions have never been confirmed by real-world practice. Typically, estimates tend to be overly optimistic (informal talks between N. Nevejan and the mussel sector).

Policy briefs and study groups (Cappell & Huntington 2023) emphasize the critical importance of ensuring food security in Europe. This aspect should be factored into the economic evaluation of offshore aquaculture. Even if aquaculture, as a "stand-alone" activity, is not financially viable, commercial production can still generate socio-economic value by providing locally produced seafood and new job opportunities, promoting innovative technologies for farming and services in extreme hydrodynamic conditions, supplying raw materials for biorefineries (such as seaweed, tunicates, etc.), and underscoring the importance of the sea to humanity. A parallel can be drawn with the agricultural sector, which, despite being more mature than aquaculture, continues to receive heavy subsidies from Europe and Member States (€264 billion for the period 2023–2027 IP_22_7639_EN.pdf; europa.eu).

3.4. Legal preconditions

The federal legislation covers most activities occurring seaward in relation to the baseline, within the territorial sea, and the EEZ (Sea Convention 1982) (Lescrauwaet et al., 2013). For instance, renewable energy production and aquaculture in the BNS fall under federal jurisdiction (with the respective responsibilities held by the Minister of Energy and the Minister of the North Sea) (Court of Audit 2013; Maes et al., 2013).

The BNS is intensively utilized by a wide range of stakeholders. To guide these activities in the right direction, numerous international and national laws and regulations are in place to mitigate, reduce, or avoid the impacts of these activities. The legal framework therefore provides critical preconditions that must be considered when developing the offshore aquaculture sector. An overview of the relevant regulations at both the European and federal levels can be found in Annex 5. For the consolidated European and Belgian policy context, references are made to Eurlex, the Belgian Official Gazette, and the Justel databases. A brief description of the most pertinent European frameworks is available in Annex 6. The Aquaculture Vision Document (Van Maele et al., 2023a) has already identified significant legal barriers to the integration of aquaculture within an OWF.

Member States bordering sea basins are obligated under European law to develop a marine spatial plan (MSP). This spatial plan is an essential tool for organizing the objectives of other European directives in a spatial context. Activities such as energy production at sea (EU Green Deal) and nature conservation (Natura 2000, Marine Strategy Framework Directive, Water Framework Directive) are spatially implemented through the MSP. In Belgium, the MRP is established by royal decree.
The current MRP (2020-2026) Royal Decree MRP 2020 | FPS Public Health (belgium.be)(Royal Decree MRP 2020 | FPS Public Health (belgium.be) is a continuation of the first Marine Spatial Plan and provides, among other things:

- a second zone for offshore energy, the Princess Elisabeth zone, which should lead to almost a doubling of energy capacity (to 20% of Belgium's electricity needs by 2025/2026). The Princess Elisabeth zone will be divided into three zones, viz. Zone 2 Noordhinder-Noord, Zone 3 Noordhinder-Zuid and Zone 4 Fairy Bank (domain concessions in Zones 3 and 4 can only be granted, subject to obtaining a Natura 2000 authorisation). Zone 1 Eastern zone (near the Dutch border) will continue to exist;
- an extra nature reserve on the Dutch border;
- three search zones for bottom protection measures;
- five specific zones in which commercial and industrial activities can be developed.

For the Eastern zone, aquaculture is permitted under the following conditions (Art. 14.§1):

- the holder of the concession for the construction and operation of a wind farm agrees;
- aquaculture reduces the level of eutrophication within the concession zone;
- the Minister granting a concession or permit may, where necessary, safeguard a control zone within the demarcated zone, as a reference for the situation without aquaculture activity.

Aquaculture is permitted for the Noordhinder-Noord zone, under the following conditions Art.14.§2):

- aquaculture reduces the level of eutrophication within the concession zone;
- the Minister granting a concession or permit may, where necessary, safeguard a control zone within the demarcated zone, as a reference for the situation without aquaculture activity.

Aquaculture is permitted for the Noordhinder-Zuid zone and Fairy Bank, under the following conditions (Art.14§3):

- aquaculture reduces the level of eutrophication within the concession zone;
- the Minister granting a concession or permit may, where necessary, safeguard a control zone within the demarcated zone, as a reference for the situation without aquaculture activity;
- a Natura 2000 permit has been obtained.

Passive fishing is permitted for the zones Noordhinder-Noord, Noordhinder-Zuid and Fairy Banks (Art.14§4).

Furthermore, aquaculture activities are subject to food safety legislation. On one hand, when importing animals (TRACES and health certificates), it is important to ensure that animals from other areas (even within Europe) do not carry diseases (such as viruses and/or parasites). On the other hand, the cultivated products must also be safe for human health. This is particularly crucial in bivalve shellfish farming, where significant attention is given to the safety of the product. These organisms are non-selective filter feeders, meaning they filter viruses, bacteria, phytoplankton, and zooplankton from the water. Under certain conditions, high concentrations of noroviruses, enterobacteria like *E. coli* and *Salmonella sp*., and/or toxic phytoplankton (single-celled algae that produce harmful substances) can be present in the water. As the shellfish filter the water, these pathogens and toxins accumulate in their tissues. While these viruses, bacteria, and toxins do not harm the shellfish, they can be dangerous to humans. Toxic phytoplankton can lead to various illnesses, including vomiting and diarrhea (Diarrhetic Shellfish Poisoning - *DSP*), disorientation and memory loss (Amnesic Shellfish Poisoning - *ASP*), and nervous disorders and paralysis (Paralytic Shellfish Poisoning - *PSP*). Routine monitoring of bacteria and toxic substances in bivalve shellfish tissue is therefore necessary (Royal Decree of 12 March 2000 amending the Royal Decree of 30 April 1976 on the inspection and trade of fish).

3.5. Preconditions OWF-Fisheries

In this study, fishing is utilized as a harvesting method for target species farmed using non-intensive cultivation techniques. The production from sea ranching activities or population-supporting techniques is harvested within the wind farm using passive fishing, while the spill-over effects outside the wind farm can be harvested through both passive and conventional fishing methods.
The RD MRP 2000-2026 includes passive fishing as an authorized activity within the new PEZ. This primarily covers fishing with rods, longlines, and pots, which present minimal risk to the operations and safety within the OWFs. Fishing with standing or drifting nets is not currently considered, given the length of the gear and the associated risks if it drifts.

Passive fishing vessels are designed for precise manoeuvring, essential for the deployment and retrieval of fishing gear. The MARIPAS project (Verhaeghe et al., 2011) highlighted that small, light vessel typically under 150 GT, used in passive fishing, pose little risk of collision or interference with turbines. Recently, there have been efforts across Europe to implement passive fishing in UWPs. For instance, in the Netherlands, "area passports" are used to designate specific areas for co-location with passive fishing (WP5 – 5.7). The safety zone around each turbine and buried cables has been reduced to 250 m to allow passive fishing (Borssele plot II) (Ministry of the Interior and Kingdom Relations, 2020). Additionally, in the Netherlands, the OWEZ, Amalia, and Luchterduinen wind farms will open for vessels up to 24 meters, recreational rod fishing, and experimental pot fishing.

Experience in Belgium

The Links and Pots project (Verhaeghe et al., 2008) demonstrated that various types of passive fishing, both using standing rigging and pots, can be applied profitably in the Flemish context. The project also showed that the main target species for the Flemish fishery, the sole, can be caught efficiently using standing nets. However, it was also evident that there is a lack of expertise in the field. The subsequent VESPAS project explored the potential of passive fishing in the North Sea, extending to more distant fishing grounds such as the Celtic Sea (Verhaeghe & Polet, 2012).

In 2016, the LIVIS project examined the transition from recreational fishing vessels to small-scale commercial fisheries. A theoretical profitability simulation was conducted for three different scenarios, focusing on transitions from both commercial and recreational fisheries to standing rigging, handline fishing, and small-scale trawl fishing. While the average net profit varied between €20,000 and €35,000 across all scenarios, small-scale fishing proved to be barely profitable, with few reserves to absorb significant setbacks or invest in the future. Additionally, weather conditions were identified as a limiting factor, restricting operations to an average of 125 days per year. As a result, a commercial small-scale fishing operation would likely need to be combined with a part-time job to ensure the necessary flexibility.

From discussions with the Rederscentrale (Annex 4), it was also clear that there is only limited enthusiasm for passive fishing. Currently, only one vessel in the Belgian fleet is registered for passive fishing. However, two new passive fishing projects, led by ILVO, are underway: the TIP-TOP and POLLUX projects.

In the United Kingdom, the Department for Business Enterprise and Regulatory Reform (BERR) has issued several recommendations for multi-use space in OWFs through the Fishing Liaison with Offshore Wind and Wet Renewable Group (FLOWW). These recommendations include "Best Practice guidance for offshore renewables developers," which addresses how fishing can be permitted near OWFs, the negotiation process, management arrangements, etc. The safety zones around turbines have been reduced to 50 meters, allowing fishing in most cases. Typically, only passive fishing gear is permitted, but towing is allowed in some OWFs.

Roach et al. (2018) successfully implemented rotating closures of lobster fishing areas in the OWF Westermost Rough, which helped prevent overfishing while also aiding the recovery of lobster populations.

In Germany, similar measures have been taken, with the safety perimeter around OWFs reduced from 500 m to 150 m, allowing passive fishing near Heligoland (Das Bundesamt für Seeschifffahrt und Hydrographie, 2021). However, despite these adjustments, passive fishing is not yet fully practiced in German UWPs due to unclear and inadequate insurance regimes, such as the failure to define coverage for costs arising from damage to turbines or cables as a result of fishing activities in OWFs (National Government, 2018).

3.6. Preconditions OWF - Access to the turbines

One of the main challenges of installing mariculture operations between wind turbines is ensuring the normal and continuous accessibility of maintenance vessels to each turbine. Any period of time when a wind turbine is not operational results in lost electricity generation. Therefore, it is critical that each turbine remains accessible for maintenance as quickly as possible. This requires that floating mariculture installations be arranged in such a way as to leave clear corridors for easy access. In the case of submersible mariculture installations, maximum use of the space between turbines can be achieved, as an installation can be placed in each quadrant (Fig. 17).

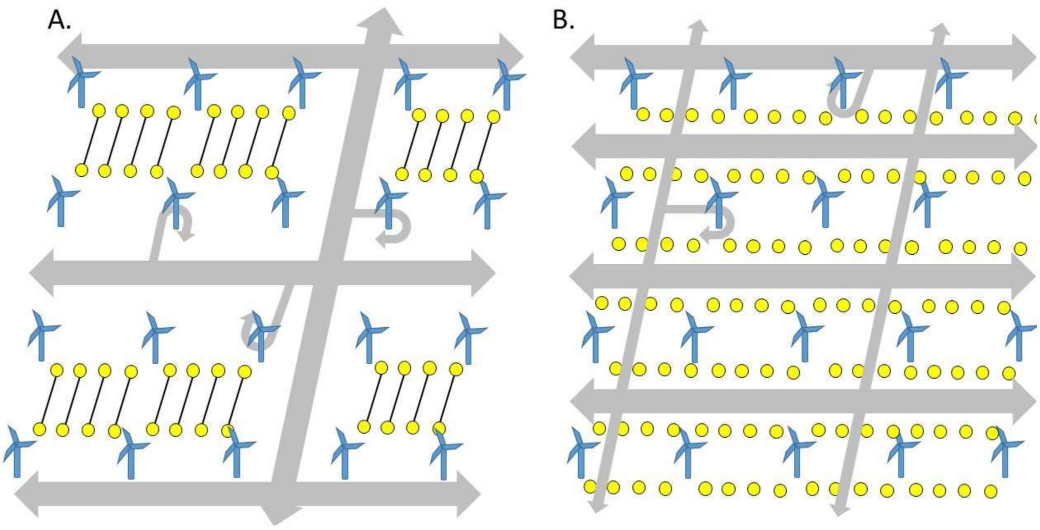


Fig. 17 Passage possibilities at A. mariculture installations on the water surface: for a smooth passage it is necessary to leave corridors free, along which rapid interventions are possible; B. bottom cultivation or submersible mariculture installations do not in themselves constitute a major obstacle (there are only surface buoys present), which can greatly increase the number of mariculture installations.

To integrate aquaculture infrastructure similar to Zeeboederij Westdiep (Colruyt Group) into an OWF, at least 200 longlines of 100 meters would need to be installed. In the Edulis project – Offshore mussel cultivation in wind farms, an estimate was made for the C-Power zone, considering space requirements for the production of 5800 tonnes of mussels, which would represent 10% of the amount imported from the Netherlands. However, this information cannot be shared. It is evident, however, that an OWF might not have enough free space for the installation of the 200 longlines mentioned above, considering safety zones between turbines.

In discussions with OWF operators (Annex 7), it was emphasized that even urgent, ad-hoc aquaculture activities—such as retrieving loose structures or conducting urgent repairs—should not disrupt the normal functioning of the wind farm.

3.7. Preconditions OWF – Safety

From discussions with the OWF operators (Annex 7), it is clear that ensuring the safety of both personnel and equipment is of utmost importance, and every effort must be made to maximize this. This explains why additional precautions are taken, such as: (1) restricting access to verified users only, and (2) permitting access only to verified companies.

Furthermore, certain areas within the wind farm are completely off-limits to third parties, such as the safety zones surrounding the turbines, cables, and substation. Diving is also prohibited unless exclusive permission is granted by the wind farm operators.

Any extra activities within the OWF are seen as additional risks for investors and will, under the current legislative framework, result in increased insurance costs. According to the OWF operators, these costs must be covered by the aquaculturist and cannot be transferred to the OWF operators.
The regulations and procedures applied to the vessels, the crew, and every activity within the concession are critical factors to consider. These lead to a strict work schedule and necessitate thorough and timely preparation. Including the aquaculturist in the consortium managing the OWF concession could help streamline processes.

WP4: Scenario's for integrating aquaculture into OWF with published tenderprocedure and outside Natura 2000 area (Cat.3)

4.1. General

After evaluating the existing cultivation techniques, various possibilities for food production within existing OWFs (or OWFs with an existing tender procedure, Cat. 3) have been identified. The techniques are categorized as outlined in WP1, covering options for intensive farming, sea ranching, and population-support measures (under 4.3, 4.4, and 4.5). Additionally, these scenarios consider what is technically feasible based on the current knowledge of the authors. However, further research is required to assess whether the proposed techniques are viable from a social, ecological, and economic perspective.

The scenarios described below apply to both the existing Eastern zone and the yet-to-be-developed PEZ I (cf. Strategy, basic knowledge, and basic principles). Currently, eight offshore wind farms (Norther, C-Power, Rentel, Northwind, Nobelwind, Belwind, Northwester II & Seamade) are operational within the Eastern zone (238 km²), producing renewable energy. These wind farms consist of 399 wind turbines, of which 344 (86%) are monopiles, with a combined installed capacity of 2.26 GW. The average annual electricity production is 8 TWh, representing approximately one-third of Belgium's gross electricity production from renewable energy sources (BMM- naturalsciences.be) (Table 8). The new PEZ (285 km²) is expected to have a total installed capacity ranging between 3.15 and 3.5 GW.

Table 8 Overview of the operational OWFs in the BNS (taken from Van Maele et al., 2023b)

Project		#	Capaciteit (MW)	Type fundering	Rotor dia-meter in m	Naaf hoogte in m LAT[6]	Totale capaciteit in MW	Opera-tioneel sinds	Diepte LAT[7] in m	Dia-meter	Afstand tot kust
Norther		44	8.4	monopile	164	107	370	2019	20-35	8-9 m	23
C-Power	phase 1	6	5	gravitair	126	94	325	2009	14-18	n.v.t.	30
	phase 2 & 3	48	6.2	jacket	126	94		2013		n.v.t.	
Rentel		42	7.4	monopile	154	106	309	2019	22-36	8 m	34
Northwind		72	3	monopile	90	72	216	2014	16-29	6-7 m	37
SeaMade = Mermaid + Seastar		58	8.4	monopile	167	109	487	2020	24,4 - 39,5 22-38	8,3	54 40
Belwind	phase 1	55	3.1	monopile	90	72	171	2011	15-37	4,3	49
	Alstom Demo	1	6	jacket	150	100		2013		n.v.t.	
Nobelwind		50	3.3	monopile	90	72	165	2017	26-38	6-7	47
Northwester 2		23	9.5	monopile	164	106	219	2020	25-40	8-9	51

4.2. Preconditions for integration

As outlined in the Vision text *Aquaculture in Offshore Wind Farms* (Van Maele et al., 2023a), aquaculture in the BNS must contribute to food production, preferably for local human consumption, with a focus on local species. Additionally, the authors emphasize that aquaculture should aim to improve the overall state of the ecosystem.

Beyond the general preconditions described in WP3, discussions with representatives from various OWFs, BOP, and the Rederscentrale have highlighted specific concerns regarding the integration of aquaculture into existing wind farms, which are summarized here.

One of the primary barriers for wind farms to incorporate aquaculture within an OWF is the increased operational risk posed by the presence of new structures and additional vessel movements. The experimental nature of most offshore aquaculture installations suitable for the BNS further compounds these risks. This leads to higher costs, not only for the grower but also for the wind farms, as insurance premiums rise, administrative burdens increase, and more frequent repairs become necessary. Furthermore, OWF operators stress that the current energy infrastructure is not designed for integration with other activities, requiring a collaborative design process in advance to enable future compatibility. The key enabling condition derived from this is that integrating aquaculture activities introduces additional risks to OWF infrastructure and operations.

Meanwhile, the Rederscentrale has indicated that (1) only one Belgian fisherman is currently engaged in passive fishing activities, (2) the fishing sector has little interest in transitioning to passive fishing, and (3) existing fishing vessels are not adapted for operations within an OWF. As a result, sea ranching and stock enhancement—two alternative aquaculture methods that rely on passive fishing for harvesting within wind farms—would require a significant awareness-raising campaign to convince the fishing sector of their economic potential. However, it may be worth noting that individual fishermen have shown increasing interest in passive fishing when approached directly, as observed in interviews conducted within the context of the Westdiep Sea Farm and ILVO projects on passive and coastal fishing.

4.3. Intensive culture Scenarios

The integration of intensive systems into traditionally designed wind farms is technically feasible but involves significant risks, requiring the grower to present a comprehensive risk management plan.

The proposed aquaculture systems are ranked based on their ease of implementation, from the easiest (green) to the most difficult to achieve(orange). Commercial bottom farming of shellfish is identified as the most straightforward aquaculture option within OWFs, whereas commercial hanging culture (floating longlines) for mussels and seaweed presents greater challenges.

4.3.1. Bottom systems / small / no feeding

Kind	*Latin name*	Price BE (€/kg)	Price EU (€:kg)	IUCN status	Achievable
Flat oysters	*Ostrea edulis*	0.8€x9/kg= 7.2€/kg	11,40 – 18,60	NE	
King scallop	*Pecten maximus*	2,58	4,35 - 5 35	NE	

For the cultivation of specific bivalves such as flat oysters and scallops, systems can be used that have minimal impact on the operation of the OWF and do not pose risks to its infrastructure. Examples of such systems include various types of oyster cages and fences (Fig. 18). These small-scale systems can be made of plastic or other materials that do not cause damage to the OWF infrastructure.

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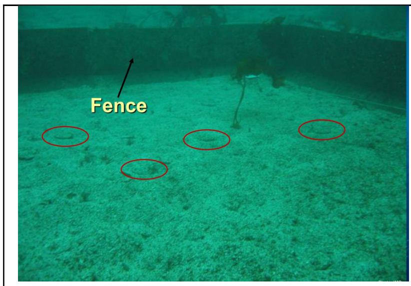
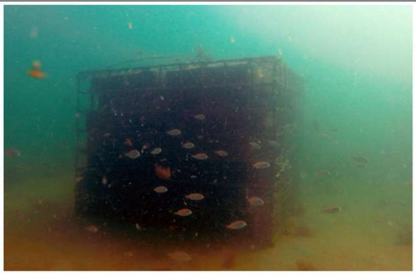
<tr><td>
</td><td></td><td></td></tr>
<tr><td>Fences to protect scallops from predation. HI presentation blue english (mote.org)</td><td>Oyster cage with several layers of https://ketchamsupply.com/product/oyster-trays/</td><td>Oyster cage with baskets. https://cottagecityoysters.com/the-process</td></tr>
</table>

Fig. 18 Bottom systems can be deployed in the short term

Furthermore, these systems can be placed in "low-risk" areas, such as deeper zones within the OWF, ensuring they do not come into contact with turbines or cables positioned higher on sand dunes. By considering the current, it is also possible to design the structures so that, in the event of anchoring failure, they drift away from the wind farm rather than towards it.

4.3.2. Harvesting mussels of turbines

Kind	*Latin name*	Price BE (€/kg)	Price EU (€:kg)	IUCN status	Achievable
Blue mussel	*Mytilus edulis*	1,80	1,70 – 6,27	LC	

Fouling on turbines contains a significant amount of biomass. For example, at North Hoyle in Ireland, fouling ranges from 1000 to 1300 kg per turbine, with the dominant species being the blue mussel, *Mytilus edulis* (Demmer et al., 2022). A study by Krone et al. (2013a) reports an average biomass of 4300 kg in the German Bight on a construction area of 1280 m² (steel jacket). In this case, blue mussels are primarily found in the upper zone, between 1 and 5 meters below the water surface, with their biomass estimated at 2180 kg.

On the monopiles off the Belgian coast, biofouling is mainly composed of blue mussels and the sea anemone *Metridium senile* (Degraer et al., 2022). The density of blue mussels in Belgium is estimated at 6468 individuals per m², with an even distribution over the first 6 meters (Ivanov et al., 2021).
As the number of turbines increases, the expansion of blue mussel populations is expected to continue. Since mussels feed on phytoplankton (primary producers), a high biomass of blue mussels could negatively affect organisms that depend on phytoplankton (secondary producers) both within and beyond the OWFs. Estimates of this impact vary significantly from a 1.5% reduction in primary standing stock in Belgium (Mavraki et al., 2020) to as much as 8% in the Southern North Sea (Slavik, 2018). These effects are not negligible, and harvesting mussels from turbine structures could help mitigate potential negative consequences from overgrazing.

The company Ashtead Technology has already developed field-proven systems for removing soft and hard marine fouling (biofouling) from structures such as ship hulls, pipelines, subsea infrastructure, mooring chains, and monopiles in offshore wind farms (Fig. 19). Given the clear stratification of biofouling organisms on turbines within OWFs, it is possible to collect a relatively pure fraction of mussels during the cleaning process using such devices (Fig. 19).

OWF operators do not consider the presence of mussels on turbines to be a problem and are concerned that cleaning the turbines could damage the coating (Annex 7). However, HexDefence panels from the company Balmoral, originally designed for erosion protection, could potentially serve as a protective barrier for the turbine (HexDefence scour protection | Home | Balmoral (balmoraloffshore.com). The harvested mussels can be hydraulically harvested and collected directly into big bags on the deck of the ship.

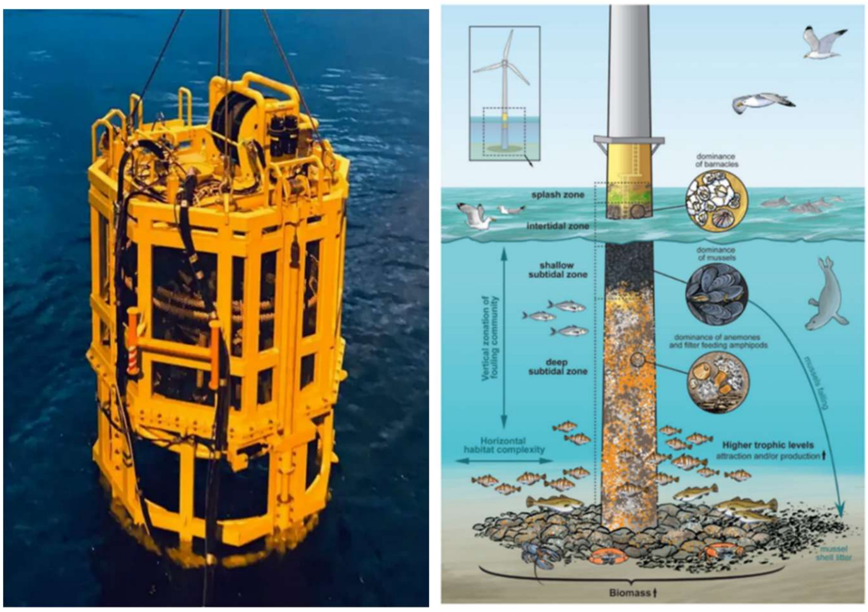


Fig. 19 L, Cleaning system for removing biofouling on turbines in OWFs (Ashtead Technology); R, Stratification in biofouling on the turbines in Belgian wind farms (Illustration by Hendrik Gheerardyn in Degraer et al., 2021).

4.3.3. Bottom breeding of flatfish with feeding

Kind	*Latin name*	Price BE (€/kg)	Price EU (€:kg)	IUCN status	Achievable
Brill	*Scophthalmus rhombus*	12,12	4,50 – 9,45	LC	
Halibut	*Hippoglossus hippoglossus*	12,49		NT	
Turbot	*Psetta maxima*	15,68	9,85 – 15,88	LC	
Sole	*Solea solea*	17,54		DD	
Sand sole	*Solea lascaris*	10,79	13,45 – 31,00	LC	

Due to the shallow depth in OWFs, the authors have little confidence in the feasibility of breeding fish in floating fish cages. However, a possible alternative could be the use of low, bottom-standing fish cages for flatfish farming, such as the PDW submerged Chinese-made fish cage (Fig. 20).

Flatfish species such as sole, brill, and turbot are commercially valuable both regionally and internationally, as they are key target species for the Belgian fishery and processing industry (cf. also Table 4). Additionally, their culture biology is well understood. Under normal conditions, the PDW cage remains on the seabed. For maintenance and harvesting, the cage can be made floatable, improving accessibility and safety without the need for divers.

Since the cage rests on the bottom, flatfish can burrow into the sand or settle on various platforms (nets) within the cage, significantly increasing the effective surface area available for farming.

Experiences with this type of fish cage at the Yantai Institute for Fisheries Research in Shandong Province have demonstrated its effectiveness for turbot cultivation. Fry of the false flounders *Paralichthys olivaceus* and *P. lethostigma* (50–100 g) were successfully grown in these cages to 800–1000 g within 6–8 months at a stocking density of 20 fish/m². During this period, the fish cages also proved their durability by withstanding a typhoon.

Fig. 20 PDW Submersible Fish Cage developed by Fishery Machinery and Instrument Research Institute (FMIRI°, Shanhai, China)

However, the flatfish in the submerged fish cage must be fed. Since only extractive aquaculture is allowed at sea in Belgium, such farming can only be applied in the BNS if combined with the cultivation of extractive species like mussels, oysters, and/or seaweed (IMTA). It must be demonstrated that the nitrogen (N) and phosphorus (P) inputs from the fish feed are smaller than the N and P outputs from harvesting the shellfish and/or seaweed.

Automatic feeding will be necessary for the flatfish, as the breeding location is not always accessible due to weather conditions. It is estimated that 130 to 160 boat trips can be made per year with a small vessel. Automatic feeding can be done using so-called feeding buoys, which float above the fish cage and deliver feed via a pipe (also serving as an anchor line). These buoys, such as those from Zeni Lite Buoy Co. Ltd (Japan), can contain one or more silos, depending on their size, allowing them to feed multiple fish cages (Fig. 21).

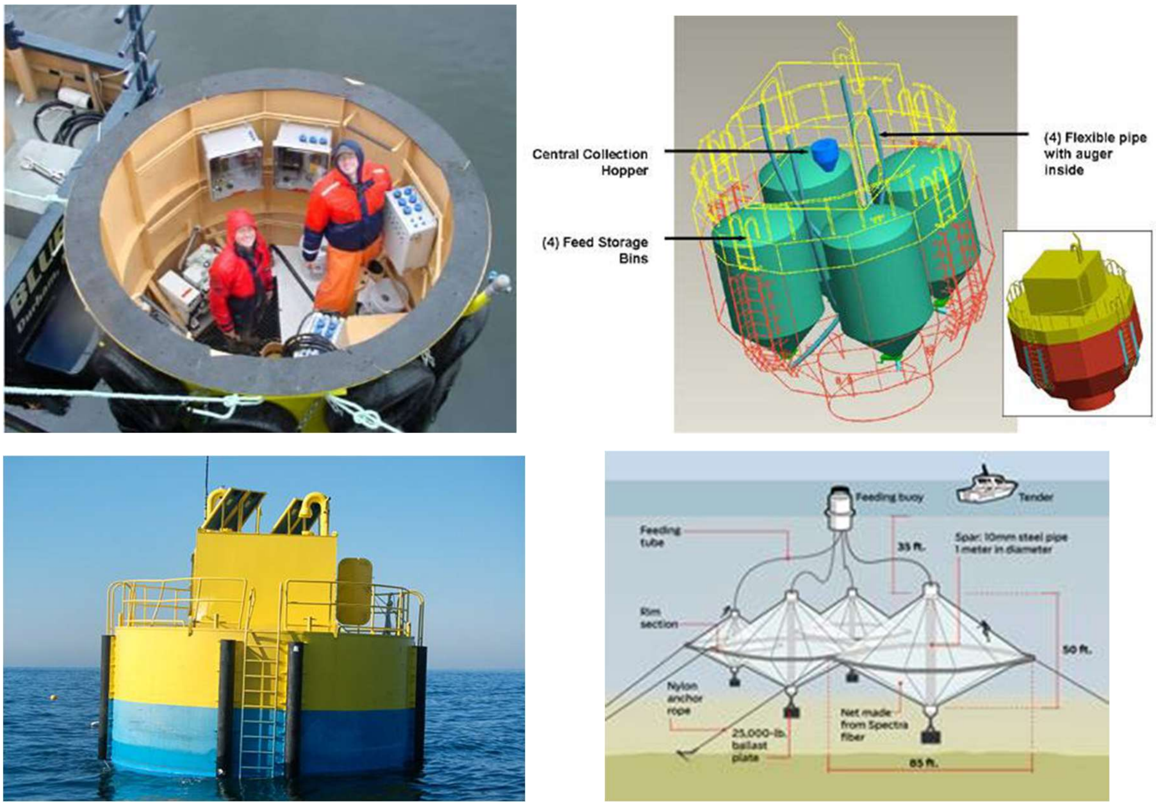


Fig. 21 Buoy for automatic feeding of the buoy: LB: Interior of the buoy with the control system (Zeni Lite Buoy CO. LTD); RB: Construction drawing with four different silos for fish feed (Zeni Lite Buoy CO. LTD); LO: The automatic buoy for feeding into the water (Zeni Lite Buoy CO. LTD); RO: Diagram of the feeding buoy above a number of sea cages SeaStation (OcenaSpar) (Goseberg et al., 2017)

4.3.4. Extractive culture of sole (Solea solea)

Kind	*Latin name*	Price BE (€/kg)	Price EU (€:kg)	IUCN status	Achievable
Sole	*Solea solea*	17,54		DD	
Blue mussel	*Mytilus edulis*	1,80	1,70 – 6,27	LC	

The authors see a great opportunity to combine the two techniques mentioned above (4.3.2 and 4.3.3), where the mussels harvested from the turbines are sorted on board. The undersized mussels can be used as feed for juvenile soles (since soles feed on shellfish) in the bottom cages, while the commercial-sized mussels are taken ashore for further processing and packaging. Additionally, the authors propose recovering juvenile soles from the by-catches of the coastal fleet, such as from shrimp fishing, and raising them into market-ready products in the bottom cages. The authors visualised the concept in an infographic (Fig. 22). Tests on board shrimp fishing vessels have been successful in keeping grey shrimp alive in tanks, and this method can also be applied to keep juvenile sole alive (Fig. 23). This approach helps avoid the problem of genetic narrowing (inbreeding) in seed stocks, which can occur in nurseries. However, this solution requires a change in legislation regarding the landing of by-catches.

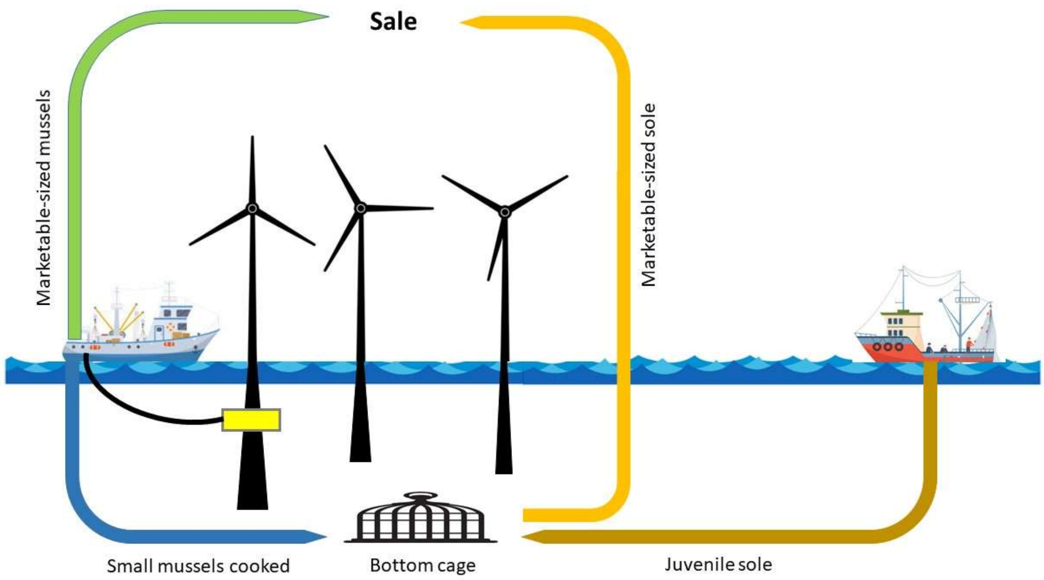


Fig. 22 Infographic 'Extractive sole culture in OWF'.

Fig. 23 Habitat tank for grey shrimp on board a shrimp fishing vessel (Photo: Xavier Vermeersch).

4.3.5. Longline cultivation of mussels and seaweed

Kind	*Latin name*	Price BE (€/kg)	Price EU (€:kg)	IUCN status	Achievable
Blue mussel	*Mytilus edulis*	1,80	1,70 – 6,27	LC	
All seaweeds					

Experience in the BNS (cf. WP1 and WP2) has shown that hanging culture of mussels and sugar kelp is both biologically and technically feasible in offshore areas. Collecting wild mussel seed is a reliable technique (cf. also the experience in the Netherlands), and unlike traditional nearshore cultivation, the grow-out could be done using "self-thinning," meaning the juveniles would not need to be re-seeded during their growth. This method could lead to significant cost savings while still producing an acceptable harvest. Densities of 10 kg per running meter can be achieved in 16-18 months (Stechele et al., 2022). One of the major challenges, however, is the space taken up by the longlines on the surface. The number of longlines (and their length) that can be installed between turbines is limited.

The current experience being gained with the commercial Westdiep Zeeboerderij could play a crucial role in addressing the technical challenges that persist offshore. The use of a specialized vessel for maintenance and harvesting will be necessary, and the layout of the farm must be designed to match the capabilities of the vessel.

Although mussels are highly valued in Belgium (cf. WP1), neighbouring countries like the Netherlands are observing a decline in consumption. There, an aging population of mussel consumers (85% over 50) and a decrease in annual volumes marketed (market penetration dropped from 12-13% to 10% in the past 5 years) are noticeable (Sintnicolaas & Nijstad, 2024). This trend has not yet affected Belgium, but it may follow in the future with some delay.

Sugar kelp grows relatively well on nets in the Belgian North Sea, although further testing is needed to confirm this (press communication Jessica Knoop, UGent). Offshore conditions provide a favourable environment for seaweed, as the lower turbidity compared to coastal waters supports growth even a few meters below the water surface. The growing interest in macroalgae cultivation across Europe, for various purposes, presents a strong reason to leverage the existing expertise in Belgium (WP2). The authors anticipate that technological innovations in farming systems and harvesting equipment, along with the development of specific breeding lines, will be key outputs in this aquaculture sector in the coming years.

The limited number of longlines that can be installed between turbines has an even greater impact on seaweed cultivation than on mussel farming, as seaweeds thrive primarily in the upper meters of the water column. Van den Burg et al. (2016) concluded that offshore seaweed production in the North Sea is not currently economically viable. Their sensitivity analysis indicated that revenues would need to increase by about 300% for the operation to become financially viable. Technical innovations and system designs that allow for multiple harvests per year could help lower production costs. Additionally, the successful marketing of seaweed as human food, alongside the development of biorefinery concepts, could enhance the value of the seaweed produced, though competition from Southeast Asian exporters remains a significant challenge.

4.4. Sea ranching scenarios

4.4.1. Feeding structures for sea ranching

Kind	*Latin name*	Price BE	Price EU	IUCN status	Achievable
Sea bass	*Dicentrarchus labrax*	10,87	4,35 – 12,30	LC	
European lobster	*Homarus gammarus*	13,84	25,93 – 44,00	LC	
Edible crab	*Cancer pagurus*	4,92	10-00 – 16,90	NE	
Red crayfish, Red lobster	*Palinurus elephas*	22,62	10,39 - 22,62	NE	

The infrastructure needed for sea ranching of species like sea bass, lobster, and crab is relatively simple and can be easily integrated into an OWF. The main components of the required infrastructure include a feeding and conditioning system. One example of such a system is the automatic feeding buoy with an integrated acoustic system proposed by Zeni Lite Buoy Co., LTD (Fig. 24).

Clear cooperation between the OWFs and the aquaculture producer is essential for feed replenishment and monitoring to determine the population size. If mobile species are farmed, we suggest harvesting the conditioned individuals outside the OWF zone in the short term, as existing fishing vessels are not equipped for such activities within the OWFs. Hiring specialized ships that can enter the OWF zone is cost-prohibitive.

One fish species suitable for this approach is the sea bass. This species forms loose schools, allowing for social association. It lives near hard substrates, and studies of its stomach contents reveal that it feeds on natural prey associated with these substrates, such as crabs, lobsters, shrimps, cuttlefish, and small fish species (Grati et al., 2011). As a result, feeding can be minimized to supplementary feeding or the provision of carbohydrate-based sweets, alongside the use of an acoustic signal.

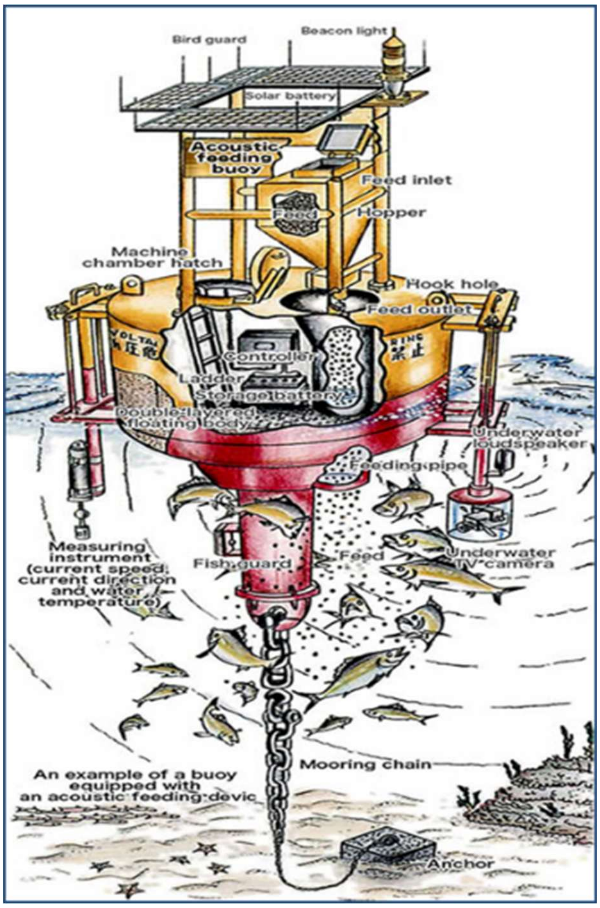


Fig. 24 Automatic feeding and acoustic buoy with a storage capacity of 80 tons (source: Zeni Lite Buoy Co., LTD).

4.4.2. Release of juveniles of the commercial target species

Kind	*Latin name*	Price BE	Price EU	IUCN status	Achievable
Sea bass	*Dicentrarchus labrax*	10,87	4,35 – 12,30	LC	
European lobster	*Homarus gammarus*	13,84	25,93 – 44,00	LC	
Flat oyster	*Ostrea edulis*	0.8€x9/kg =7.2€/kg	11,40 – 18,60	NE	
King scallop	*Pecten maximus*	2,58	4,35 – 5,35	NE	

Preconditioned seabass juveniles from hatcheries could be released and through their social behaviour, wild seabass will quickly be trained to respond as well to the conditioning signal and the reward (small amount of feed). Another species suitable for sea ranching with previous stocking, is the European lobster. Lobsters are home-bound and prefer hard substrates. Juvenile lobsters are available from hatcheries in the UK and Norway and can be released for sea ranching. Their territorial behaviour must be considered, and supplementary feeding is unnecessary. When recapturing the lobsters, traps should be placed close to the erosion protection layer, as their foraging distances are limited (5–124 meters), and the scent trail from the bait is only effective within 11 meters (Lees et al., 2018; Watson et al., 2009). Hatchery-produced oyster and scallop spat can be sown on the bottom of the sea for grow-out (WP1 - 1.3). Success will depend on the predation pressure, the size at stocking and re-capture success after some years.

The authors express the view that releasing juveniles may carry environmental risks and should be considered with the necessary scrutiny.

4.4.3. Introduction of artificial substrate and habitat to promote specific stocks

Kind	*Latin name*	Price BE	Price EU	IUCN status	Achievable
Sea bass	*Dicentrarchus labrax*	10,87	4,35 – 12,30	LC	
European lobster	*Homarus gammarus*	13,84	25,93 – 44,00	LC	
Edible crab	*Cancer pagurus*	4,92	10-00 – 16,90	NE	
Red crayfish	*Palinurus elephas*	22,62	10,39 - 22,62	NE	

The farmer is responsible for placing artificial reefs to support managed stocks, especially for target species that are considered private property. These artificial structures serve multiple functions: providing nutrition, protection, habitat, and reproductive opportunities. Successful examples can be found in the Japanese literature for scallops, where large-scale introduction of artificial reefs has proven effective, and in Norway for lobster.

The authors see potential applications for artificial reefs primarily for species such as sea bass, European lobster, and possibly the red crawfish. These target species can be harvested either within the wind farm itself or with traditional fishing techniques outside the wind farm using passive fisheries techniques.

4.5. Scenarios for population-support measures

Stock enhancement (population-support measures) are considered a feasible technique that can be implemented in existing offshore wind farms (Cat. 3). In theory, the construction of OWFs already boosts productivity due to the provision of hard substrate, shelter and by locally increasing food availability (fouling growing on the artificial hard substrate). However, these functions are not species specific, and mainly boost species with low commercial interest (e.g., whiting).

Commercial stocks can be supported on three levels:

4.5.1. Structural measures to support commercial target species

Kind	*Latin name*	Price BE	Price EU	IUCN status	Achievable
Eel	*Anguilla anguilla*	10,37	18,28	CR	
Sand sole	*Solea lascaris*	10,79	13,45 – 31,00	LC	
Sea bass	*Dicentrarchus labrax*	10,87	4,35 – 12,30	LC	
European lobster	*Homarus gammarus*	13,84	25,93 – 44,00	LC	
Edible crab	*Cancer pagurus*	4,92	10-00 – 16,90	NE	
Squid	*Loligo vulgaris*	7,42	8,15 – 15,07	NE	
Cuttlefish	*Sepia officinalis*	3,18	3,07 – 4,50	NE	

In 2020, Hermans et al. (2020) from Witteveen + Bos developed a catalogue to support nature-inclusive designs (NIDs) in offshore wind farms (available at: https://edepot.wur.nl/518699). The report recommends structural measures, such as placing artificial reefs or modifying offshore infrastructure, to help support stocks of target species like Atlantic cod, pygmy bolk, North Sea crab, European lobster, and flat oyster. The document outlines the biological and physiological information, commercial value, and habitat preferences for each species at various life stages. It also evaluates various commercially available NIDs, assessing their potential benefits as nurseries, shelters, and attachment substrates for eggs. Among the structures evaluated are add-on options like Biohut®, as well as modifications to scour and cable protection layers.

Additionally, the study highlights species that could benefit from structural adaptations to infrastructure (or additional infrastructure), including sea bass, cuttlefish, and squid. While examples of structural adaptations to infrastructure for sea bass populations were not found in the literature, there is existing research on supporting cuttlefish and squid populations, particularly with infrastructure designed for egg deposition (Kitahara et al., 2004; Cabanellas-Reboredo et al., 2014; Barillé et al., 2013; Carral et al., 2018; Grati et al., 2018) (WP1).

4.5.2. Release of juveniles of the commercial target species

Kind	*Latin name*	Price BE	Price EU	IUCN status	Achievable
Sea bass	*Dicentrarchus labrax*	10,87	4,35 – 12,30	LC	
European lobster	*Homarus gammarus*	13,84	25,93 – 44,00	LC	
Flat oyster	*Ostrea edulis*	0.8€x9/kg =7.2€/kg	11,40 – 18,60	NE	

The release of juveniles from migratory species, which are not bound to the offshore wind farm (OWF) zone, is not considered. However, juveniles from non-migratory species can be released to support the stocks of commercial target species. The authors express the view that while releasing juveniles can help, it may carry environmental risks and is likely not the most cost-effective method for increasing populations of commercial target species (WP1 – 1.4.1) .

Potential candidates for such releases might include species like sea bass, lobster and flat oyster. However, the authors also suggest that other population-supporting measures, such as adjusting fishing quotas, adapting fishing techniques, and creating fisheries-free zones, should be prioritized over juveniles releases.

4.5.3. Structural measures for habitat restoration

Kind	*Latin name*	Price BE	Price EU	IUCN status	Achievable
Flat oyster	*Ostrea edulis*	Na	Na	NE	
Sand mason worm	*Lanice conchilega*	Na	Na		
Ross worm	*Sabellaria spinulosa*	Na	Na		

The general assumption that habitat restoration enhances ecosystems and increases species richness and biomass holds true for offshore wind farms (OWFs) as well. The authors see opportunities for restoring biogenic reefs, particularly in Category 3 OWFs, at the scale of the wind farm. The restoration of biogenic reefs, such as those formed by flat oysters, is seen as a potential way to increase biodiversity, providing habitat, nutrition, and protection for various species, which could indirectly support commercial target species.

In Europe, including Belgium, there is a consensus that the biogenic reefs of flat oysters, which have disappeared, will not naturally return just by banning seabed-disturbing activities in the areas where they once thrived. The main challenge is the absence of breeding animals capable of producing larvae to recolonize these sites. Flat oysters are a commercially valuable species, and there is a significant amount of knowledge about their reproduction, as they are bred in hatcheries across Europe, particularly in France and the UK.

To address this issue, a promising technique called "remote setting" is being tested in various places, including Belgium (Project Belreefs). In this method, competent larvae from hatcheries are released and allowed to settle in new locations, helping to seed artificial reefs. This technique has shown potential as a cost-effective and efficient way to establish artificial reefs on a large scale.

The erosion protection layer of wind turbines offers a particularly suitable environment for this technique. Specifically, in areas like PEZ I, where historical oyster reefs once existed, this layer can provide an ideal surface for oyster larvae to settle and establish new biogenic reefs. The combination of the remote setting technique and the infrastructure offered by wind turbine erosion protection layers could be an effective strategy for restoring these valuable habitats. (De Mesel et al., 2018, Annex 3).

For other species, such as the sand mason worm, the ecological restoration potential is also noteworthy. ILVO (Belgium) (Wyns et al., 2020), has recently closed the cycle of this species, and while large-scale production still needs further investigation, this species can form reefs in sandy areas.
There are only a few reports in the literature about the breeding of *Sabellaria* species and attempts at restocking (Van Duren et al., 2016). Wild breeding animals can be encouraged to reproduce and larval breeding has also been described in the literature (Pawlik 1988). The species can occur as separate individuals or as reef structures. However, the reef structures are only formed in locations where there is a lot of suspended sediment (Callaway et al., 2010). Bangor University (Wales, UK) conducted experiments in 2013 on the cultivation of honeycomb worms (*Sabellaria alveolata*) in laboratory conditions, with the intention of releasing them into the field. The establishment of honeycomb worms on slate was successful, but a week after placing these structures in the field, all worms had disappeared (http://ukbars.defra.gov.uk/action/show/5926).

The erosion protection layer around wind turbines is seen as a key opportunity for supporting reef-forming species. One potential improvement is introducing a filter layer beneath the erosion protection layer (consisting of a smaller rock fraction and gravel), which would increase the surface area for the honey comb worms or Ross worms (*S. spinulosa*) to settle, creating better conditions for their establishment. The Ross worm prefers to settle on the border of the filter layer from where it starts to colonize more sandy seabed (https://doi.org/10.3389/fmars.2022.854986). Although it should be possible to establish reef structures with these species, challenges persist.

Additionally, increasing the complexity of the erosion protection layer itself—through mixing large and small stones or creating vertical stone structures—could support a wider variety of colonizing organisms, fostering greater biodiversity and increasing the food supply for target species. Groen (2019) showed how the structure of the erosion protection layer can be made more bioreceptive by mixing large and small stones in certain proportions so as not to compromise the stability of the structure and by stacking stones into vertical structures. In this way, the erosion protection layer offers more shelter to the colonizing organisms and the animals that are attracted to them.

4.6. Recommendations - short term

In order to make the proposed aquaculture activities possible in the short term, the authors have formulated recommendations.

Recommendations for OWFs

- To allow tests for harvesting mussels from the turbines.
- Install artificial structures to support commercial target species or endangered target species (https://www.witteveenbos.com/nl/nieuws/nieuwe-catalogus-voor-ontwerp-van-natuurinclusieve-offshore-windparken/).
- Seeding of erosion protection layers with oyster larvae via remote setting to create flat oyster populations in those zones where historic oyster beds were present (PEZ I).
- Adapting the erosion protection layer (complexity) to support commercially or ecologically interesting species.
- Restoration of natural or biogenic habitat in the PEZ I (not on OWF infrastructure but in the gravel beds between the turbines)
- Access to electricity supply for the aquaculturist and the fisherman. The local need for energy will increase in the future, especially if one also takes into account that the vessels serving the OWFs are making the transition to (hybrid) electric engines. Integrating aquaculturists and fishermen into the development process of providing energy at sea is required.

Recommendations for the government

- The current legislation is unfavourable for the integration of aquaculture into OWFs. The existing OWFs and OWFs for which the tender procedure is fixed (Cat. 3) have no obligation to multi-use and, given the additional cost, multi-use will not be carried out. An adjustment to the tender procedure for the future OWFs in which an obligation to multi-use (food production and/or nature restoration) is laid down would be an important step forward.

- Legal consequences of the integration of aquaculture activities in offshore wind farms are underexposed in this study, but will need to be mapped out in the near future. The authors see three important aspects that will need to be clarified:

- The period during which the entrepreneur carries out aquaculture activities is not necessarily synchronised with the duration of the licences of the wind farms. It will therefore be important to guarantee the right of exploitation to the grower, even if the OWF is decommissioned. Rotating through aquaculture locations could be a solution here, where an active grower has access to different locations (within an OWF or in different OWFs). This idea could also contribute to limiting impact on seabed ecology by spreading the impact of aquaculture activity over different locations. However, this is not feasible for all cultivation techniques, but would, for example, be possible for bottom cultivation of bivalves.
- The obligation to remove artificial structures in an OWF during the decommissioning phase will have to be adapted if it concerns artificial reefs or other structures that have been released as population-support measures (cf. 4.2. Preconditions). For example, artificial structures can be moved during dismantling, and can be put back after the construction of the new OWF.
- An amendment to the legislation on the landing obligation of bycatch for sole (*Solea solea*) is necessary to allow the cultivation of sole in bottom cages (cf. 4.2. Preconditions). It is important to note that only a very small fraction (<0.1% of the bycatch) of juvenile sole will be needed to support aquaculture activity (order of magnitude 40 000/year).

- The Rederscentrale currently has little interest in a switch to passive fishing (conversation 18/03/2024). This means that an awareness campaign will be needed to stimulate interest in passive fisheries techniques. In the light of future European fisheries measures, this is certainly recommended.

- Our North Sea is a very energetic and dynamic system. As shown in several research projects, storms often cause damage to aquaculture prototypes. Commercial systems that can withstand such weather conditions are not yet readily available. This means that there is a need for test zones. In Belgium, the 'Blue Accelerator' is an example of a test platform that is easily accessible and also offers the necessary legal support to users (insurance, licenses, etc.). Nevertheless, the Blue Accelerator is not representative for offshore conditions and therefore not suitable for testing the optimization of the integration of cultivation systems with an OWF. In addition, the location is not ideal for growth testing with major aquaculture species (mussels and oysters) due to the turbulence, poor water quality, and amount of fine sand in the water column. The authors therefore recommend setting up an offshore test platform in or near wind farms. Examples are available abroad. In the Netherlands, the North Sea Farmers have set up a plot of 6 km2 for testing all kinds of offshore activities or infrastructure (Offshore Test Site - North Sea Farmers). The site consists of 6 plots of 1 km2 and the North Sea Farmers facilitate research through access to licenses, insurance, protection, expertise, logistics optimization, ships and weather forecasts. In Germany, there are several research platforms, including the FINO3 research platform, which has been in operation since 2009 (FINO3 - research platform in the North Sea and the Baltic No. 3). The platform is placed 80 km away from Sylt in the middle of the DanTysk OWF. While the platform was originally intended to support the construction and operations of the surrounding OWFs, it is now also being used for testing aquaculture infrastructure (e.g. within the H2020 UNITED and the Horizon Europe Ocean Mission ULTFARMS project).

- Support measures for the further exploration of offshore aquaculture in the BNS. As indicated earlier, most cultivation techniques for offshore applications are still in an experimental phase and further research is needed to determine their technical and economic feasibility on a commercial scale. Support is requested for both intensive cultivation and for the development of large-scale and low-cost seeding techniques for habitat formers.

- Technological innovation in breeding systems is needed and must be stimulated now to make integration possible in the future. We are thinking specifically of automation of maintenance of the cultivation systems or the automatic adaptation of the systems to the changing hydrodynamic conditions and in function of the growth of the target species and the seasonal fouling on the systems. Innovative monitoring systems will contribute to greater safety. Close cooperation with the aquaculture sector in Europe must be set up for this purpose.

- Certain forms of aquaculture discussed in this work may be eligible for support measures through ecological trading programmes. A carbon marketing scheme is already in use, but the eligibility of aquaculture needs to be explored. There is also talk of setting up nitrogen and biodiversity credits. Some forms of aquaculture, mainly population-support measures, would be eligible for such marking schemes of ecosystem services. The authors of this work consider it important that such financing methods for nature restoration (and creation) are officially accredited. According to the authors of this work, it is up to the government to regulate such sources of funding to prevent abuse and greenwashing.

Recommendations for the aquaculturist

- The local need for energy will increase in the future with the technological development of the cultivation systems. How green energy can be made available will have to be investigated in close cooperation with OWFs.

- One area where innovation is imperative is the development of multi-purpose vessels. The military sector is already working this, whereby the same ship can be used for both humanitarian purposes and for warfare, by modifying the deck (Why complex and multi-mission ship designs are the wave of the future (naval-technology.com)). Modular shipbuilding could therefore be used to develop a ship that can be used for various activities, ranging from turbine maintenance to harvesting mussels. This evolution towards multi-purpose vessels started within the wind energy sector (Annex 7), but should be extended to other sectors such as the aquaculture sector.

Recommendations for all stakeholders in preparation for the co-design process

- Following the proposal by Schupp et al. (2021), we recommend that the different stakeholders (OWF operators, fisheries, aquaculture sector, nature restoration sector) develop a good practice guide that includes technical guidance to guide the co-design process of an OWF. To integrate commercial passive fishing within an OWF, one could, for example, draw up a protocol for the collection and interpretation of fisheries data. To promote safety, a list can be made of the specifications of fishing gear that can be safely used in an OWF and of the adjustments that are required to the design of the wind farm (e.g. distance between the turbines, burial depth of cables, specifications of cable protection measures, which erosion protection layers to use, etc.). The guide can arrange how company data (bathymetry and sediment surveys, ROV images, etc.) can be shared with fishermen in order to further increase safety within the OWF. It can also include which service activities OWFs need (Hattam et al., 2015). The Rederscentrale has indicated that the Belgian fishing industry is interested in providing services for the OWFs when their quota has been fished out and the vessel is unused (Annex 4). Schupp et al. (2021) also recommend that such good practice guidelines be developed under the supervision of the regulatory authority to avoid creating a power imbalance between stakeholders, which would hinder the formation of an integrated model.

WP5: Integration with OWFs without defined tender procedure and outside Natura 2000 area (CAT. 1)

5.1. General

After an evaluation of the existing cultivation techniques, several possibilities for food production within an OWF have been identified for the long term. Over time, new species may also be considered (5.3 New species). The long-term scenarios incorporate the short-term scenarios (sensu strictu (WP4)), and while they often reappear, they have been adapted with modified techniques to facilitate large-scale aquaculture and/or nature restoration activities. Additional possibilities for intensive farming, sea ranching, and population-support measures (under 5.4, 5.5, and 5.6) have been explored, given the fact that OWFs in this chapter are considered to be adaptable to co-use.

The authors refer to culture systems as classified in Table 2 in WP1, using a letter and number code. The text also outlines why certain culture techniques may not be applicable or may present significant challenges, even in the long term. A color-coded system has been used to assess feasibility (green = easily achievable; yellow = feasible; orange = difficult to achieve)

This classification is based on the expertise of the authors and requires validation through further research to determine whether the proposed techniques are viable from a social, ecological, and economic perspective. As in WP4, the proposals are ranked in order of implementation difficulty, from the easiest (green) to the most challenging (orange).

This chapter does not systematically specify which species can be cultivated using the proposed systems. We refer to WP4 for this, with the understanding that the Pacific oyster (new species) is included under the term 'shellfish' and that new species are specially mentioned for each farming system. The chapter but instead focuses on the broader technical feasibility.

5.2. Preconditions for long-term integration

The current MRP in Belgium stipulates that commercial offshore aquaculture can only be conducted within wind farms and the five CIAs. The preliminary draft of the MRP 2026-2034 extends the possibility of aquaculture to the Eastern zone and the PEZ, as well as areas outside OWFs, but excludes the 6-mile zone and locations where activities would interfere with military operations, coastal defense, and nature restoration.

Still, current legislation is unfavourable to the integration of aquaculture into OWFs, as space sharing is not mandatory. Establishing zones for multiple use of space, where additional activities need however the approval of the OWF operators, as is currently the case, will not encourage large-scale food production. While there are applied multi-use research projects within OWFs (Project Horizon2020 UNITED), integrating commercial aquaculture remains challenging due to the additional costs incurred by OWF operators. To enable large-scale aquaculture development, legislative adjustments should be introduced for future OWFs, making multi-use an obligatory condition. A key approach to fostering multi-use integration would be to include food production and/or nature restoration in the award conditions of tender procedures. This would allow aquaculture growers and/or nature restoration organizations to be part of the OWF consortium, enabling co-design and simplifying communication, logistics, monitoring, and insurance processes.

For large-scale aquaculture within OWFs, infrastructure modifications are necessary. One frequently suggested approach is functional integration (WP1 – 1.2.1. Turbines as anchor points), where aquaculture installations such as mussel longlines, oyster tables, or seaweed structures are directly attached to wind turbines. While this method appears straightforward, it requires a co-design process, as turbines are designed with a strict lifespan (Annex 7), and anchoring aquaculture structures to them could negatively impact durability. Thus, unless integrated design is considered from the outset—requiring adapted tender procedures—this approach remains problematic. Alternatively, modified infrastructure designs could provide protection to OWF structures, including special coatings to facilitate mussel harvesting. A co-design approach would optimize integration, reduce costs, and enhance efficiency across various aspects of aquaculture operations.

Fully integrated multi-purpose platforms, whether fixed or floating, such as energy islands, could offer a long-term solution. These platforms could incorporate storage facilities, processing units, docking stations, and staff accommodations. By reducing the number of vessel movements to and from the port, operational costs would decrease, while also lowering risk, positively impacting insurance premiums. The integration of aquaculture in multi-purpose platforms will also increase time efficiency. Typically for the BNS, the operational time window for offshore work on board of a ship is limited to two short periods of approximately one hour each during tidal shifts, when currents are minimal. The use of platforms would substantially increase this window.

A crucial precondition for large-scale aquaculture in OWFs is local energy access. Traditional power solutions include electrical cables from shore, which are economically unfeasible (White et al., 2013), and diesel-powered generators, which are discouraged due to the shift towards green energy. Co-location with OWFs provides a solution by ensuring local availability of renewable energy for aquaculture. Multi-use platforms could also be designed to be energy self-sufficient (Nassar et al., 2020), integrating floating solar panels and wave or tidal energy sources.

Several pilot projects demonstrate the feasibility of offshore renewable energy integration. Seaworthy by Floating Power Plant (Floating Power Plant sign groundbreaking EU Innovation Fund grant for €26m - Ocean Energy Europe (oceanenergy-europe.eu)) and Oceans of Energy (Home | Oceans of Energy | Offshore solar: clean and renewable energy) are examples of such projects. Belgium hosts one of the Oceans of Energy's pilot projects, where floating solar energy is connected to the wind turbine network. The integration of hybrid energy sources can be applied at both individual wind farm and broader energy zone levels, enhancing sustainability and operational efficiency for offshore aquaculture.

To further **maximize efficiency**, routine maintenance tasks such as biofouling removal, sorting, thinning and restocking should be minimized through smart design and automation and submersible culture systems, whether in the water column or seabed, should be considered, as they are less vulnerable to high waves reaching up to 12 meters.

5.3. New species

A vast number of species hold potential for mariculture, yet for many, suitable breeding techniques and methods are still lacking. In the AquaValue project, a table was compiled outlining the key factors for selecting target species (Annex 8). A crucial requirement is that the species in question must cope with offshore conditions. Some new species with offshore farming potential include tunicates, which can be used for extraction of bioactive substances; bristle worms, valuable for fish feed or extracellular haemoglobin production; and sea urchins, which have market potential for human consumption mainly abroad.

The European abalone (*Haliotis tuberculata*) (Fig. 25) and the Pacific oyster (*Magallana gigas*, triploid animals) also show strong potential. Both are high-value exotic species that could be considered for cultivation if research confirms they pose no risk to the marine environment. However, further studies and legislative adjustments are necessary before these species can be widely farmed offshore.

Spider crabs (*Maja brachydactyla*) have become increasingly common in Belgian waters in recent years. In 2023, large aggregations were discovered on shipwrecks in the BNS. These crabs have the potential to feed on mussels growing on wind turbine structures. They can be caught using pots (passive fishing), allowing for selective harvesting where large specimens—meeting the minimum landing size of 12 cm carapace length—are marketed, while undersized individuals can be further cultivated in underwater cages until they reach market size.

Within Europe and the Far East, there is a high demand for high-quality live abalone. The price of French abalone (live) within Europe exceeds 60€/kg. Quality seed stock is available in Brittany from France Haliotis, the largest abalone breeder in the region (www.francehaliotis.com). Experimental trials using various types of sea cages for abalone farming are currently underway in England and France (Ablox) (Syvret et al., 2013).

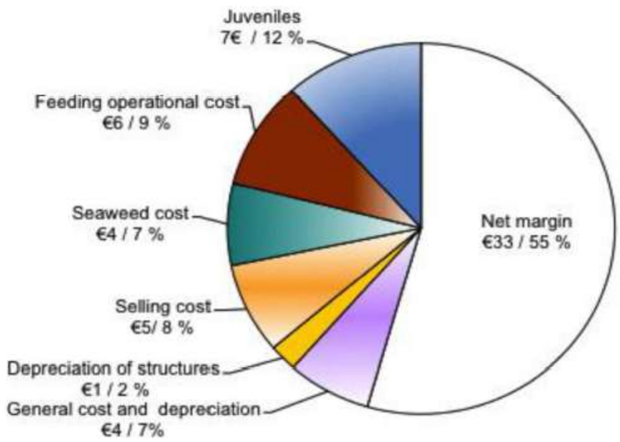


Figure 35: Economic analysis of France Haliotis abalone sea cage system based on a sale price of €60/kg
(Ref: SUDEVAB, 2010)

Fig. 25 Economic analysis of the French Haliotis abalone cage farming at sea, based on a sales price of 60€/kg (Sudevab, 2010 in Syvret et al., 2013)

5.4. Intensive Cultivation Scenarios

1. Bottom cages for bivalves (B3) ; See 4.3.1. Installing fixed anchor points to secure bottom culture systems would enable bottom cultivation throughout the entire OWF, reducing the likelihood of additional risks.

2. Submersible longlines in the water column (W2) ; See 4.3.5. Longlines with remotely controllable buoyancy offer the advantage of being submersible during storms, positioning them

deeper in the water and reducing exposure to strong waves. For bivalve applications (e.g., flat oyster, blue mussel, king scallop) and new species such as sea urchins, these systems can remain submerged permanently, ensuring they do not obstruct passage. In abalone culture, depth adjustments could be made throughout the day. Such systems require on-site operation or a connection to an energy source. Increased spacing between turbines or a modified OWF layout would enable the installation of longer and more numerous longlines.

3. Bottom cages for flatfish farming (B3); See 4.3.3. and 4.3.4. The installation of fixed anchor points for attaching bottom culture systems enables the safe scaling up of flatfish bottom cultivation.

4. Fixed platforms (P1); The large-scale cultivation of target species on fixed platforms closely resembles land-based aquaculture (Fig. 26). Fixed platforms provide protection against storms and create more controlled conditions for farmers. Water can be filtered before or after use, ensuring optimal conditions for cultivation. Additionally, these platforms offer essential infrastructure for monitoring, maintenance, and harvesting. Beyond farming, they can also support processing activities and provide housing for aquaculture staff. Fixed platforms can be equipped with mooring facilities for aquaculture vessels and integrated into OWF infrastructure, such as substations, energy islands, or even turbines. Expanding fixed infrastructure, such as the planned Princess Elisabeth Island, could enhance aquaculture operations. However, staffing offshore platforms may present a challenge.

Fig. 26 Engie - Multipurpose offshore platform (Multi-purpose offshore platforms | ENGIE Innovation)

Smaller infrastructures, like the turbines themselves, can also host tanks for rearing species such as flatfish, crabs, lobsters, bivalves, or macroalgae (Fig. 27). In the distant future, these turbines could even be repurposed as photobioreactors, enabling the cultivation of micro- or macroalgae under semi-controlled conditions (Fig. 27).

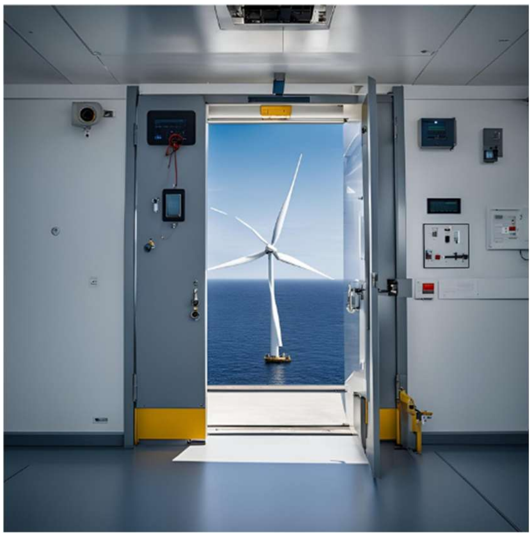
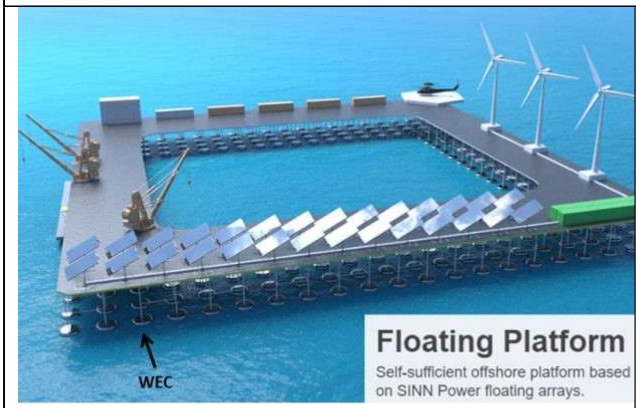
	
Turbine as incubator and laboratory with a view (image AI-generated, inspired by authors)	*Turbine as a photobioreactor (Image AI-generated, inspired by authors)*

Fig. 27 Inspiration for future use of turbines (images AI generated)

5. Longlines at the water surface (F3); See 4.3.5. Provided the layout of the OWF is adjusted, longer longlines (>200m) can be installed. For seaweed cultivation, a large-scale roll-out of these systems is essential to make it financially viable (cf. WP4). The installation of fixed anchor points during the construction of the OWF could simplify this technique. Longlines on the water surface have been tested in several Belgian projects, and while they are functionally applicable, they come with significant drawbacks, such as susceptibility to storms, obstruction of service vessel passage, and challenges in harvesting the products.

6. Floating platforms (P2); Floating platforms can be anchored within the OWF and used for shellfish farming (either under or on the platform) or for seaweed cultivation (on the platforms in tanks). These platforms offer protection against storms and provide safe conditions for monitoring, maintenance, and harvesting. Additionally, the platforms can be repurposed for other activities, such as processing the harvest or housing aquaculture staff. While floating platforms designed for energy production (Fig. 28) serve as an inspiring model, no floating platforms have yet been tested or made commercially available for offshore aquaculture. Anchoring floating platforms in the OWFs, however, may introduce additional risks.

<table>
<tr><td colspan="2"></td></tr>
<tr><td colspan="2">Poseidon (Denmark, in use) Floating-Power-Plant-Poseidon-07064_10035.pdf (knudehansen.com)</td></tr>
<tr><td>
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<tr><td>Sinn (not yet built) This Week in Green Tech: Offshore Energy Production, Stabilizing Perovskite Solar Cells, AI Battery Management | Engineering.com</td><td>Ideol floating wind turbine acquired by Gaelectric, Ireland Floating offshore wind | BW Ideol (bw-ideol.com)</td></tr>
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Fig. 28 Concepts for offshore wind platforms

7. Aquaculture vessels (F1); Ships present opportunities for cultivating bivalves, seaweed, and fish species. When anchored in offshore wind farms, these vessels offer protection against storms and enable cultivation in more controlled conditions. Depending on weather conditions, they can be positioned closer to or farther from the coast. These vessels utilize Recirculating Aquaculture Systems (RAS) to pump water from greater depths, ensuring optimal growth by maintaining the right temperature and quality. The water can be filtered before and after use to reduce environmental impact. Additionally, the ship is equipped with infrastructure for monitoring, maintenance, and harvesting, and it can also be used for processing the cultivated products or housing aquaculture staff.

However, anchoring large ships in the OWFs may introduce increased risks. The movement of the ship, known as "tank sloshing," can be problematic for fish farming, particularly during storms. This aspect should be examined more closely, but the available expertise with LBG ships may provide valuable insights. Fish farming has already been successfully implemented in aquaculture vessels in China (e.g., Guoxin1), and the protection provided by such systems seems to justify the additional costs (Long et al., 2024).

5.5. Sea ranching scenarios

1. Feeding structures for sea ranching ■ (SR1, SR2); See 4.4.1. Co-feeding buoys can be used in wind farms to condition fish, crabs, or lobsters, helping to increase their populations. This co-feeding can also take place from fixed structures, such as substations or turbines, which could be equipped with feeding equipment or used for feed storage. Another possibility is a combined technique, where mussels are harvested from the turbines and processed on-site into feed for sea ranching purposes. These techniques would be feasible if the necessary infrastructure for processing, drying, freezing, heating, and storage is available within the OWF.

2. Placement of artificial substrate and habitat to promote specific stocks ■ (SR3); see 4.4.2. The large-scale installation of artificial reefs in support of stock management of specific target species, is carried out by the farmer who is considered to be owner of the stock. However, further research is needed on the design of artificial structures that can support specific species for sea ranching. These artificial structures can serve various functions, as outlined in WP1.3.

5.6. Scenarios for population-support measures

1. Large-scale restoration or creation of natural (biogenic) reefs ■ (PO4, 5 and 6); This intervention will enhance the productivity of the entire ecosystem. The intended surface area for this method is distributed across several OWFs and can easily be applied outside of them (e.g., energy islands, ports, wrecks, etc.). On one hand, we recommend restoring the natural hard substrates where they were historically present (Annex 3), such as gravel beds. Additionally, we propose supporting measures to encourage the formation of biogenic reefs, such as *Sabellaria* sp. and flat oysters. On the other hand, nature creation initiatives, particularly related to (unavoidable) scour protection, can also be considered : erosion protection layers can be adapted to resemble natural gravel beds or can be seeded with habitat-forming species like Ross worms or flat oysters.

Creating hard substrate habitats on sandy bottoms will be difficult due to their high mobility in the BNS,

2. Large-scale placement of artificial substrate to promote stocks (PO3); The placement of artificial reefs that support specific species and life stages can help bolster local populations (WP2, all IUCN codes except LC, DD, NE). There are successful examples in Japanese literature, where food production at sea has been enhanced through the government- and privately funded introduction of large volumes of artificial reefs. The authors primarily see applications for overfished stocks, such as eel, sturgeon, cod, and sea bass. These artificial reefs should be considered an addition to the scour protection.

3. Increasing food production for target species (PO3); Making prey species available can significantly enhance the productivity of the local ecosystem. These prey species, such as mussels, sand mason worms, and amphipods (*Jassa* sp.), are low trophic species and can be encouraged by the placement of substrates like longlines, artificial reefs, or nets. Some knowledge has already been developed in the Belgian part of the North Sea through projects like SYMAPA.

5.7. Recommendations – long term

- The creation of mariparks (as defined in the glossary), as recently implemented in the Netherlands, presents an interesting option where the production of energy, food, and nature protection/creation/conservation are combined within designated zones (Bonsu et al., 2024). The management of such a marine park can be handled by the government, privately, or through a mixed model. This allows candidate farmers/growers to submit applications independently of wind energy concessionaires, as the latter only hold licenses for the turbines and the safety zones around them. In this form of co-design, the layout of a renewable energy production zone is carefully planned, considering the need for space for different activities—both on the surface (wind farm layout, access to turbines, manoeuvring space for various vessel types, distance between breeding systems, etc.) and on the seabed (cables, anchoring, breeding systems, scour protection layers, etc.)(Fig. 29).

- The authors recommend considering bottom cultivation whenever feasible. Routine bottom culture operations are simpler, less dependent on weather and tidal conditions compared to longlines, and submerged systems also pose fewer risks. However, further research is required to validate the growth potential and assess the impact of suspended sand on aquaculture yields (Barillé 1995).

- Installing fixed anchor points for bottom culture during the construction of the OWF will expedite and simplify the integration of aquaculture activities. The location and dimensions of the anchor systems should be determined in consultation with the relevant sectors.

- The provision of locally produced green power for aquaculture facilities, as well as for electrical vessels and monitoring equipement and the provision of electrical sockets at sea, is crucial for the development of commercial offshore aquaculture.

- Private ownership (or temporary licensing) of parts of the OWF for sea ranching activities will ensure that the plot owner provides the necessary structural adjustments to increase productivity. Given that current regulations within the Common Fisheries Policy do not allow for this, there is limited experience with production-enhancing structures. These structures are currently mostly developed for nature restoration or creation to "green" OWFs or "repair" damage caused by OWF construction. Nevertheless, structural adjustments to support well-defined target populations are species- and function-specific. The current proposals for nature-inclusive designs (NIDs) are likely not the best solution, as they are more focused on enhancing general biodiversity (Kingma et al. 2024). By granting private ownership of certain parts of the OWF for sea ranching activities, the extraction potential will be close to the 'maximum sustainable yield' but will not exceed it, as is currently the case for many stocks (The State of World Fisheries and Aquaculture 2024 (fao.org)).

- The concept of a multi-use platform will foster true integration and synergy between energy production and offshore aquaculture. A permanent presence on-site will reduce risks and offer greater flexibility for organizing maintenance work and harvesting. The sharing of vessels, personnel, and monitoring systems can be efficiently managed in such a setting. The extensive reach of these platforms will also improve the financial profitability of aquaculture. Additionally, such platforms can meet the energy needs of aquaculture infrastructure located nearby.

Examples of mariparks in Dutch OWFs

A maripark is a nature-inclusive business park at sea, where various economic activities can take place together, optimizing the use of space at sea. It facilitates synergies between the activities, which can make logistics, security, and monitoring more efficient and cost-effective, potentially accelerating economies of scale. Management can be carried out by the government, privately, or through a mixed approach. By integrating nature into the maripark, its social value is enhanced, ensuring the protection and promotion of local biodiversity and natural assets.

In front of Scheveningen lays the NSF Offshore Test Site (OTS), which is privately operated, with basic infrastructure like demarcation buoys, monitoring systems, and vessels. This site seeks synergies, particularly in logistics, and rents plots to industries or NGOs for specific research projects: https://www.northseafarmers.org/offshore-test-site. Other forms of mariparks are also possible within offshore wind farms, as detailed in the EY advisory report blueprint (ey-adviesrapport-blueprint-maripark-online-version.pdf).

In the 'North Sea Policy Document 2016-2021', The Netherlands have chosen to open up offshore wind farms for shared use of space. These include marine aquaculture (such as seafood and seaweed farming), other forms of renewable energy generation and storage (including solar and tidal energy), nature development (e.g., oyster restoration, fish catchments, artificial reefs), and passive fishing (e.g., crab traps, lobster baskets, ground longlines, and handlines). These zones are divided by passages or corridors, ensuring space for recreational vessels as well.

For the Borssele wind farm zone, the Area Passport Guide has been created to outline area-specific characteristics that determine which shared uses are feasible and which forms of multi-use are most likely to succeed and are therefore preferable (Fig. 29). The Area Passport Guide serves primarily as a reference for granting permits, as co-use activities within offshore wind farms (OWFs) require a permit application under the Water Act and must be processed through the "Noordzee loket" (www.noordzeeloket.nl/functie-gebruik/).

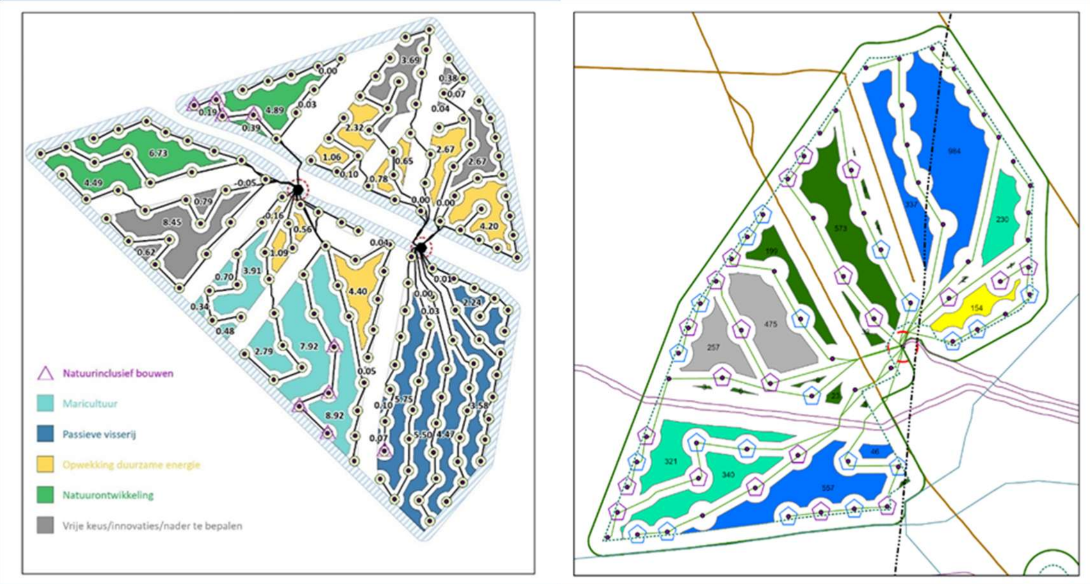

Fig. 29 Zoning map of wind farm areas with available areas for shared use: mariculture, passive fishing, generation of renewable energy other than wind energy, nature development and other activities (free choice, innovation & research or to be determined). Left: Borssele Wind Farm Area; Right: Hollandse Kust (North) Plot V (source: Borssele wind farm zone - Noordzeeloket UK)

For an aquaculture permit application, the activity is first assessed for safety, liability, and its environmental impact. This assessment is carried out by Rijkswaterstaat, not by the OWF operators. In contrast, for passive fishing, the permit application is handled through a tender procedure by the Ministry of Agriculture, Nature and Food Quality.

Additionally, a new insurance system has been developed for passive fishing within an OWF, which includes a risk assessment focusing on safety protocols, weather conditions, seasonal changes, marine equipment, and agreements with OWF operators. This makes the Netherlands one of the most advanced countries in terms of safety and insurance for co-location practices within an OWF (Bonsu et al., 2024).

5.8. Recommendations for tender procedures – long term

As mentioned earlier, the current legislation is not favourable for the integration of aquaculture into an OWF because the sharing of space is not mandatory. Establishing zones for multiple use of space, where integrated activities must be approved by the OWF operators, will not lead to large-scale food production. Discussions with BOP and OWF operators show that while they are open to aquaculture within their concession, many obstacles still need to be overcome before this can become a reality (cf. 4.2. Preconditions for integration).

It is therefore important to conclude that, given the current legislative framework and the potential abolition of CIAs, there is limited potential for the development of commercial offshore aquaculture in Belgium.

For large-scale commercial aquaculture to thrive in OWFs, adjustments to the tender procedure are necessary. In the tender procedures issued for the Eastern Zone and the new procedure for the Princess Elisabeth Zone (PEZ), nature restoration, passive fishing, and/or aquaculture were not included as permit criteria. The most significant criterion was the price of the electricity supplied (the "strike price"). Any additional activity would directly or indirectly increase costs, thus impacting the Levelized Cost of Electricity (LCOE), and in turn, the energy price.

However, the tender procedure plays a key role in determining which systems can be deployed, and thus which species can be cultivated in OWFs (Fig. 30). It will be crucial to mention aquaculture in the tender procedure if we aim to facilitate the production of more seafood. Additionally, introducing non-price criteria in the tender, such as aquaculture production or nature restoration goals, could help achieve this. These criteria could serve as pre-qualification conditions to ensure aquaculture activities are part of the process.

To ensure a level playing field across Europe, Member States should advocate for the inclusion of non-price criteria in OWF tender applications at European forums. Some key non-price criteria that could be integrated include:

- Food production conditions per area of the wind farm: The tender could specify how food production should be achieved, offering options such as intensive aquaculture, sea ranching, or population-supporting measures. Population-supporting measures closely align with nature restoration, and a one-to-one area compensation approach could be adopted—meaning that the surface area impacted by the construction and ongoing operation of the OWF is fully restored.

- Compensation for habitat impact: Restoration efforts should offset the ecological footprint of the OWF construction, by implementing habitat restoration projects.

- Spatial planning conditions within the OWF: Clear guidelines should be set for the allocation of space, including amongst others:
    - Minimum distances between turbines.

- Designated zones for additional activities namely nature restoration, passive fishing and aquaculture (for the latter linked to a business plan).
- Free zones ensuring the passage of maintenance vessels.

- Conditions for decommissioning: The tender should address whether aquaculture operations can transition to other concessions upon OWF decommissioning or if dismantling can occur while aquaculture operations continue. Similarly, for NID elements used for habitat restoration, the tender should clarify whether they must be removed or under which conditions they can remain in place to sustain their ecological function.

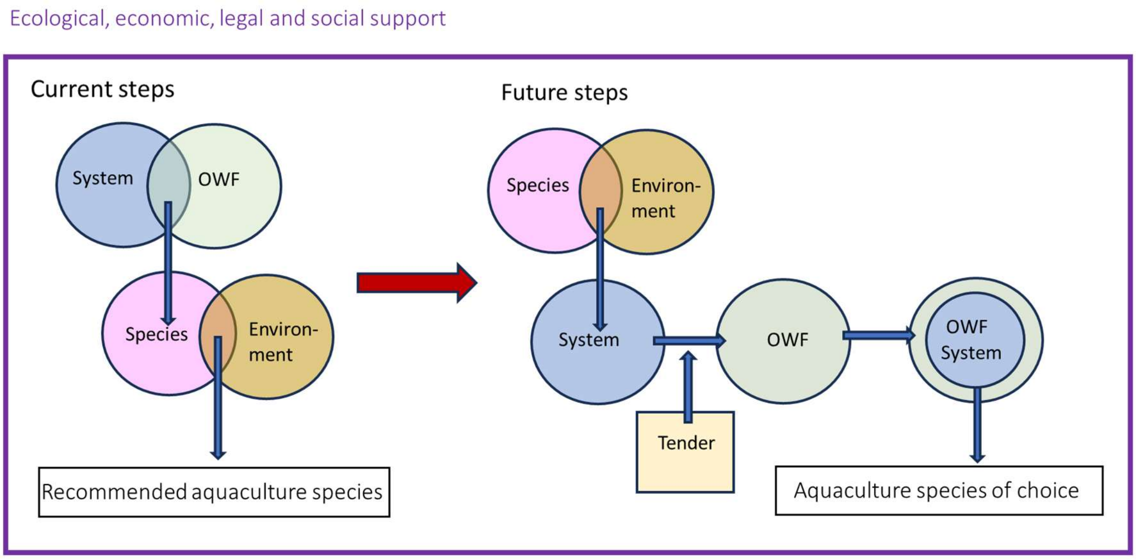

Fig. 30 The author's perspective on the evolution of the selection process for aquaculture species in OWFs.

Advocating for these criteria at the European level would help integrate aquaculture and nature restoration into OWF planning while ensuring consistency in regulations across Member States.

Example: Co-design in Dutch OWFs

The complexity and uncertainties surrounding the integration of aquaculture, nature restoration, and passive fishing within offshore wind farms (OWFs) highlight the need for a "Roadmap for Nature and Shared Use" in the Netherlands. This roadmap should run parallel to the existing offshore wind energy Roadmaps 2030 (Min.EZK, 2018) and 2030+, ensuring that nature and shared use goals are incorporated into each new OWF development.

A key aspect of this roadmap is goal setting for each new wind farm, with clearly defined objectives related to nature enhancement, passive fishing, aquaculture, or a combination of these activities. To achieve an integrated design based on local characteristics, a structured step-by-step approach is necessary to address key uncertainties and sub-questions. The designation of new wind energy areas involves balancing various maritime functions, as outlined in the North Sea Agreement (4.16 et seq.), reinforcing the need for government-led evaluation of tender instruments that facilitate integrated development. The National Environmental Vision (Min. BZK, 2020) emphasizes that multi-functional OWFs should take precedence over single-use developments, ensuring a more efficient use of marine space.

A flexible approach to tendering is crucial in this process. The site decision should establish only minimum shared-use requirements, leaving room for innovation and allowing bidders to propose creative solutions. Competitive bidding processes could include comparative testing, where non-financial bids encourage innovative solutions for co-use. If comparative testing does not sufficiently enhance nature restoration, passive fishing, and aquaculture, alternative government-driven innovation programs or stricter site decision requirements should be considered. Additionally, revenue generated from financial bids could be redirected toward strengthening nature restoration, passive fishing, and aquaculture initiatives under government oversight.

The evaluation of the Hollandse Kust (west) tender will provide valuable insights into the effectiveness and efficiency of comparative testing as a method to achieve shared-use objectives. Furthermore, the North Sea Programme 2022-2027 includes a shared-use assessment framework for wind farms and details the permit application process (Fig. 31).

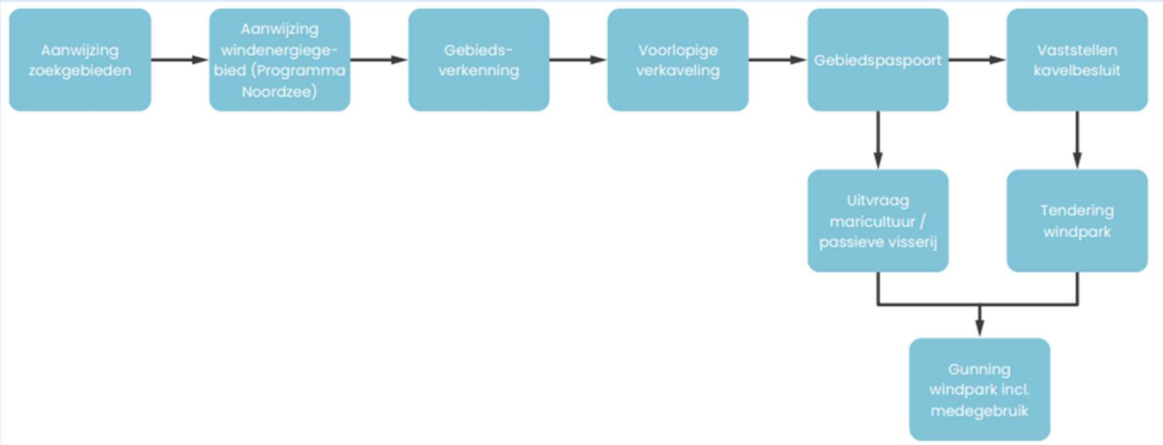

Fig. 31 Process description towards awarding an offshore wind farm including shared use (North Sea Foundation, 2022)

WP6: INTEGRATION INTO NATURA 2000 Habitats directive area

6.1. General

In Belgium, environmental policy at sea is a federal responsibility. The Federal Law on the Protection of the Marine Environment and the Organisation of Marine Spatial Planning in the Belgian Sea Areas, (known as the 'Marine Environmental Act' or 'MMM law') was passed on December 11, 2022. This law forms the foundation of marine policy and aims to preserve the natural environment, biodiversity, and integrity of marine ecosystems through protective and restorative measures.

The European Habitats Directive (Annex 6) seeks to maintain and restore endangered European habitats, as well as wild fauna and flora. In the BNS, there are two habitats of Community interest : shallow sandbanks and reefs. Additionally, species of Community interest include the harbour porpoise, grey seal, harbour seal, and twait shad, and are listed in Annex II of the Directive.

The 'Flemish Banks' Habitats Directive area was designated to protect permanently submerged sandbanks (Habitat type 1110), as outlined in the study by Degraer et al. (2009). This sandbank complex also includes *Lanice conchilega* aggregations and gravel beds, which fall under Habitat type 1170 ('reefs').

The scenarios described in this context apply to OWFs located within Natura 2000 areas, regardless of whether there is an existing tender procedure. The presence of such a procedure will influence the voluntary or non-voluntary implementation of the scenario, but not its substance. In Belgium, this concerns the scenarios planned for the PE II part 2 and PE III zones.

6.2. Conditions

The preconditions for OWFs to be constructed in a Natura 2000 habitat area are the same as the preconditions discussed in WP5. However, an important additional condition must be considered: every activity conducted within a Natura 2000 area must contribute to achieving the conservation objectives. Aquaculture activities that could put additional pressure on the ecosystem will only be considered once a favourable conservation status has been reached.

The authors assume that a favourable conservation status will not yet have been achieved during the construction phase of the OWFs in this area. Therefore, scenarios are proposed that could accelerate the achievement of this status. Once a favourable conservation status is attained, extensive aquaculture activities can be developed, provided they do not negatively impact the favourable status.

The EU document "Guidance on Aquaculture and Natura 2000 - Sustainable Aquaculture Activities in the Context of the Natura 2000 Network" (https://oceans-and-fisheries.ec.europa.eu/system/files/2016-09/guidance-aquaculture-natura2000.pdf) serves as a valuable guide for these activities.

Moreover, fishing, including passive fishing, is not expected to contribute to the improvement of the ecosystem's conservation status. The authors assume that this activity will not be permitted within these areas.

6.3. Scenario's

Taking these preconditions into account, only a limited number of types of aquaculture can be authorized. These are farming systems that have minimal impact on bottom habitats and actively support the ecosystem. Some scenarios are also described in WP4 and WP5, but they will be applied in Natura 2000 areas under stricter conditions. We distinguish 4 possibilities.

6.3.1. Extensive cultivation of flat oyster to restore oyster reef habitats (PO4)

In this scenario, the cultivation of the European flat oyster (from the Atlantic population) is permitted using off-bottom farming systems. This type of cultivation has minimal impact on the seabed. By growing oysters till reaching reproductive life stage, the culture systems mimic an oyster reef, which will also attract natural communities that are typically associated with oyster reefs. The oyster larvae from such extensive farming system can then colonize other substrates. A practical implementation of regenerative aquaculture with flat oysters, applicable to Natura 2000 areas, can be found in Stechele et al. (2023) (cf. also 4.3.1.).

6.3.2. Harvesting mussels from the turbines (T1)

Artificial hard substrates attract fouling organisms. The installation of turbines in a Natura 2000 area, therefore, creates a different community and leads to an adaptation of the local ecosystem. For instance, an accumulation of organic matter in the sediment layers around the turbines has been observed in the Eastern zone, which can be attributed to the fouling organisms on the turbines (Mavraki et al., 2020). This fouling community is causing damage to the benthic ecosystem and, consequently, to the habitats protected under the Habitats Directive. Regular removal of biofouling from the turbines can help minimize this effect (cf. also 4.3.2).

6.3.3. Population-support through nature restoration, combined with fishing outside the Natura 2000 areas (spill-over)

Nature restoration of natural hard substrates and biogenic reefs is a key objective under the marine strategy, the implementation of the Habitats Directive, and is also part of the priority goals of FPS Health, Food chain safety and Environment for nature restoration (https://www.health.belgium.be/nl/natuurherstel-onze-noordzee). The restoration efforts focus on: (1) the restoration of flat oyster habitats (PO4), (2) the restoration of natural gravel beds (including boulder landscapes, PO6)), and (3) the enhancement of other types of reefs. These interventions have also been outlined for OWFs in Category 3 (cf. 4.5.3) and Category 1 (cf. 5.6). If these restoration efforts lead to an increase in commercial target populations, spill-over effects may occur, allowing target species to be harvested through passive or conventional fishing gear outside the Natura 2000 areas.

6.3.4. Population-supporting measures via adapted artificial hard substrate (PO3)

Given that the construction of OWFs in Natura 2000 areas leads to an increase in artificial hard substrate (e.g., turbines and erosion protection layers), we recommend modifying these artificial substrates to enhance their ecological value. Specifically, we suggest minimizing the erosion protection layers around the turbines and incorporating designs that mimic the complexity of natural gravel and boulders. If this approach increases the populations of commercial target species, it could lead to spill-over effects, where these target species can be harvested outside the Natura 2000 areas.

Furthermore, the authors recommend that other proposals, such as the installation of artificial reefs, bioreceptive coatings, and similar interventions (NIDs), be carefully evaluated. These measures should contribute to achieving a favourable conservation status of the area, rather than solely increasing species richness or boosting specific target commercial populations. The ultimate goal should be a healthy marine ecosystem that provides a variety of ecosystem services (including food supply) and can be used sustainably. Additional research is necessary to verify the effectiveness of these interventions in supporting the good conservation status of the area.

6.4. Recommendations - Natura 2000 areas

- One-to-one compensation for impacted areas through OWF construction : OWFs must restore the same amount of natural habitat that has been affected by the installation of infrastructure (including turbines, cables, cable crossings, and substations) and erosion protection layers. The type of habitat to be restored is determined by FPS Health, Food chain safety and Environment, in consultation with the Institute of Natural Sciences, and must contribute to the achievement of conservation objectives.

- A lasting compensation for continuous impacts on benthic communities : The financial contributions to the environmental compensation fund (already existing) are used to mitigate the ongoing impact of OWFs on benthic ecosystems. These funds are effectively used to support environmental enhancement measures.

- Mandatory removal of fouling organisms : OWFs must regularly remove fouling organisms from turbines. Where possible, the harvested products from this process should be marketed.

- Allow passive fishing in Natura 2000 areas only under certain conditions : Passive fishing within OWFs in Natura 2000 areas will only be permitted if it contributes to the favourable conservation status of the ecosystem. This includes fishing for exotic species or species that hinder the recovery of the ecosystem.

6.5. Recommendations for the tender procedure - Natura 2000 areas

The tender procedure for the construction of OWFs in Natura 2000 areas is a sensitive issue. Under the legal framework of the Habitats Directive, activities within Natura 2000 areas are permissible as long as they do not significantly impact the achievement of the conservation objectives. However, it is not required that activities necessarily contribute to these conservation objectives. The environmental impact report indicates that the effects of an OWF in a Natura 2000 area are deemed acceptable (Arcadis, 2023). The construction of an OWF also ensures the prohibition of seabed-disturbing fishing activities within the area, which benefits the natural value and will contribute to achieving the conservation objectives at sites unaffected by the construction.

Given the local impacts of OWF construction, as well as the ongoing presence and subsequent decommissioning of the OWF within a Natura 2000 area, the authors recommend that strict and mandatory nature restoration and monitoring conditions be prioritized in the environmental permit and Natura 2000 authorization. It is crucial to include these additional conditions in the tender process to clarify from the onset what requirements must be met. Conditions related to food production and/or nature restoration should be included as non-price criteria or as pre-qualification conditions. Recommendations for non-price criteria—such as food production through extensive farming, sea ranching, or population-support measures—are outlined in Chapter 6.4, and must ensure that the conservation objectives of the area can be met.

Furthermore, the authors emphasize that, given this tender process takes place within a vulnerable nature reserve, the tender should be developed in consultation with the marine environment service of FPS Health, Food chain safety and Environment, in collaboration with MUMM Scientific Service (KBIN) .

CONCLUSION

The coming years will be crucial for the expansion of and transition to a green energy sector at sea. Both European and Belgian ambitions are significant, with a target of installing 260 gigawatts of offshore capacity by 2050 within the EU. Belgium, having also signed the Climate Agreement 2020-2050, has outlined plans for a new renewable energy zone in the Belgian Marine Spatial Plan (2020-2026), specifically the Princess Elisabeth Zone (PEZ). This zone spans 285 km² (comprising the Noordhinder-Noord and Noordhinder-Zuid areas) and is projected to have an installed capacity between 3.15 and 3.5 GW. Overall, the renewable energy zones in Belgium will cover 523 km². As in the Eastern zone, bottom trawling will not be permitted within the PEZ.

While marine aquaculture has seen limited growth across Europe in recent decades (apart from salmon farming in Norway), fish production remains a crucial component of Europe's strategy for enhanced food security and a faster protein transition. The expansion of offshore energy production presents a unique opportunity for the aquaculture sector to explore the offshore waters and leverage established offshore technologies. However, integrating these two sectors is not straightforward, and the synergies suggested in the literature are rarely realized in practice.

Throughout the preparation of this report, it has become evident that the tender procedure plays a pivotal role in enabling future aquaculture activities within OWFs, whether for intensive farming, sea ranching, or population-supporting measures (see WP5 - 5.7 and WP6 - 6.5). Without the incorporation of local food production as a non-price criterion or pre-qualification condition in the tender procedure, the commercial offshore aquaculture sector will not develop within OWFs in the BNS. This is particularly concerning given that both the current and draft versions of the new Marine Spatial Plan (MSP) clearly indicate OWFs as potential areas for offshore aquaculture.

The content of the tender criteria for the Princess Elisabeth Zone (PEZ) was, therefore, a significant disappointment for the aquaculture sector. The tender failed to include any conditions that would promote increased food production, nature-inclusive measures (which could support commercial stocks), or nature restoration (which enhances ecosystems and commercial stocks). The authors hope that future tenders (repowering of Eastern zone) will focus on a balanced approach that integrates energy production, food production, and nature conservation in OWFs, as seen in the Netherlands. Moreover, the absence of such conditions hinders innovation and the development of sectors like food production, nature-inclusive design (NID), and nature restoration, which could provide substantial social, economic, and ecological value for Belgium. Furthermore, discussions with concessionaires and OWF operators revealed that they are also ready for a more sustainable, integrated approach and are open to innovation. This study has, therefore, formulated concrete recommendations that can be included in the future selection process (WP4 – 4.7; Cat. 3, WP5 – 5.8; Cat. WP1, WP6 – 6.4; Cat. 2).

Bottom farming presents several advantages that make it a promising option. Notably, the risks of damage to the OWF infrastructure are considerably lower. The proposed technologies range from simple approaches (such as shellfish and crustacean farming) to more complex systems (like flatfish farming), which allows for the accumulation of valuable experience and expertise over time. Given these benefits, the authors strongly advocate for prioritizing the approval and support of bottom farming systems. These techniques can be applied in the short term, leveraging existing or tested methods (even if not yet specifically tested in the North Sea).

Additionally, the authors see significant potential in applying sea ranching, species-specific nature-inclusive design (NID), and nature restoration measures to boost productivity—specifically in terms of food production—within OWFs. A notable example comes from Japan, where large-scale population-support measures have led to a significant increase in food production in the Japanese Exclusive Economic Zone (EEZ).

Passive fishing plays an important role in these proposals. While there is currently limited enthusiasm within the fishing sector (cf. Rederscentrale), the authors believe passive fishing will be a key part of the future of Belgian fisheries. Several studies highlight the complementary nature of passive fishing, particularly in relation to coastal fishing and aquaculture (e.g. the SYAMAPA project). Furthermore, the European Union has plans to phase out bottom trawling in the medium term, which will necessitate a shift in the sector. While the fishing fleet is not yet prepared for this transition, ongoing projects led by ILVO are expected to provide solutions to the uncertainties within the fishing sector regarding the economic and technical feasibility of these changes.

Structured consultations between the offshore energy sector, fisheries, and farmers will be essential to clearly define the social, technical, and economic measures required for diversifying the sector and enabling access to production and harvesting within the OWFs.

The integration of offshore wind energy with marine aquaculture presents significant challenges, and the synergies proposed in the literature often struggle to materialize in practice. However, the authors have identified two key concepts that could facilitate integration in the near future: co-design and large-scale development.

Co-design is a concept that has broad agreement, but the authors highlight that the urgency of this issue is often overlooked. Since the construction of wind farms and potential turbine modifications are planned years in advance, the authors stress the importance of prioritizing co-design today.
Furthermore, the authors argue that the development of an offshore aquaculture sector integrated with OWFs can only succeed if approached on a large scale. Due to the high risks, investment needs, and operational costs, achieving scale is crucial to making offshore aquaculture economically viable. The authors see two main ways to achieve this scale: creating marine parks and developing multi-use platforms (either fixed or floating).

The idea of marine parks, as defined in the glossary, is not new, and there are good examples worldwide. In the Netherlands, for example, the Borssele wind farm area has effectively divided space to ensure that each activity has sufficient room without conflicting with others. “Multi-use of space” is one of the most straightforward and easily implementable forms of integration. With appropriate policies and strong cooperation between wind farm operators and aquaculture growers, this concept can be relatively simple to implement. Additionally, consultations are needed on how the government can facilitate the development of aquaculture and nature restoration within OWFs. Including these activities in the permit criteria can help ensure that the grower or nature restorer is part of the consortium, streamlining co-design. This collaboration also simplifies communication, logistics, monitoring, and insurance procedures, as a single consortium can handle all aspects.

A second, more challenging, but innovative option is the creation of multi-use platforms. These platforms could provide far more synergies than just space-sharing. Energy platforms being developed today could be adapted to support aquaculture activities (and research). Floating or fixed renewable energy islands could also provide essential infrastructure for aquaculture, such as long-term accommodation for staff near aquaculture zones, as well as storage, processing, and research facilities. The platforms could house observation stations, support drone operations, and offer ecological research opportunities. They could even serve as real-life test sites for automation systems in aquaculture. This would allow users to share costs for transport, monitoring, and personnel, effectively increasing efficiency. Additionally, it would reduce dependence on weather conditions, expanding the available time for maintenance work and harvesting.

Of course, this kind of proposal would require large-scale development and consultations with various sectors—renewable energy production, fisheries, processing and storage, research, tourism, education, etc.—to ensure its success.

Technological innovation is essential and must be actively promoted to facilitate the integration of aquaculture within OWFs. Advances in automation, innovative monitoring systems, and more accurate weather forecasting will play a pivotal role in the future. Given the anticipated increase in local energy demand—driven partly by the electrification of vessels within the OWFs—the development of a robust local energy network is critical.

Moreover, the authors believe that there is a strong need for innovative, multi-purpose modular vessels designed for maintenance of aquaculture systems, harvesting, infrastructure rehabilitation, and research. These vessels should be versatile enough to equally support routine activities for both the fishing and OWF sectors.

Legal adjustments necessary to promote aquaculture activities within OWFs have not been fully explored in this study. Further legal research is required in several key areas, including: (i) facilitating private ownership and exploitation of commercial stocks (e.g. sea ranching), (ii) the use of bycatch for further breeding, such as intensive flatfish breeding, (iii) the issuance of aquaculture exploitation licenses, (iv) providing exception rules to maintain specific and long-term effective population support structures when the OWF's permits expires, (v) the cultivation of exotic species with an acceptable environmental impact, (vi) the conditions for extractive farming (e.g.shellfish farming) and (vii) addressing the potential for a level playing field for aquaculturists, with particular attention to harmonizing legal differences between neighboring countries. Finally, it’s important to consider the long-term sustainability of aquaculture in OWFs, including the possibility of continuing aquaculture activities after the expiration of OWF licenses. This would ensure continuity and support for the development of integrated, sustainable systems at sea.

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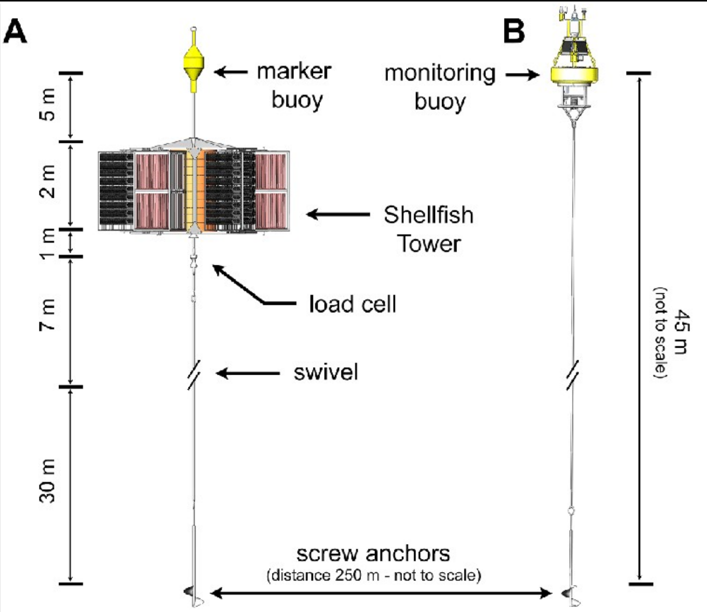
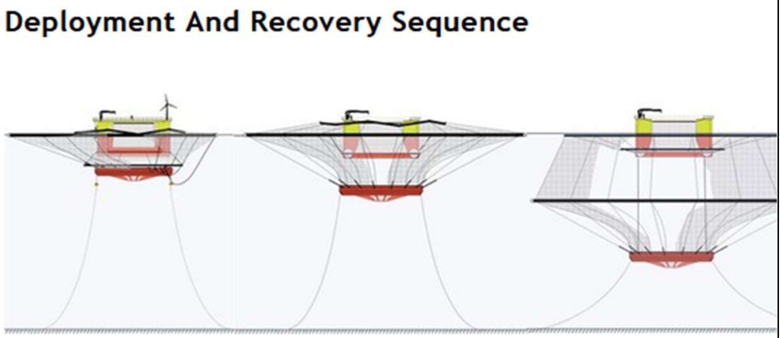
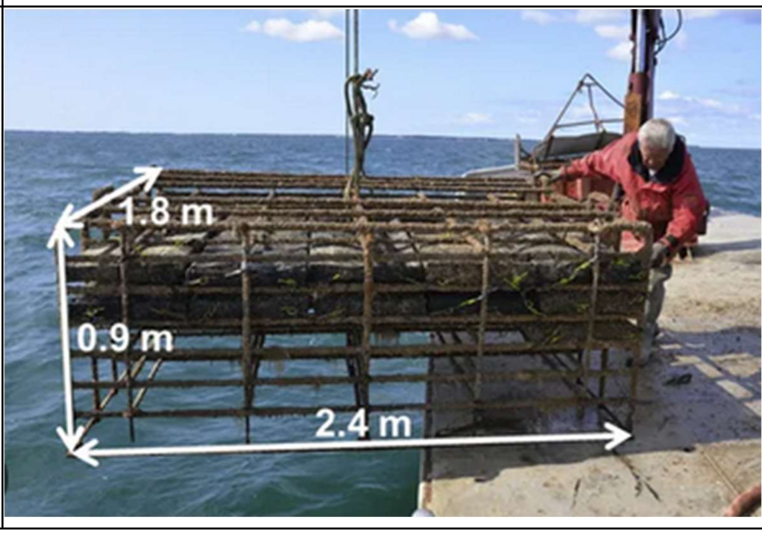
ANNEXES

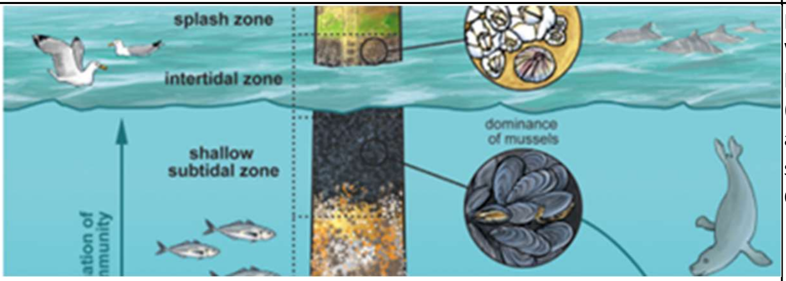
Annex 1: Examples of intensive cultivation techniques

Code	Technique	Reference or supplier
D1		MMC FIRST PROCESS Eloxiras LOGISTIC Wellboat - MMC FIRST PROCESS
D1		Siemens (Manufacturing giant Siemens invests in aquaculture firm farming fish on floating platforms | Intrafish)
D1		RasXFloater from Next Tuna and Seafarming Systems (https://www.seafood.media/fis/worldnews/search_brief.asp?l=e&id=126193&ndb=1)

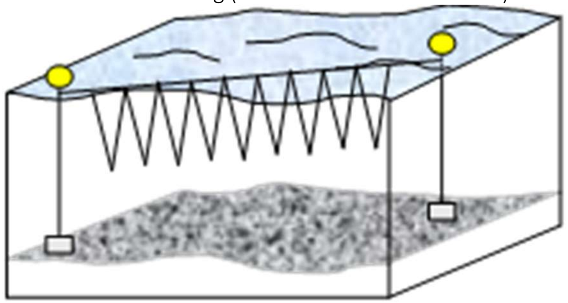
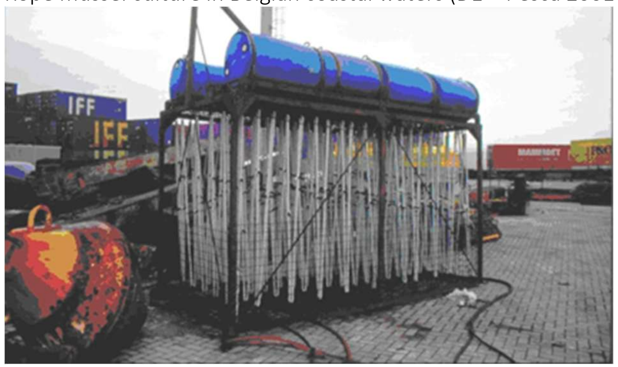
Code	Technique	Reference or supplier
D2		Caruso, M. C., Pascale, C., Camacho, E., & Ferrara, L. (2022). Comparative environmental and social life cycle assessments of off-shore aquaculture rafts made in ultra-high performance concrete (UHPC). The International Journal of Life Cycle Assessment, 27(2), 281-300.
D3		Project Edulis (Edulis: Offshore mussel culture in wind farms | BLUEGent (ugent.be))
D4		Mowi Scotland, nets produced by AKVA group

Code	Technique	Reference or supplier
W1	 	Shellfish Tower – Project OLAMUR Heasman, K. G., Scott, N., Smeaton, M., Goseberg, N., Hildebrandt, A., Vitasovich, P., ... & Buck, B. H. (2021). New system design for the cultivation of extractive species at exposed sites-Part 1: System design, deployment and first response to high-energy environments. Applied Ocean Research, 110, 102603.
W2		SeaStrut ™ from Impact-9 (Impact-9)
W3	 	Net9 ™ from Impact 9 (Impact-9)

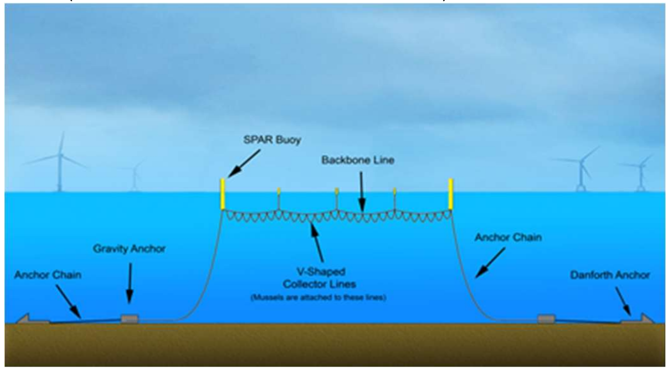
Code	Technique	Reference or supplier
W3		SalMar Aker Ocean is likely to be the first offshore salmon farm in Norway. Smart Fish Farm was developed for this purpose, with a depth of 70 m, it can hold twice as many fish as their existing Ocean Farm fish cage (Photo: Salmar, in Furuset & Gezelius, 2023 in Intrafish).
W3		China will launch the largest submersible salmon farming cage off the coast of Shandong on January 17, 2024. The Sea Granary N° 1 was constructed by Shandong Caijin Wanzfeng Marine Technology and has a volume of 60 000 m³ (89 m x 45.4 m x 35.9 m), good for an annual yield of 1000 tons of Atlantic salmon (Salmo salar) (Photo: Wanzefeng Group, in Mutter 2024 - Infrafish).
W4		SeaStation from INNOVASEA (SeaStation Net Pens for Aquaculture - Innovasea)
B1		Barillé, L., Le Bris, A., Goulletquer, P., Thomas, Y., Glize, P., Kane, F., ... & Gernez, P. (2020). Biological, socio-economic, and administrative opportunities and challenges to moving aquaculture offshore for small French oyster-farming companies. Aquaculture, 521, 735045.

Code	Technique	Reference or supplier
V1		Degraer, S., Carey, D. A., Coolen, J. W., Hutchison, Z. L., Kerckhof, F., Rumes, B., & Vanaverbeke, J. (2020). Offshore wind farm artificial reefs affect ecosystem structure and functioning. Oceanography, 33(4), 48-57.
V2		https://www.youtube.com/watch?v=t3k21vF9gNk
V5		Jinghai No 2 Fish Farming Platform – Yantai Utex Fishery Equipment Co., Ltd.

Annex 2: Overview of aquaculture systems used in Belgian projects

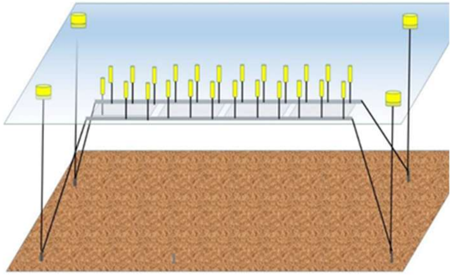
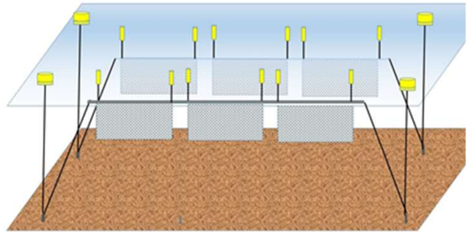
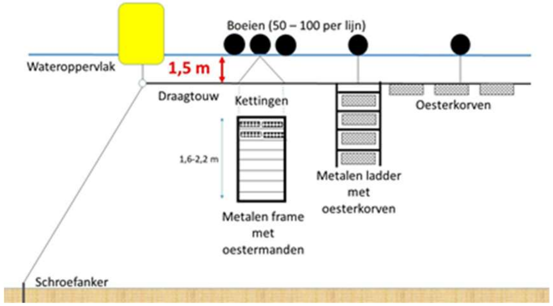
Project	Target species	System	Advantages	Disadvantages
Flemish mussel farming (Buitenratel – 5b 1998-2001)  Source: Daan Delbare@ILVO	Blue mussel (*Mytilus edulis)*	Longline of 200m with V-shape continuous mussel rope, anchored with gravity anchors	Good spatfall and growth of the mussels	Because the area was not clearly demarcated, the longlines were sailed over and destroyed.
Rope mussel culture in Belgian coastal waters (D1 – Pesca 2001-2003)  Source: Daan Delbare@ILVO	Blue mussel (*Mytilus edulis)*	Mussel rope is hung in loops in a cage structure to protect the ropes from passage. The cage is kept afloat with floating bodies and the whole is anchored with a concrete block.	Very good growth, without major losses	Difficult to harvest

Flanders Queen Mussel (5 concessions - FIOV 2005-2011)  Source: Kris Van Nieuwenhove@ILVO	Blue mussel (*Mytilus edulis)*	Mussel cage consisting of one floating body with arms, around which mussel rope is wound and a concrete block as an anchor.	Very good growth of mussels. First sale of Belgian mussels	Special vessel needed with rotating platform for harvesting and winding mussel rope. Mooring vulnerable due to the constant need to cut and weld the chain during harvesting
Belgica mussels (D1 – Private 2005-2011)  Source: Kris Van Nieuwenhove@ILVO	Blue mussel (*Mytilus edulis)*	Floating pontoon with lifting bridge for bringing the mussel cages to the surface.	Good growth on the outside	Less growth centrally; difficult to work with at sea; pontoon and mussel cages not suited for hydrodynamic conditions of BNS

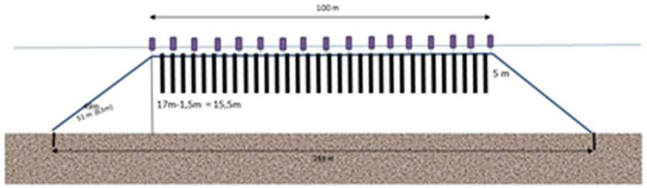
<table>
<tr><td>Edulis (Belwind/C-Power – EFMZV 2016-2019)


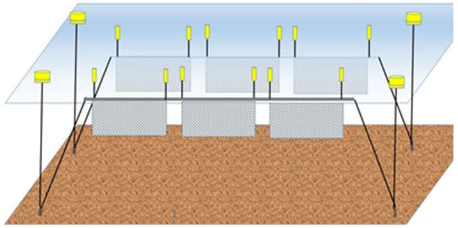
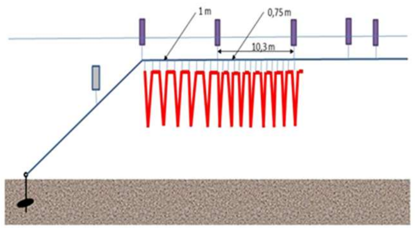
Source: Pribadi, A. B. K., Donatini, L., Lataire, E., Vantorre, M., Nevejan, N., & Bossier, P. (2018). Cultivating mussels in the Belgian North Sea. In J. Mees & J. Seys (Eds.), Book of abstracts : VLIZ Marine Science Day. Bredene, Belgium, 21 March 2018 (Vol. 81). Oostende, Belgium: Vlaams Instituut voor de Zee (VLIZ). http://hdl.handle.net/1854/LU-8669500

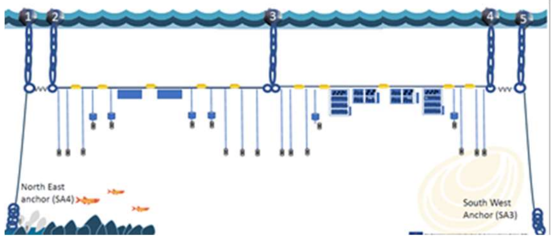
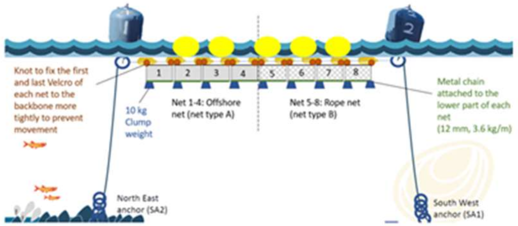
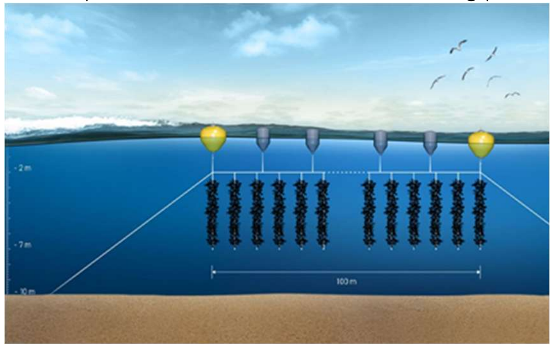
Source: Nancy Nevejan@Ugent-Edulis</td>
<td>Blue mussel (Mytilus edulis)</td>
<td>Semi-submerged longline with dropper lines (5m) and V-shaped line; anchoring with 15T steel weight anchors and danforth anchors; stainless steel anchoring line; spar buoys (D3)</td>
<td>Can be placed anywhere; no UXO required; known technique; droppers work; fouling under control</td>
<td>Specialized vessels needed for installation and maintenance; corrosion anchor chains; use of zinc anodes; position longline in water column difficult to control; V-shaped line revolves around backbone</td></tr>
</table>

<table>
<tr><td>Value@sea (Westdiep, nearshore – EFMZV 2017-2019)

Source: Daan Delbare@ILVO – Value@Sea.</td><td>Sugarweed (Saccharina latissima)</td><td>Application of a seaweed farm (AtSeaNova) with horizontal 2D nets and screw anchors as anchoring.</td><td>Can be placed in series, technology is used in protected conditions; known technique.</td><td>Specialized work; not suitable for the BNS.</td></tr>
<tr><td>
Source: Daan Delbare@ILVO – Value@Sea</td><td>Sugarweed (Saccharina latissima)</td><td>Vertically placed (upper meters) 2D nets on longlines with screw anchors as anchoring.</td><td>More suitable for BNS, but attention to buoyancy is necessary.</td><td>Due to too high turbidity, only the top of the 2D nets overgrown with sugarkelp</td></tr>
<tr><td>

Source: Daan Delbare@ILVO – Value@Sea</td><td>Flat oyster (Ostrea edulis) & scallop (Pecten maximus)</td><td>Longline with baskets, ladders or cages.</td><td>Good results with ladders and cages for flat oyster.</td><td>Very strong biofouling on baskets, too much movement for animals in baskets on longline, a lot of broken baskets in ladders and cages.</td></tr>
</table>

Mussel Nearshore (private initiative Versluys 2017-2019)  Source: Daan Delbare – Mussel Nearshore	Blue mussel (*Mytilus edulis)*	Longline of 100 m anchored with screw anchors.	Very good growth results and meat values. Longlines stayed in the water for 6 years. Good results with dropper lines.	Harvesting problematic : no suitable harvester

Symapa (Westdiep, nearshore – DBC/VLAIO 2020-2022)  Source: Daan Delbare@ilvo – Symapa	Sugarweed (*Saccharina latissima*)	Vertically placed 2D nets on longlines with screw anchors as anchors.	.	Due to loosened buoys, the entire system was lost (was recuperated after the project)
 Source: David Vuylsteke@Ilvo – Symapa	Flat oyster (*Ostrea edulis*)	Testing with ladders, cages, horizontal and OysterGro systems.	Best results with specially developed ladder.	Problems with biofouling; system OysterGro not an option in the BNS because they flip too quickly
 Source: Daan Delbare@ilvo – Symapa	Blue mussel (*Mytilus edulis*)	Testing ropes and harvesting systems	Best results with dropper lines	Stiffening of V-shape continuous line

UNITED (Horizon2020 2021-2023) - *Belwind*  Source: UNITED	Flat oyster (*Ostrea edulis*)	Semi-submerged longline with oyster baskets, oyster cages, droppers and lantern nets (W2), Cages (B3)	Can be placed in series; new technology for offshore conditions.	UXO needed; specialized work; DP2 system necessary for installation and dismanteling; no cultivation system turned out to be very efficient.
 Source: UNITED	Sugarweed (*Saccharina latissima*)	Surface longline with anchor chain and Dyneema rope; with 2D nets with velcro attachment; anchoring with screw anchors (D3).	Good growth.	Harvesting system must be developed; Timing is very important.
Westdiep Sea Farm - Commercial mussel farming (from 2022, concession for 20 years)  Source: Colruyt Group starts with first phase of Westdiep Sea Farm - Maritiem Media | Printing | Printing | Advertising	Blue mussel (*Mytilus edulis*)	System largely based on the results of Value@Sea and SYMAPA.	Unknown	Unknown

Annex 3: Biogenic reefs in the Belgian part of the North Sea: past and present

Examples of species that create biogenic reefs in the BNS (Habitat type "Reefs" - H1170) include the native flat oyster *Ostrea edulis*, the honeycomb worm *Sabellaria aveolata*, the Ross worm *Sabellaria spinulosa*, and the sand mason worm *Lanice conchilega*. These species offer a habitat for commercially important organisms, as well as food, predator protection, and nurseries for higher trophic species (Fig. 1). Due to the heavy use of beam trawls, biogenic reefs are now almost absent from the North Sea (Kerckhof, et al., 2018).

Fig.1 *Species richness in flat oyster reef in Brouwersdam (photo: Omroep Zeeland https://nos.nl/artikel/2383453-verbod-op-vissen-bij-oesterrif-voor-de-kust-van-de-brouwersdam)*

The historical locations of oyster reefs are well-documented and typically linked to gravel beds or stable substrates. Flat oysters are key ecosystem engineers, as they create structural reefs that can last for centuries. These reefs offer shelter, breeding, and spawning grounds for a wide range of species, including commercially valuable ones. In addition, oysters filter substantial amounts of plankton from the water, converting these organic particles into (pseudo-)faecal pellets that are accessible to other organisms. As a result, oysters also supply food that sustains the reef community.

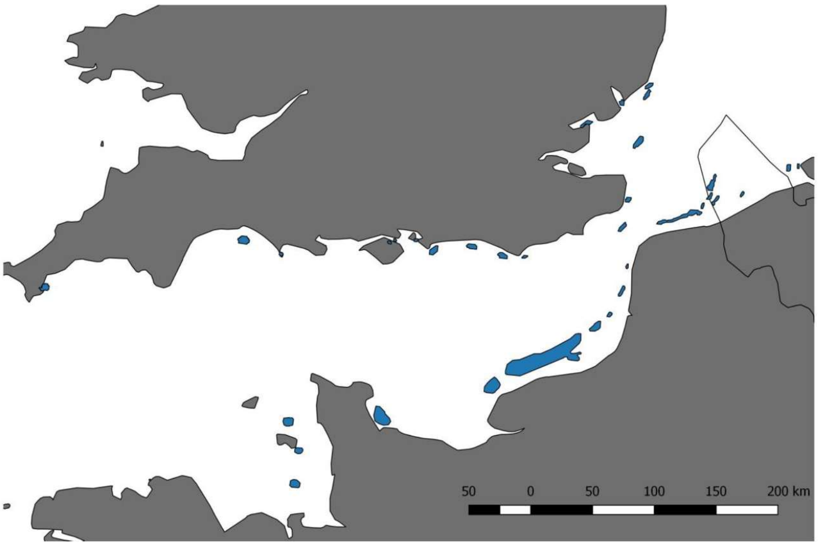


Fig. 2. Historical distribution of wild oyster beds, Ostrea edulis (1815-1910) along the Belgian coast and the English Channel (© ODN / RBINS, Laurence Vigin, 21/06/2018, projection: UTM 31 - WGS1984) (source: De Mesel 2018).

The recovery of *Sabellaria* reefs could also have a positive secondary impact on fish stocks. The Ross worm, a type of polychaete, relies on floating sand grains to construct its tube. When multiple *Sabellaria* worms are in close proximity, the glue they use to form their tubes can also attach to neighboring tubes, forming typical hummocks of interconnected tubes These biogenic reefs are typically found in areas exposed to strong currents, such as tidal channels. The reefs can grow to a thickness of 0.5 to 1.0 m (https://www.health.belgium.be/nl/opwaardering-van-sabellaria-riffen).

The current and historical presence of the *Sabellaria* is poorly documented. Historically, they were abundant, often associated with oyster beds, such as those between Zeebrugge and the Bol van Heyst (Hoziaux, unpublished). From 1889 to 1910, hummocks were found in the BNS at locations including Wielingen, Wandelaar, Thorntonbank, Noordhinder, Westhinder, and Ruytingen (Fig. 3) (Pype, 1911 in Rappé, 2008). By the 1970s, *Sabellaria* had been overfished in areas like Westhinder. Recently, isolated specimens have been found across the BNS, as well as small reefs on some artificial hard substrates in the subtidal (data RBINS-MUMM, unpublished).

Although *Sabellaria* is still present in the North Sea, large reefs have vanished due to seabed-disturbing fishing activities. The use of artificial substrates seeded with *Sabellaria* could aid in their recovery, though creating the proper hydrodynamic conditions for reef formation is also essential (pers. comm. Thomas Kerckhove, project UNITED).

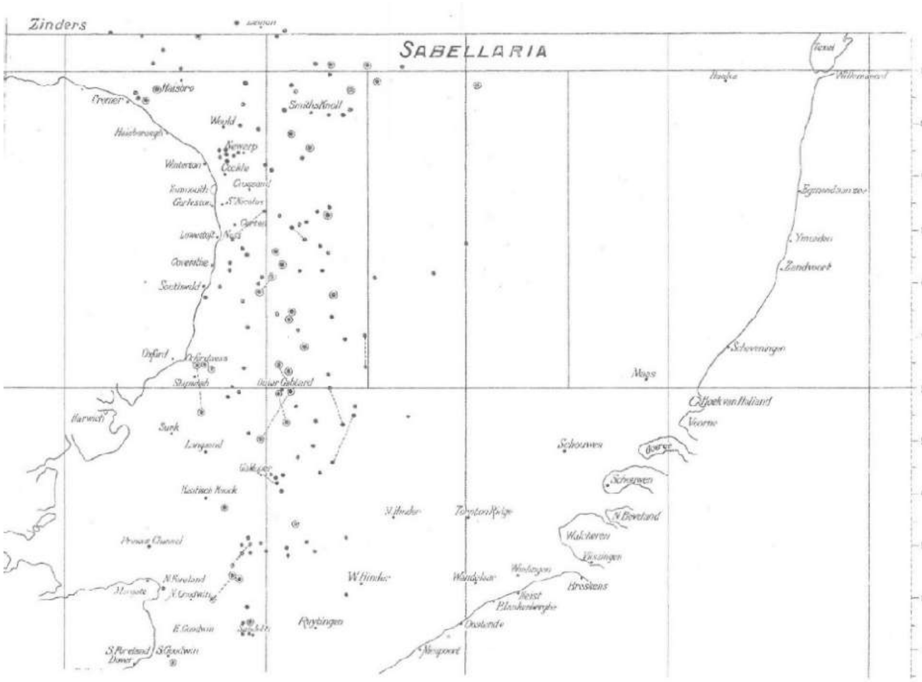


Fig. 3 Distribution of Sabellaria reefs in the southern part of the North Sea in 1911 (Pype, 1911 in Rappé, 2008).

The habitat type "reefs" (H1170) also includes aggregations of sand mason worms (*Lanice conchilega*), which are part of the macrobenthic community of *Abra alba*. By clustering together, these worms create their own microhabitat, which, in turn, attracts other species. As such, sand mason worms are often referred to as "habitat engineers" because they significantly increase local biodiversity. Sole is frequently associated with these *Lanice* reefs (Ernst, W. & Goerke, H. (1974). European razor clam (*Ensis ensis*) reefs also serve a similar ecological function (pers. comm. Francis Kerckhof).

The leaf-like hornwrack (*Flustra foliacea*), also known as sea moss or clack manure in local dialects, was commonly found between 1889-1910 (Pype, 1911 in Rappé, 2008), mainly north of the Ruytingen, west and north of the Westhinder, and near the Noordhinder, including areas to the west. These bryozoans form extensive colonies that attract a variety of other species due to their 3D structure. Initially, epibionts, such as other bryozoans (*e.g. Crista eburnean*, *Bugulina flabellata*, and *Scrupocellaria* spp.), hydrozoa, sessile polychaetes, porcelain crabs (*Pisidia longicornis*), sea urchins (*Echinus esculentus* and *Psammechinus miliaris*), slugs (*e.g. Crimora papillata*), and pycnogonids (*e.g. Achelia echinata*, which preferentially feeds on *Flustra foliacea*), thrive on these colonies. These colonies can live for up to 12 years, offering complex 3D habitats for many species.

Additionally, **glacial bouldering landscapes**, which are part of the gravel beds, can also be restored. These landscapes were removed with the advent of bottom trawling, as the boulders posed a hazard to fishing activities. Many of these glacial boulders ended up in fishermen's gardens (Rappé, 2008). Restoring these bouldering landscapes has positive effects on biodiversity, rare species, and commercial fish stocks (Støttrup et al., 2017; Liversage & Chapman, 2018; Liversage, 2020).
During the period from 1889-1910, glacial erratic boulders were found south and west of the Westhinder (often overgrown with large patches of *Flustra foliacea*), especially between the Westhinder and Fairy Bank. They were also discovered to the W-NW of the Noordhinder toward the Galloper, as well as between the Noordhinder, Oosthinder, and Bligh Bank (Fig. 4) (Pype, 1911 in Rappé, 2008).

Installing hard substrates can help restore areas where fishermen have removed these erratic boulders. Hard substrates provide attachment surfaces for various species, such as sponges, hydrozoa, dead man's fingers (*Alcyonium digitatum*), sea anemones, bryozoans, barnacles, bivalves, and sea squirts. These, in turn, attract species that live on these structures, including crustaceans, slugs, and benthic fish (https://www.health.belgium.be/sites/default/files/uploads/fields/fpshealth_theme_file/brochure_levend_water.pdf).

The substrate can also serve as a site for egg-laying, not only for snails, such as whelk (*Buccinum undatum*) and the red whelk (*Neptunea antiqua*), but also for squid and fish. In the English Channel and Bristol Channel, the majority of small-spotted catshark (*Scyliorhinus canicula*) egg cases were found associated with dead man's fingers and colonies of the bryozoan *Flustra foliacea*. Other significant substrates included the bryozoan *Cellaria* sp., hydrozoa (e.g. *Hydrallmania falcata*, *Nemertesia antennina*, and *Tubularia indivisa*), and sponges (e.g. *Haliclona oculata*) (Ellis et al., 2004). While the egg cases of the blue skate (13 x 6 cm) and flapper skate (20 x 10.5 cm) are larger, such substrates may still be suitable for these rays (van Moorsel, 2022).

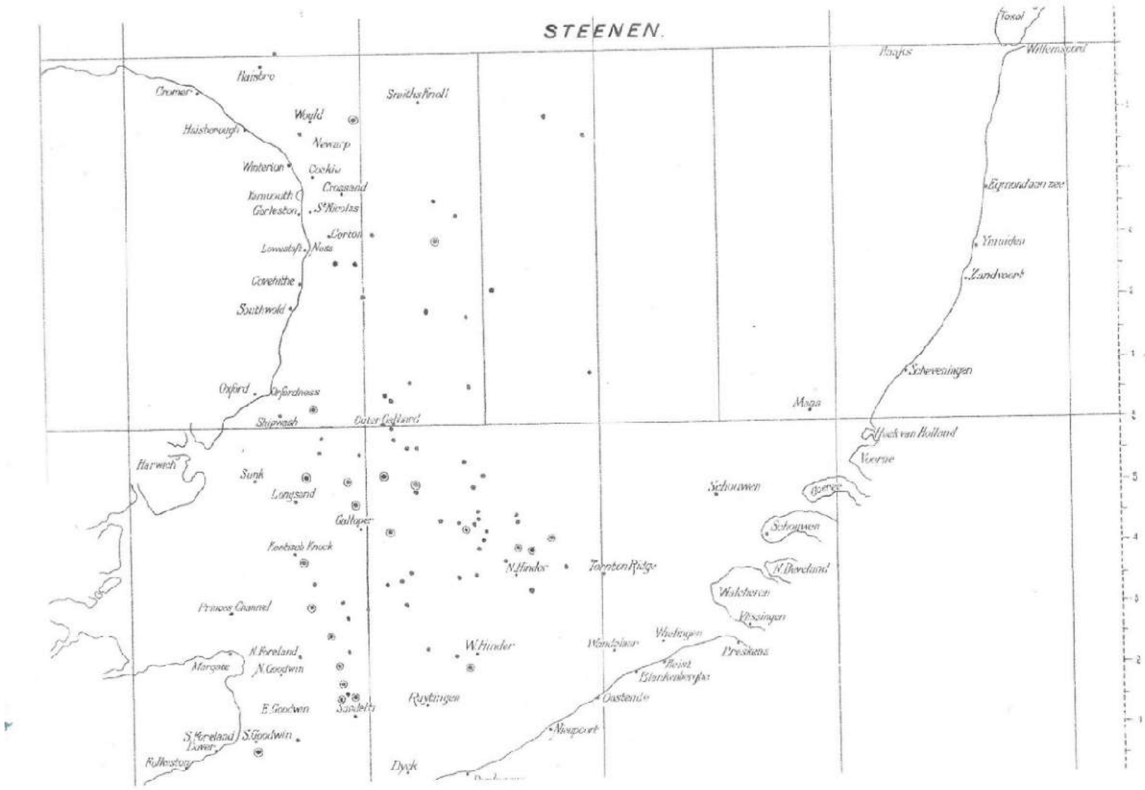


Fig.4 Distribution of "stones" or glacial boulders in the southern part of the North Sea (Pype, 1911 in Rappé, 2008).

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Annex 4: Consultation with the Redercentrale (18/03/2024) (online)

Attendees

Rederscentrale	Sander Meyns Falke De Sager
Consortium	Daan Delbare Brecht Stechele Nancy Nevejan

On March 18, 2024, the authors of this vision document met with the Rederscentrale to discuss their perspective on fishing in offshore wind farms (OWFs). The Rederscentrale expressed the view that, even with turbines spaced further apart, bottom trawling between turbines is not advisable due to the high risks involved (such as turbine collisions, entanglement in scour protection layers, or cable damage). However, they do see potential in participating in fisheries-enhancing, nature-restoring measures, and scientific monitoring campaigns, as well as cooperating with the OWF industry. They expressed limited enthusiasm for further collaboration between the fisheries sector and aquaculture (such as shared use of vessels, introducing passive fishing activities in wind farms, or retraining fishermen to work in aquaculture).

Passive Fishing in OWFs

Regarding the viability of passive fishing in OWFs, the Rederscentrale referenced a study by Luc Louagie, which concluded that this type of fishing is not profitable in the Belgian North Sea (BNS). There is minimal interest in this fishing method. Currently, only one vessel, the N93 *Cormorant* (an old beam trawler not specifically adapted for passive fishing), is involved in passive fishing. This situation is primarily due to the lack of funding options for new vessels within the European Maritime, Fisheries, and Aquaculture Fund (EMFAF). Additionally, there is the risk of damaging turbines, which would significantly increase insurance costs for civil liability, making it financially unfeasible for fishermen. During the meeting, the Rederscentrale mentioned the ILVO projects *VESPAS* (Verhaeghe, D., Polet, H. 2012) and *TIP-TOP* (Testing Innovations in Passive Fishing – Technical Optimization of Pot Fishing, OVIS project OV22303), which focus on using light and fragrance in pots to increase fishing potential.

The Rederscentrale also shared that the main commercial fish species for the Belgian fishing fleet are cod, sole, plaice, squid, and sea bass (although sea bass may only be available in limited quantities due to stock issues). Many of these species are found in OWFs. When asked whether passive fishermen from other Member States should be allowed access to Belgian OWFs, the answer was affirmative. The Rederscentrale pointed out that Belgian fishermen have historically operated in various international waters and Exclusive Economic Zones (EEZs), including the English Channel, Bay of Biscay, Celtic Sea, Irish Sea, Kattegat, and Skagerrak. Therefore, they believe that fishing restrictions should not be imposed on fishermen from other Member States in the BNS.

Aquaculture in OWFs

Regarding potential aquaculture activities in OWFs, the Rederscentrale expressed little interest. One example of possible aquaculture in OWFs was sorting juvenile fish, such as sole, from the catch and keeping them alive in a bottom cage for further growth (possibly for a fee). However, the Rederscentrale found this process too complex, especially since it goes against the European Discard Ban. They emphasized the need for a cost-effective, sustainable solution that adheres to European regulations.

Electrification of the Fleet

On the topic of electrifying the fleet, the Rederscentrale noted that only a small portion of the coastal fishing fleet could operate on electricity. However, large Eurotrawlers, which fish farther offshore (in places like the Irish Sea, Celtic Sea, Bay of Biscay, or Skagerrak/Kattegat), would not be able to run on batteries. Hybrid systems are being considered for larger vessels, but this would only be feasible for new-built ships.

Modular Ships

The concept of a "vessel of the future," a modular ship that can easily adapt to various activities such as scientific monitoring, providing services to OWFs (currently, OWF operators spend significant funds on leasing fishing vessels with crews for certain offshore tasks), was also discussed. Today, shipowners typically fish in three seasonal blocks (January-June, July-October, and November-December) and try to manage their quotas within these periods. A modular vessel could help absorb quotas (e.g., monkfish, rays, megrim, and lemon sole—due to limited quotas) in a short time (1 to 2 weeks), allowing the vessel to focus on other tasks at sea. An analysis showed that 280 fishing days are necessary to break even. However, the problem with such modular vessels is that regulations prevent switching between activities. A vessel must meet strict specifications set by maritime inspection regulations for a particular activity. If a vessel is used for a different purpose (e.g., removing fishing gear and taking on extra lifeboats), it must undergo a new stabilization test, a maritime inspection for its new role (workboat), and re-certification. This involves submitting a fishing license, updating safety plans, and meeting all necessary specifications (Royal Decree 20-06-1973).

Annex 5: Overview of the relevant regulations at European, federal and Flemish level for the development of offshore renewable energy and aquaculture in the BNS

European legislation and policy context			
Abbreviation	Title	Year	Number
EU Directives			
Directive 92/43/EEC	Directive on the conservation of natural habitats and of wild fauna and flora (Habitats Directive)	1992	43
Directive 2000/60/EC	Directive establishing a framework for Community action in the field of water policy (Water Framework Directive)	2000	60
Directive 2008/56/EC	Directive establishing a framework for Community action in the field of marine environmental policy (Marine Strategy Framework Directive) Consolidated text: 07/06/2017	2008	56
Directive 2009/147/EC	Directive on the conservation of wild birds (Birds Directive)	2009	147
Directive 2010/75/EU	Directive on industrial emissions (integrated pollution prevention and control)	2010	75
Directive 2014/89/EU	Directive establishing a framework for maritime spatial planning	2014	
Directive (EU) 2019/904/EU	Directive on the reduction of the impact of certain plastic products on the environment	2019	904
Regulations			
Regulation (EC) No 708/2007	Regulation on the use of alien and locally absent species in aquaculture	2007	708
Regulation (EU) 1379/2013	Regulation of the European Parliament and of the Council of 11 December 2013 on the common organisation of the markets in fishery and aquaculture products, amending Council Regulations (EC) No 1184/2006 and (EC) No 1224/2009 and repealing Council Regulation (EC) No 104/2000		
Regulation (EU) 2016/429	Regulation on transmissible animal diseases and amending and repealing certain acts in the area of animal health (Animal Health Law)	2016	429
Belgian legislation			
Royal Decrees			
Abbreviation	Title	Number	
Royal Decree of 21 December 2001	Royal Decree on the protection of species in the marine areas under the jurisdiction of Belgium	2001-12-21/72	
Royal Decree of 18 May 2008	Royal Decree establishing that an environmental impact assessment is required for the National Operational Programme for the fisheries sector and	2008-05-18/32	

	that an environmental impact assessment is not required for the National Strategic Plan for the fisheries sector	
Royal Decree of 23 June 2010	Royal Decree on the establishment of a framework for the achievement of good surface water status	2010-06-23/04
Royal Decree of 23 June 2010	Royal Decree on the marine strategy for the Belgian sea basins	2010-06-23/05
KB October 27, 2016	Royal Decree on the procedure for designating and managing marine protected areas	
Royal Decree of 22 May 2019	Royal Decree establishing the marine spatial plan for the period from 2020 to 2026 in the Belgian sea areas	2019-05-22/23
Royal Decree of 22 July 2019	Royal Decree laying down the procedure for obtaining a user permit for the zones for commercial and industrial activities in the sea areas under the jurisdiction of Belgium	2019-07-22/17
Royal Decree of 4 February2020	Royal Decree establishing a safety zone around the artificial islands, installations and devices for the generation, the installations and devices for the generation, storage and transmission of energy from the water, currents and winds in the sea areas under Belgian jurisdiction.	Royal Decree of 4 February 2020
Royal Decree of 26 April 2024	26 APRIL 2024. - Royal Decree on the procedure for the establishment of marine protected areas, for Natura 2000 authorisation and Natura 2000 approval and for environmental authorisation in Belgian sea areas	
Ministerial decrees on the adoption of conservation objectives		
MB of 23 December 2020	Ministerial Decree granting Codevco V BV an authorisation for the construction, a permit for the operation and a Natura 2000 authorisation for an aquaculture project in zone C in the sea areas under the jurisdiction of Belgium	
MB of 16 May 2024	Ministerial decree amending the Ministerial decree of 15 June 2021 establishing a safety zone around the sea farm	
MB of 11 January 2022	Ministerial Decree on the revision of the conservation objectives for marine protected areas	
MB of September 1, 2023	Ministerial Order supplementing the Ministerial Order of 11 January 2022 on the revision of the conservation objectives for marine protected areas	
MB of 16 May 2024	Ministerial Decree amending the Ministerial Decree of 15 June 2021 establishing a safety zone around the sea farm	
Laws		
Law of 11 December 2022	Law on the protection of the marine environment and on the organisation of marine spatial planning in the Belgian sea areas	
Law of 22 April 1999	Law on the exclusive economic zone of Belgium in the North Sea	1999-04-22/47

Annex 6: Relevant nature and environment-related policy instruments for the BNS and the coastal zone

RAMSAR Convention (1971)

The Ramsar Convention is an international treaty that aims at the global conservation and sustainable management of wetlands, in particular the protection of waterfowl habitats (Goffin et al., 2007), through local and national measures and international cooperation.

United Nations Convention on the Law of the Sea (1982)

The United Nations Convention on the Law of the Sea (UNCLOS) sets out a comprehensive legal framework for the use of the seas and oceans. Part of this Convention, Part XII of UNCLOS (Protection and Preservation of the Marine Environment), deals specifically with the protection and conservation of the marine environment. The Intergovernmental Conference drafted an International Legally Binding Instrument (ILBI) for the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (BBNJ). This was established by the UN General Assembly (UNGA) in 2017 (UN Resolution A/RES/72/249).

Convention on Biological Diversity (1992)

The Convention on Biological Diversity (CBD) was established at the UN Conference on Environment and Development (UNCED, 3-14 June 1992, Rio de Janeiro) and addresses all ecosystems, species and genetic resources. The objectives of the Convention are: 1) the conservation of biological diversity, 2) its sustainable use and 3) a fair distribution of the benefits arising from the use of genetic resources. Each country should appoint a node to boost the implementation of the Convention on Biological Diversity. For Belgium, the Institute of Natural Sciences has been designated as the National Hub for the CBD, with the national biodiversity strategies and action plans being the policy instruments to ensure the conservation and sustainable use of biological diversity. The contracting parties cooperate in the event of bilateral interests or where there is no national jurisdiction.

OSPAR Convention (1992)

The OSPAR Convention is a cooperation of 15 countries and the EU for the protection of the marine environment in the Northeast Atlantic Ocean (including the North Sea). The OSPAR Convention replaces the Oslo Convention (1972) and the Paris Convention (1974) and defines the general provisions for the protection of the marine environment against a number of specific sources of pollution, such as pollution from land-based sources, from landfill or incineration and from offshore activities. In addition, clear agreements are made for the unambiguous evaluation of the quality of the marine environment (OSPAR Quality Status Report 2023, OSPAR Intermediate Assessment 2017) and for the protection and conservation of ecosystems and biological diversity (Goffin et al., 2007). To this end, the contracting parties apply the precautionary principle and the polluter pays-principle, the use of the best available techniques (BAT) and the best environmental practice (BEP), including clean technology. OSPAR's Northeast Atlantic Environment Strategy (NEAES 2030) focuses on three challenges that address the main threats to the oceans, i.e. biodiversity loss, pollution (incl. marine litter) and climate change. Based on OSPAR's mid-term review (OSPAR IA 2017), OSPAR QSR 2023 was adapted.

Habitats Directive (1992)

The European Habitats Directive (Directive 92/43/EEC) aims to conserve and restore European natural habitats and their wild fauna and flora. Each Member State must designate special areas of conservation, known as Habitats Directive areas, for habitats and species of Community interest. These habitats and species are listed in Annexes I and II of the Directive respectively. Two habitat directive areas have been designated for the BNS, namely the Flemish Banks (111,198 ha) and the Plain of the Raan (6,296 ha). The zone with Flemish Banks is formed by permanently flooded shallow sandbanks in which biogenic and geogenic reefs also occur. Near the border with the Netherlands is the Plain of the Raan, which also consists of permanently flooded shallow sandbanks within which biogenic reefs occur. Conservation objectives have been set for these two areas (MD of 11 January 2022 & MD of 01 September 2023). Member States are obliged to report to the EC every six years for the Habitats Directive (art. 17).

Marine Strategy Framework Directive (2008)

The European Marine Strategy Framework Directive (MSFD) (Directive 2008/56/EC) aims to protect and, where necessary, restore the good status of the marine environment in European seas and oceans. It is the environmental pillar of the European Union's Integrated Maritime Policy (IMP) (COM (2007) 575) and aims to achieve the good environmental status (GES) of European marine waters by 2020 and to protect the resources on which economic and social activities depend. The GES is defined in Article 9 of this Directive on the basis of 11 descriptors for which Member States are required to develop indicators with associated environmental targets (DG Environment 2012, OD Nature) (https://www.health.belgium.be/nl/herziening-van-de-initiele-beoordeling-2018).

Birds Directive (2009)

The European Birds Directive (Directive 2009/147/EC) aims to protect all wild bird species. Special protection measures shall be taken for the habitats of the bird species listed in Annex I and the species that occur in internationally important numbers as breeding birds, migratory birds or wintering birds in a given area. Each Member State must designate special protection areas, the so-called Birds Directive areas, which, together with the Habitats Directive areas, are part of the European ecological Natura 2000 network. The Member States are obliged to report to the EC every six years for the Birds Directive (art. 12). The MD of 2 February 2017 contains the IHDs that were adopted for the BNS in the context of the Birds and Habitats Directives. The translation of the Habitats and Birds Directives into federal legislation is provided for by various implementing decrees linked to the Act of 20 January 1999: Royal Decree of 16 December 2022 Law on the protection of the marine environment and on the organisation of marine spatial planning in the Belgian marine areas (NOTE: Consultation of earlier versions as of 16-12-2022 and text update until 04-07-2024).

Invasive alien species regulation ('Exotic Species Regulation') (2014)

The Invasive Alien Species Regulation (Regulation (EU) No 2011 1143/2014) sets out a set of measures to be taken across the EU with regard to invasive alien species. At the heart of the Regulation is the list of invasive alien species of Union concern (Union list). The species included in this list apply to the restrictions and measures laid down in the Regulation. These include restrictions on keeping, importing, selling, breeding, growing and releasing into the environment.

Member States are obliged to

- take action on pathways of unintended introduction (i.e. prevention);
- take measures to detect and rapidly eradicate these species and to ensure that they are
- species that are already widely distributed in their territory.

References

Goffin, A., Lescrauwaet, A. C., Calewaert, J. B., Mees, J., Seys, J., Delbare, D., ... & Peeters, B. (2007). MIRA Milieurapport Vlaanderen, Achtergronddocument 2006: Kust & zee.

Annex 7: Preconditions for integration of aquaculture in Belgian wind farms, as formulated during interview with Belgian Offshore Platform, 13/03/2024 (hybrid)

Attendees in the Parkwind office

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Subject	Problem	Position of the OWF
Insurance	Integration of aquaculture will increase the risk. This risk translates into an additional cost of insurance	The additional cost for the insurance is paid by the aquaculturist and cannot be passed on to the OWFs
Compensation fund	OWFs pay for the environmental impact they cause. These funds end up in the compensation fund	Aquaculture companies also have to pay for the compensation fund
Decommissioning	The installation of aquaculture infrastructure in OWF will increase the cost of decommissioning	Integration of aquaculture should not result in an increased dismantling cost, and the aquaculturist is responsible for removing the installed infrastructure
Adapting infrastructure for integration	The infrastructure of offshore wind farms is designed with a specific lifespan. Older types of wind turbines had an age buffer. This is no longer used to save on production costs. The current wind turbines are designed with a strict lifespan. Modifications to the structures after installation are at the expense of the life of the turbine. This applies to. (1) scour protection layers, (2) foundations,	Specific aquaculture requirements must be taken into account in the design of the park. Adjustments are no longer possible after installation The integration of aquaculture with offshore wind turbine would first be tested on a small scale on 1 turbine, e.g. with an integrated design process.

	(3) coatings on turbines, (4) cables and (5) the substation.	Offshore aquaculture systems are still too immature to be used on a large scale.
Integrating aquaculture with turbines that still have a service life left	After the expiration of the license period, some turbines may not have reached their service life yet. It can be considered to use these pylons for integration with aquaculture.	This should be possible, but as a kind of test turbine (not for commercial purposes)
Operation of energy infrastructure and aquaculture		It should be possible to have the same operator for offshore wind farms and offshore aquaculture
Which cultivation systems can be integrated into OWF?	This is possible but subjected to following conditions: (1) The aquaculture installations do not prevent the operation of the offshore wind farm (2) When grown at a depth of -10m, all passage is assured (3) safety distance to the turbines is ensured (4) All systems (buoys, lines, anchors, structures) must be tracked non-stop. (5) Bottom structures must also be anchored and must also be tracked.	
What if you fail?	In the event of damage to aquaculture systems, a clear plan of action must be put in place. How will the system be restored? Which ships will be used to restore the system? What are the risks for the OWF? How will the restoration activities impact the operation of the OWF?	There must be a clear plan that predicts the risk of different scenarios. Damage and repair work to aquaculture infrastructure must not hinder the operations of the OWF.
How can repair operations be performed?	Restoration operations on offshore aquaculture infrastructure use specific vessels and rescue techniques.	Diving is not allowed because it is too unsafe. (Culverts are often used for net restoration) All ships must have permission to enter the park (repair operations must be predicted).
PR issues for OWFs in case of damage to aquaculture	If aquaculture and OWFs are carried out in the same location, OWFs can have PR problems without being responsible for it.	
Which locations are available?	The installation of aquaculture infrastructure can prevent the operation of wind farms.	The locations around the turbines are not available. The locations around the cables are not available.

		The locations around the substation are not available.
Use of the substation for aquaculture infrastructure	The substation could potentially be used to anchor aquaculture installations	The substation is also designed with a fixed service life. Modifications will ensure a shorter lifespan. This is not desirable.
How can integration of aquaculture with OWFs be made possible?	At the moment, OWFs have no incentive to allow aquaculture. Allowing extra activities entails risks, which creates extra costs.	Allowing other activities in the offshore wind farm is possible under two conditions. (1) the tender demand for this, (2) the integration of a new activity creates an economic win-win (taking into account increased insurance costs, operating costs, etc.). The distance to the coast is a limitation for most initiatives.
Is it possible to harvest organisms around the turbines?	By installing artificial hard substrate, an enrichment of the ecosystem will occur. This enrichment can be a source of food production.	(1) The OWFs see the fouling as an extra protection, and have no interest in removing it. So the removal of mussels that grow on the pillars is also not desirable. (2) On the contrary, interactions between harvesters and the coating on the steel can increase the risk of corrosion. (3) A risk analysis must also be made for the harvesting of organisms around the turbines. This activity should preferably be included in the design of the turbines. (4) Retrofitting the infrastructure is impossible.
Security of the OWF	OWFs are considered critical infrastructure. This gives them a protection status. This allows for extra precautions, such as; (1) access for verified users only, (2) access for verified companies only.	This creates an additional cost to integrate aquaculture. (1) plan which aquaculture operations will take place where. (2) managing access, (3) controlling access, (4) new software for planning, (5) more difficult process during critical moments such as damage to aquaculture infrastructure.
Is the safety zone suitable for aquaculture?	The safety zone is laid down by law around all objects at sea. The Belgian government has laid down the guidelines for the safety zone around OWF.	The safety zone must be able to perform its function. Risks can be reduced by placing the aquaculture infrastructure in the safety zone. But the safety zone in itself is not the location where there is the least risk associated with activities. Other zones may be less risky and therefore more suitable. The most

		important parameters are flow and distance from pillars. These are park-dependent.
How can risks of damage be avoided	Offshore aquaculture is prone to damage. Damage in OWFs is difficult to manage.	Breeding in storm-free periods can be preferred.
Is there access to electricity in the OWF	At the moment, there is no access to electricity in the OWFs. Several ideas have been published to provide electricity at sea. This mainly concerns the switch to electric ships of the operators themselves, or allowing the charging of electric ships at turbines.	At the moment, there is no technical solution to charge at sea. It may be possible to create electricity supply for mariculture, but this must be integrated from the design phase.
Can modular ships be counted on that can be used for aquaculture and UWP activities?	Modular ships are used for various applications (marine).	Nowadays, two types of ships are used. Multi-use ships that have different applications, or very specific ships for specific activities. The multi-use vessels could be used for aquaculture. This must be taken into account in the design of the ship. Most operators do not have ships themselves, but subcontracts ships for maintenance.
Are OWFs in favor of including food production in the tender application	Non-price criteria can be used in the tender application. If the tender application does not meet the non-price criteria, the applicant is not eligible to win the tender, even if he has the lowest price.	Non-price criteria are broadly supported by the OWF. Several OWFs do R&D according to non-price criteria. Non-price criteria are mainly about reducing the impact and are therefore about sustainability in general, nature restoration is also sometimes included as non-price criteria. Despite this, food production at sea is often seen as an additional pressure on the environment and is not recommended.
Are there opportunities to adapt the layout of the park to aquaculture activities	Turbines are often too close together to allow aquaculture. New OWFs are built with larger spaces between turbines. Nevertheless, an adjustment of the park layout could simplify integration with offshore aquaculture.	Adjustments to the layout of the park are possible but must be included in the design phase. Adjustments to the layout of the park will result in a reduced yield and therefore an increased price for electricity production. This is therefore only possible if an economic win-win can be created, or if the tender application requires it.

Are the OWFs interested in supporting aquaculture projects?	Aquaculture projects can take place in OWFs and OWFs are a unique location for multi-use research.	Aquaculture projects must test their activities in protected areas near the coast before they can be integrated with offshore wind. The activities must be predictable and manageable, and not create additional risks that create additional costs. Furthermore, neither aquaculture nor nature restoration are the core business of OWFs and the inclusion of these activities will only result in an additional cost of personnel.

Annex 8: Key factors in target species selection – AquaValue

Economic feasibility	**1. Market size**
	2. Market position of the end product?
	    a. For human consumption?
	    b. Extraction of chemical components?
	    c. Conversion for pet food
	    d. Biofuel? -> less attractive
	3. Identifying potential markets
	4. Question
	5. Competition
	6. Operational costs
	    a. Mechanizable? (reducing labor costs)
	    b. Kwh/kg vis
	7. Meat yield, or yield of product
	8. Tolerance for live transport or mode of transport
	9. Market price: €/kg
	10. Marketing

Technical feasibility	1. Understanding and providing seed and egg production or checking the availability of juveniles 2. Understanding the grow-out systems 3. Knowledge of nutrition 4. Availability of off-the-shelf power supply 5. Type of aquaculture best suits the requirements of the species 6. Limitations in existing forms of commercial production

Biological feasibility	1. Growth, survival and performance
	    a. Feed Conversion Rate (FCR)
	    b. Behavior in captivity
	    c. Swimming behaviour
	    d. Susceptibility to diseases
	    e. Market size growth time
	2. Understanding Growing Conditions
	    a. Variables
	        i. Temperature
	        ii. Salinity
	        iii. Oxygen
	        iv. Turbidity
	        v. Ammonium
	        vi. Maximum stocking density
	    b. Offshore: Selection of species that can be grown in BNS conditions (light, temperature, nutrients)
	    c. Land-based: Assessing the feasibility of growing conditions (Cost of maintaining optimal growing conditions)
	3. Integration with other species (IMTA)

Extra	1. Social acceptance? 2. Sensory test? 3. Local story? 4. Durability 5. Life Cycle Assessment 6. Comply with legislation (VLAREM, exotics, Novel Foods, monitoring,..)

Source: Blondeel, L. (2015) AquaValue – Work package 1.2: Evaluation of integration possibilities for aquaculture.