Non-technical report

AQUACULTURE in

OFFSHORE WIND FARMS

in the Belgian part of the North Sea

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Aquaculture in offshore wind farms in the Belgian part of the North Sea

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Glossary

BNS: Belgian part of the North Sea

CIA: Commercial and Industrial Activities

Farm gate price: is the market price of the product minus the sales costs (transport, marketing)

FAO: Food and Agriculture Organization of the United Nations

IUCN: International Union for Conservation of Nature

IUCN status: indicates whether an animal or plant species is threatened with extinction in its natural habitat

Longline: breeding system in which the horizontal bearing line ("backbone") is kept in the correct position in the water column with buoys and anchors

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.

MSP: Marine Spatial Plan

OWF: Offshore wind farm

PEZ: Princess Elisabeth zone, offshore renewable energy development zone

Rederscentrale : federation that represents the Belgian fishing industry

WUR - Wageningen University & Research

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NON-TECHNICAL REPORT

1. Introduction

The coming years will be crucial for the expansion and transition of the offshore green energy sector. European ambitions, including those of Belgium, are significant, aiming for a total offshore capacity of 260 gigawatts by 2050. In addition to offshore wind energy, offshore solar energy is also advancing rapidly in Belgium and the Netherlands, making the integration of various systems a key research priority.

Meanwhile, marine aquaculture in Europe has seen little growth in recent decades—except for salmon farming in Norway—and remains small compared to Asia. However, seafood production is increasingly recognized as a vital component of Europe's efforts to enhance food security (ensuring sufficient, healthy, and affordable food by increasing domestic primary production, including aquaculture) and support the protein transition (shifting towards more sustainable and less animal-based food production).

Between 2022 and 2023, the study "Vision development for Aquaculture in the Belgian part of the North Sea" was initiated on behalf of the Minister of the North Sea, facilitated by the Marine Environment Service of the FPS Public Health, Safety of the Food Chain, and Environment. Its objective was to identify opportunities and challenges for the development of marine aquaculture off-coast through stakeholder consultations. Fundamental conditions for aquaculture in the Belgian part of the North Sea (BNS) were proposed such as the use of native species and extractive farming methods. The primary focus is food production for human consumption, with a strong emphasis on the multi-use of space.

Currently, the most viable example of multi-use of space in the BNS is aquaculture within offshore wind farms (OWFs). The current Belgian Marine Spatial Plan (MSP 2022-2026) permits commercial aquaculture only within OWFs and designated zones for Commercial and Industrial Activities (CIAs). However, in the preliminary version of the new MSP (2026-2034), all CIA zones—except the one where the Westdiep Zeeboerderij operates—have been removed, allowing aquaculture activities to expand beyond OWFs. Since this version of the MSP is not yet finalized, it hasn't been considered in this study.

Building further on this stakeholders' process, this document aims to provide a more concrete perspective on aquaculture within Belgian offshore wind farms. Here, aquaculture is interpreted broadly, also encompassing nature restoration efforts within OWFs when these contribute to increasing commercial stocks. The expansion of the offshore energy sector into the new Princess Elisabeth Zone, along with the planned repowering of the Eastern Zone, presents an excellent opportunity for the aquaculture sector to explore offshore areas. This study seeks to equip stakeholders with the necessary tools to advance this development.

2. Material and methods

2.1. The foundation of this study

The authors based this study on the document *"Vision Development for Aquaculture in the Belgian Part of the North Sea"* and an extensive literature review to develop concrete proposals for offshore aquaculture in Belgium—the so-called scenarios. Practical experience from various nearshore and offshore aquaculture projects in the BNS provided valuable insights into what is realistically feasible and the challenges that arise, whether technical, biological, legal, or organizational. These "lessons learned" form a crucial foundation for this study. Additionally, an analysis was conducted on developments in European member states and the rest of the world regarding the integration of nature restoration in OWFs.

To further strengthen the study, the team organized meetings with the Rederscentrale, representing the Belgian fishing industry, and the Belgian Offshore Platform, advocating for the offshore wind energy sector. Insights from these discussions helped define key preconditions to facilitate offshore aquaculture opportunities.

2.2. Approach

This study focuses on the possibilities to develop aquaculture activities in the Belgian OWFs. They can be grouped into 3 categories. (Table 1 & Fig 1.). In the existing OWFs or the OWFs for which the tender procedure has already been established, and which are located outside the Natura 2000 area (Category 3 - Cat. 3), the aquaculture systems and species must be adapted to the existing layout and imposed conditions. Under these circumstances, it is advisable to first identify suitable techniques and then select aquaculture species that can be farmed using these techniques, provided the environmental parameters are favourable.

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

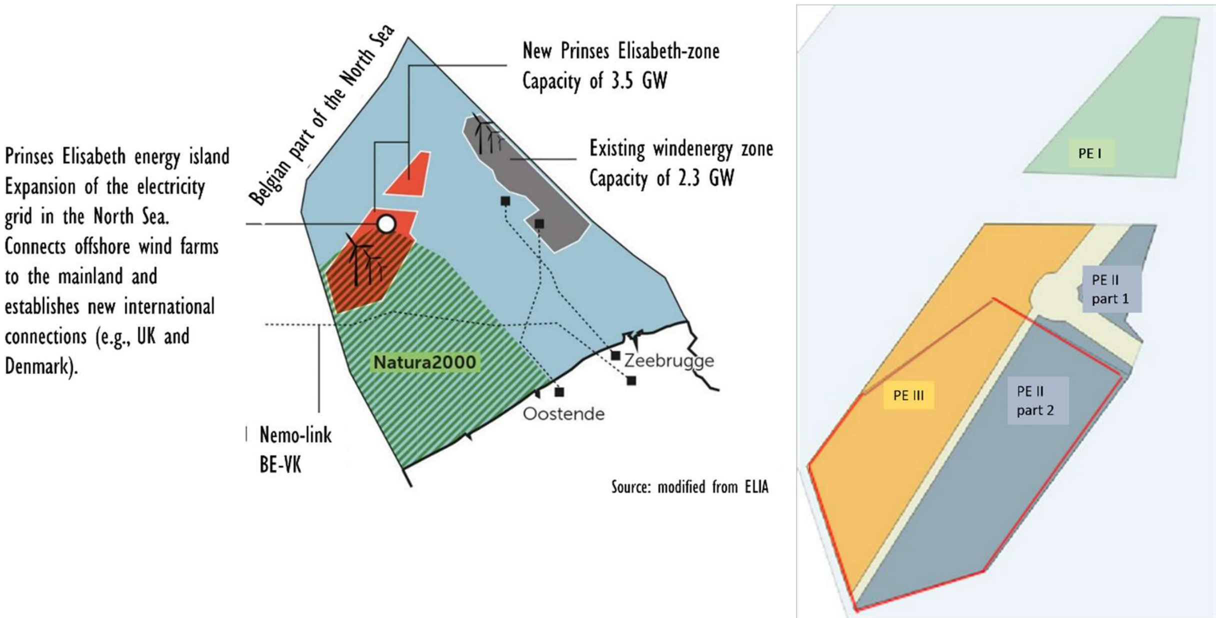


Fig. 1. Location of offshore wind farm zones (Left, source: [Belgian dredging companies Jan De Nul and DEME have been awarded permission to build 'energy islands' in the North Sea | De Morgen](#)) in BNS and parcelling of the Princess Elisabeth zone (Right, source: [Identification of the sites for the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

For future wind farms outside Natura 2000 areas, a profitable and sustainable aquaculture sector can be developed based on selected species driven by market demand. Therefore, cultivation techniques

[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

that support these species should be integrated into the issued OWF tender (Category 1 - Cat. 1). It is crucial that the preconditions for an integrated aquaculture system are established through an adapted tender procedure, transitioning from multi-use of space to full integration, with a strong emphasis on creating synergies.

For wind farms planned within Natura 2000 areas ([Category 2 - Cat. 2]), ecological and legal constraints will play a major role, significantly limiting aquaculture opportunities. Aquaculture will only be permitted if a favourable conservation status has been achieved within the nature reserve and if the activity does not cause further damage to seabed habitats.

To fully harness the potential of Belgian offshore aquaculture and enable the transition described above, this study follows a structured approach:

- Selection of Techniques & Species – A comprehensive overview of aquaculture techniques suitable for offshore conditions in the BNS was compiled, along with a list of potential aquaculture species selected based on price, conservation status, native character, and ecological value.
- Scenario Development – Specific scenarios were formulated, combining techniques and species that meet the identified preconditions. These scenarios are designed for future OWFs (new or repowered) but some of them can also be implemented in existing OWFs and, in some cases, adapted for OWFs located in a Natura 2000 area.

Aquaculture techniques are classified into three main groups. In intensive culture techniques, target species are cultivated in high density. Mobile species such as fish are mainly farmed in nets, baskets, or cages. Non-mobile species such as shellfish are grown on the bottom or on structures that ensure they stay in place.

Sea ranching or herding fish (open sea farm) is a specialized aquaculture method where farmers support local populations before harvesting. The stock is considered private property. Different techniques can be applied: conditioned juveniles may be released to support local populations (*stock enhancement*) or artificial reefs may be installed to support or keep the target species in place. Artificial structures provide nutrition, protection, habitat or reproductive opportunities. Without the introduction of juveniles, locally present target populations can also be conditioned by administering food (or ‘candies’ can be used as lure instead of food) or kept on site by installing specific structures. The target species can be harvested selectively (by size and species) using passive fishing techniques within the OWF, or with traditional fishing techniques outside the OWF, possibly by using the same attractive stimuli.

Taking population-support measures can also support commercial target species populations through the release of juveniles or installation of artificial structures. In addition, supporting measures may also include habitat restoration, either biogenic habitats such as sand mason worm reefs or habitats of non-biological origin such as gravel beds. Unlike sea ranching, supported populations remain communal property rather than belonging to individual entrepreneurs.

A list of potentially valuable species for aquaculture in the BNS has been compiled based on commercially viable fish species for the Belgian fishery. Various sources were consulted, including interesting species lists from reference works, EU publications, project outcomes, and price lists published by the Rederscentrale (prices in Belgium), FAO, and WUR (prices in EU). The prices for target species are given in €/kg for the total product or for the product without guts. These potential aquaculture species were categorized into fish, crustaceans, molluscs, seaweeds, and species relevant for habitat restoration (linked to population support measures).

For each category, reference species were identified to establish a minimum price, above which a species was considered viable for aquaculture. The reference price for fish and molluscs corresponds to the price of a species for which aquaculture is already a well-established sector in Europe (potentially even offshore aquaculture). Atlantic salmon was selected as the reference species for fish, with a rounded reference price of €5/kg, while blue mussels were chosen as the reference species for molluscs, with a reference price of €2/kg. In the case of crustaceans, the edible crab was chosen as a reference species due to the absence of an established shellfish aquaculture sector in Europe. The edible crab is frequently mentioned in literature as a promising aquaculture species and is highly valued in neighbouring countries. The crab has a rounded reference price of €5/kg.

No farm-gate prices were provided for seaweed as it is not sold through the Belgian fish auctions, nor for species relevant for habitat restoration. IUCN status is displayed for each species to highlight those that could qualify for population support measures.

In addition to technology and species, the selection of a specific aquaculture activity will be influenced by social, ecological, economic, and legal factors, which can vary significantly between OWFs that have already been granted a license and those still undergoing the tender process or located within a Natura

2000 area. The tender procedure for offshore wind production serves as a key tool that can impose additional criteria to promote nature conservation and food-sustaining activities. However, OWFs also introduce extra requirements to ensure that the extra risks associated with new activities in their concession area remain manageable.

3. Results

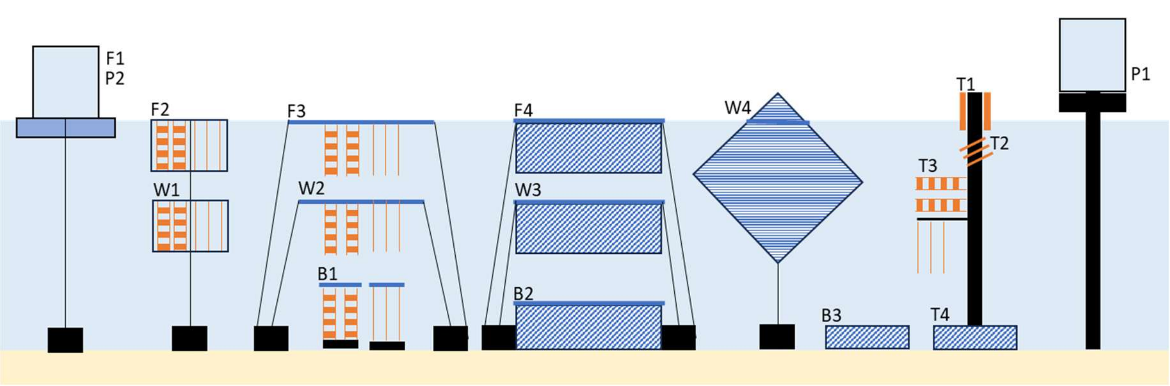
3.1. Techniques

Intensive culture systems were categorized based on type, anchoring method, and floating device. For intensive cultivation, the integration of these systems into offshore wind farms can occur in several ways: (1) as independent units, (2) with the turbine serving as the anchor, and (3) as fully integrated systems. Each farming system also utilizes different production techniques to maintain high-density populations of target species, such as ropes, baskets, breeding nets, or tanks. Table 2 provides an overview of the classification of intensive farming techniques, sea ranching, and population-support measures that can be implemented in offshore areas.

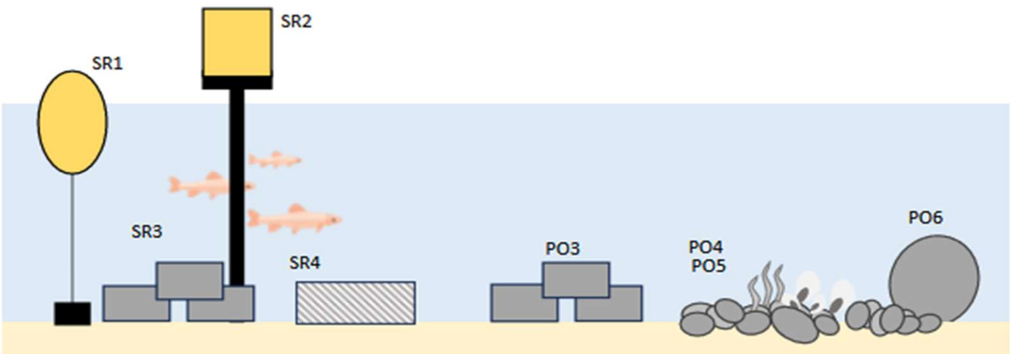
Table 2. List of potential intensive culture techniques, sea ranching and population support measures

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

Code	Anchoring	Flotation device	Production system/technology	Target species
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



3.2. Species

The outcome of species selection for offshore aquaculture, based on local landings and price (equal to or above the reference species price), is presented in Table 3.

*Table 3. List of potential aquaculture species for farming in the BNS including market prices and IUCN protection code. *Price for dried product (AlgaProBanos http://vis4nlp.com/APB/) ; **No market value.*

No.	Kind	Scientific name	Price (€/kg) Belgium 2023	Price (€/kg) EU 2023	IUCN
	FISH				
1 (REF).	Farmed salmon	*Salmo salar*		5,66 – 11,40	NT
2	Brill	*Scophthalmus rhombus*	12,12	4,50 – 9,45	LC
3	Halibut	*Hippoglossus hippoglossus*	12,49		NT
4	Eel	*Anguilla anguilla*	10,37	18,28	CR
5	Sturgeon	*Acipenser sturio*	6,01	7,50	CR
6	Turbot	*Psetta maxima*	15,68	9,85 – 15,88	LC
7	Sole	*Solea solea*	17,54		DD
8	Tuna	*Thunnus Thynnas*		10,01-11,77	LC
9	Sand sole	*Solea lascaris*	10,79	13,45 – 31,00	LC
10	Sea bass	*Dicentrarchus labrax*	10,87	4,35 – 12,30	LC
11	Monkfish/lot	*Lophius piscator*	9,55		LC
12	John Dory, Peter's fish	*Zeus faber*	8,81	13,83 – 23,50	DD
	CRUSTACEANS				
13	Brown shrimp	*Crangon crangon*	8,85		
14 (REF).	Edible crab	*Cancer pagurus*	4,92	10-00 – 16,90	NE
15	European lobster	*Homarus gammarus*	13,84	25,93 – 44,00	LC
16	Red crayfish, Red lobster	*Palinurus elephas*	22,62	10,39 - 22,62	
17	Norway lobster	*Nephrops norvegicus*	10,39		
	MOLLUSCS				
18	Razor shells	*Solenidae*		3,85-18,30	
19 (REF.)	Blue mussel	*Mytilus edulis*	1,80	1,70 – 6,27	LC
20	European flat oyster	*Ostrea edulis*	7,20	11,40 – 18,60	NE
21	King scallop	*Pecten maximus*	2,58	4,35 – 5,35	NE
22	Squid	*Loligo vulgaris*	7,42	8,15 – 15,07	NE
23	Cuttlefish	*Sepia officinalis*	3,18	3,07 – 4,50	NE

	SEAWEEDS				
24	Sugar weed	*Saccharina latissima*			
25	Sea lettuce	*Ulva lactuca**		23,08	
26	Oarweed	*Laminaria digitata*			
27	Dulse	*Palmaria palmata**		165,87	
28	Toothed wrack	*Fucus serratus*			
29	Bladder wrack	*Fucus vesiculosus*			
30	Wing kelp/Atlantic wakame	*Alaria esculenta **		23,08	
31	Laver, nori	*Porphyra umbilicalis*			
32	Irish moss	*Chondrus crispus*			
	FOR HABITAT RESTORATION – **REEFS****				
33	Ross worm	*Sabellaria spinulosa*			
34	Sand mason worm	*Lanice conchilega*			
35	European flat oyster	*Ostrea edulis*			
36	Keelworm/Christmas tree worm	*Pomatoceros (Spirobranchus) triqueter*			

3.3. Prevailing preconditions

As a prerequisite, this study assumes that aquaculture activities must comply with legally established conditions regarding environmental impact (negative impact) and contribute to achieving a good or improved environmental status (positive impact). Specifically, in Natura 2000 areas, no significant negative effect on sediment habitats should result from new activities, in addition to offshore wind farms. Therefore, we propose that new aquaculture activities should only be permitted in Natura 2000 areas if they contribute to achieving the conservation objectives of those areas. Activities that place additional pressure on the ecosystem can only be considered once a favourable conservation status has been achieved (European Habitats Directive). In the case of PEZ in the Natura 2000 area, it is assumed that a favourable conservation status will not yet be reached when the southernmost plots for renewable energy production are utilized. Hence, this study only suggests activities that improve the conservation status of the ecosystem. Since fishing, including passive fishing, does not contribute to the ecosystem's improved conservation, the authors assume that this activity will not be allowed in these areas either.

Ensuring food security in Europe is crucial, and this factor should be incorporated into the economic evaluation of offshore aquaculture. It is evident that the harsh offshore conditions of the Belgian North Sea, coupled with the long distance to the coast, lead to high costs in terms of both operational (OPEX) and investment (CAPEX). However, even if aquaculture as an independent activity is not financially viable, commercial production will still generate socio-economic added value.

Renewable energy production and offshore aquaculture are under federal jurisdiction, with relevant regulations at both the European and federal levels. The federal government (FPS Economy) grants concessions or permits for the construction and operation of offshore electricity production installations via a tender process. It establishes qualification conditions, the maximum strike price, and award criteria with corresponding weightings, that influence pricing by the bidders.

According to wind farm operators, one of the major barriers to integrating aquaculture into OWFs is the increased operational risks associated with the presence of new structures within the site and additional navigation activities. The experimental nature of most offshore aquaculture installations also contributes to this concern. These risks inevitably lead to higher costs, not only for the aquaculture operators but also for the wind farm operators. Risk avoidance should therefore be the guiding principle when choosing aquaculture techniques. To minimize risks as much as possible, certain areas within the wind farm are completely off-limits to third parties. Additionally, the normal and continuous accessibility of maintenance vessels to each turbine is a critical prerequisite. All these factors limit the potential for aquaculture in wind farms.

3.4. Scenario's

By combining culture techniques and species while considering the preconditions, several aquaculture activities, referred to as scenarios, were developed for future (to be repowered) OWFs, located outside Natura 2000 areas (Cat. 1) (Table 4). For comparison, the scenarios applicable to OWFs that already have a tender procedure (Cat. 3) are also indicated. Only a small subset of these scenarios can be considered for use in Natura 2000 areas as well (Cat. 2) (Fig. 2).

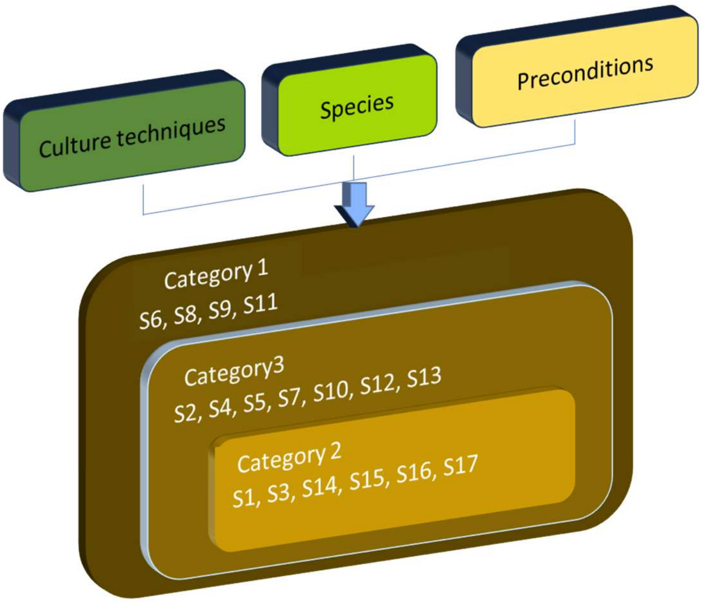


Fig. 2. Overview of possible scenarios to integrate aquaculture into the different categories of OWFs

This study has outlined a total of 17 scenarios that could be implemented in future Belgian OWFs, provided all necessary preconditions are met. Some of these scenarios depend on innovative systems that have not yet been extensively tested under offshore conditions or are still in the design phase. A selection of the easiest achievable options (green) for future OWFs are explained below. However, to enable large-scale commercial development, this study has identified four additional preconditions for scaling up.

Precondition 1: Without integrating food production into the tender conditions, OWF operators are unlikely to voluntarily incorporate aquaculture, particularly the proposed scenarios, as they involve additional costs related to preparation (co-design), insurance, and logistics. While OWFs are currently open to nature-supporting measures and nature-inclusive design (NID), these initiatives will not be voluntarily implemented as long as electricity price remains the sole determining award criterion. Simply designating areas for multi-use (as is currently the case) is insufficient to support offshore aquaculture, without government-imposed incentives or conditions.

Precondition 2: The functional integration of aquaculture production systems with wind turbines requires a collaborative co-design process. Wind turbines are engineered with a fixed lifespan, and anchoring aquaculture infrastructure to turbines could negatively impact this. For example, harvesting mussels growing on the turbines may require specialized coatings. Similarly, modifications to erosion protection layers, such as the placement of artificial reefs, would need to be factored into the design. While this approach optimizes offshore space use, it necessitates that technical solutions be incorporated during the bid preparation phase of the tender process, known as the pre-planning phase.

Table 4. Offshore culture scenarios in OWFs. Cat. 1 no tender procedure yet, Cat. 2 Natura 2000 Habitats Directive area, Cat. 3 existing tender procedure/already built; Green = easily achievable, yellow = feasible, orange = difficult to achieve

Code	Scenario	Technique	Kinds	Cat. 1	Cat. 2	Cat. 3
			Intensive systems			
S1	Bottom culture for bivalves in cages	B3	20-21	X	X**	X
S2	Bottom farming flatfish in cages	B3	2,3,6,7,9	X		X
S3	Mussel harvest from turbines	V1-V2	19	X	X	X
S4	Extractive bottom farming of sole in cages	V1&B3	7 & 19	X		X
S5	Floating longlines	D3-D4	19,24,25,26, 27,29,30,31	X		X
S6	Submersible longlines	W2	19-21	X		
S7	Fixed platform	V5-V6	All species	X		X
S8	Floating platform	D4	All species	X		
S9	Aquaculture vessels	D1	All species	X		
			Sea ranching			
S10	Feeding buoy	D2	10,14,15,16	X		X
S11	Turbine as a feed silo	V1	10,14,15,16	X		
S12	Release of juveniles for sea ranching	D2 of V1	10,15,20,21	X*		X
S13	Artificial reefs for on-site herding of specific species (incl. erosion protection layer)	SR3	10,14,15,16	X*		X
			Population support measures			
S14	Extensive cultivation of flat oyster	B3	35	X*	X	X
S15	Restoration ofl biogenic reefs	P04	33,34,35	X*	X***	X
XS16	Artificial reefs (incl. erosion protection layer)	P03	4,9,10,14,15, 22,23	X*	X***	X
S17	Restoration of non-biogenic reefs	P06		X*	X***	X

* Applied on a large scale

** Extensive culture

***The harvesting of the target species is planned outside the Natura 2000 area (spillover effect)

Precondition 3: The use of renewable energy sources for aquaculture is a key driver for promoting the multi-use of space in offshore wind farms. Future intensive production systems must have access to locally generated green electricity. As aquaculture systems become increasingly automated, energy access is a critical requirement for scaling up production.

Precondition 4: Sea ranching and population-support measures—two alternative forms of aquaculture—depend on passive fishing for harvesting within wind farms. However, the Rederscentrale has indicated that (1) only one Belgian fisherman currently engages in passive fishing, (2) the fishing sector is not currently interested in transitioning to passive fishing, and (3) existing fishing vessels are not adapted for operations within OWFs. Raising awareness among fishermen is therefore essential. Individual discussions with fishermen in other forums, however, reveal a genuine interest in both passive fishing and aquaculture. Some fishermen are willing to explore these activities if their economic viability is clearly demonstrated.

3.4.1. Intensive aquaculture (S1, S3, S4, S6)

S1 – Bottom culture for bivalves in cages

Bottom cages (B3) for cultivating specific bivalves, such as flat oysters (*Ostrea edulis*) and scallops (*Pecten maximus*), have minimal impact on OWF operations and do not pose risks to infrastructure. These systems can also be placed in "low-risk" zones, such as deeper areas, ensuring they do not interfere with turbines or cables positioned higher on sand dunes. Installing fixed anchor points for bottom culture systems during wind farm construction would enable bottom cultivation throughout the OWF without introducing additional risks.

Various oyster cage designs exist, allowing baskets to be securely held together while providing reinforcement against deformation. If necessary, these cages can be easily anchored. The bivalves rely on naturally available phytoplankton for sustenance, eliminating the need for additional feeding. However, maintenance and periodic sorting of the animals will be required.

For commercial cultivation in Natura 2000 areas (Cat. 2), the authors recommend low-density breeding in the cages, preferably placed on the erosion protection layers of the turbines to minimize impact on the bottom habitat.

S3 - Harvesting blue mussel from turbines

Fouling on offshore wind turbine structures represents a significant biomass. On monopiles off the Belgian coast, epifauna is predominantly composed of blue mussels (*Mytilus edulis*) and sea anemones (*Metridium senile*) within the first six meters below the sea surface. In other parts of Europe, the mussel biomass on turbines is estimated at 1,000–2,000 kg per turbine, and with the increasing number of turbines, blue mussel populations will inevitably expand. The impact of such large mussel volumes is not negligible—harvesting them could help mitigate potential negative effects on primary production. Since mussels feed on phytoplankton, their proliferation may increase competition with other filter feeders both inside and outside OWFs.

The company Ashtead Technology has developed field-proven systems for removing soft and hard marine fouling from offshore structures, such as monopiles in wind farms. Given the distinct stratification of biofouling organisms on Belgian offshore turbines, it is feasible to harvest a relatively pure fraction of mussels during the cleaning process using such technology.

Currently, Belgian OWF operators do not consider mussels on turbines to be a problem. However, they are concerned that cleaning the turbines could damage the protective coating due to the scratching action of rotating bristles and mussels. The HexDefence panels from Balmoral, originally designed for erosion protection, could serve as a protective barrier for the turbines while enabling mussel harvesting. Harvested mussels could be hydraulically suctioned and collected directly in big bags on the deck of a vessel.

The potential ingestion of toxic substances from turbine coatings by mussels must be investigated. However, this risk could be fully mitigated in the future through the use of protective panels or specially adapted coatings (Cat. 1).

S4 - Extractive culture of sole in submersible bottom cages

Sole (*Solea solea*) is a commercially significant species for Belgium, and its cultivation in submersible bottom cages presents a viable option for the shallow waters of the Belgian North Sea. This technique is already in use in China, where PDW cages (developed by the Fishery Machinery and Instrument Research Institute) allow for efficient flatfish farming. Under normal conditions, these cages rest on the seafloor, but they can be floated to the surface for maintenance and harvesting, improving accessibility and safety by eliminating the need for divers.

Since the cages are placed on the bottom, the sole can naturally rest in the sand or on structured platforms (nets) within the cage, significantly increasing the available surface area for cultivation.
To maintain an extractive production system, sole can be fed with undersized mussels harvested from offshore wind turbine structures (S3). Feeding will be carried out automatically using specialized feeding buoys floating above the cages. These buoys will dispense food through a submerged trunk with a floater, which also serves as a signal buoy for cage identification.

In this scenario, juvenile sole will be sourced from by-catches of the coastal fleet, such as shrimp fishing operations. Trials have demonstrated that shrimp fishing vessels can successfully keep live shrimp onboard, a technique that can also be applied to juvenile sole. This method ensures that genetic homozygosis (inbreeding)—a common risk in hatchery-based aquaculture—is avoided. By safeguarding genetic diversity, the potential impact of escapees on wild populations is minimized. However, implementing this approach requires legislative adjustments to allow for the legal landing of by-catch juveniles for aquaculture purposes. A graphic presentation of the concept can be found in Fig. 4.

Although this scenario is in principle also applicable to OWFs under Cat.3, the size of the fish cage as well as the harvesting of mussels from turbines will pose increased risks to the infrastructure of the OWF, arising the imminent need for co-design with OWF developers to ensure safe integration.

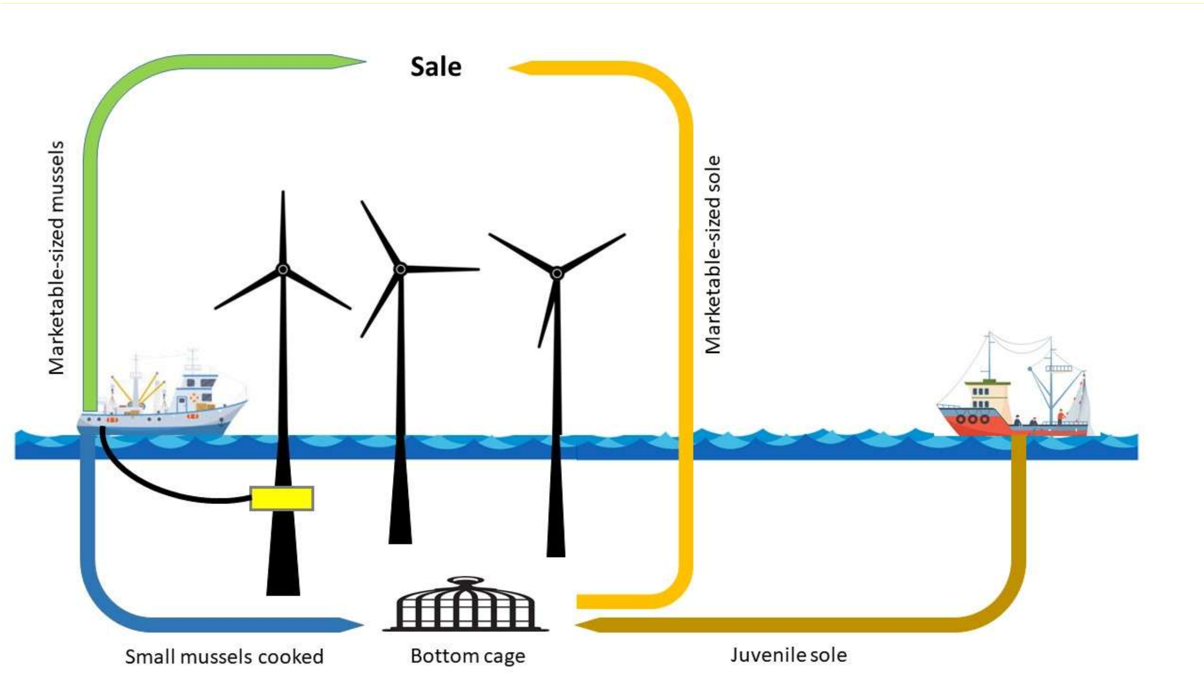


Fig. 4. Infographic extractive sole culture in OWFs

S6 - Shellfish on submersible longlines

For intensive shellfish aquaculture, submersible longline systems present a promising solution. In this system, buoyancy is controlled by regulating air within the backbone structure (W2), allowing the installation's depth to be adjusted remotely. Prototypes, such as those developed by Impact-9, are currently undergoing testing.

This method offers several advantages. The structure can be submerged during storms, reducing wave exposure and minimizing damage risk. During maintenance and harvesting activities, the backbone remains at the surface, ensuring easy access. When submerged, the system allows for unrestricted passage of wind farm maintenance vessels. A greater distance between turbines or an adapted park layout in OWFs can accommodate longer and more numerous longlines. The automation of submersible longlines requires electricity, which may be supplied directly from the turbines. The base of wind turbines can also serve as anchor points for longline installations, optimizing the use of space within OWFs.

This technology is not only applicable to shellfish but also presents an opportunity for the cultivation of high-value new species such as sea urchins and abalone.

3.4.2. Sea ranching (S11, S13)

S11 - Sea ranching with integrated feeding and conditioning equipment in turbine

Sea ranching of sea bass (*Dicentrarchus labrax*) in offshore wind farms is a promising concept that has been frequently proposed in the Belgian context. However, the legislative framework poses a significant challenge, as the species is under pressure and current fishing regulations are highly restrictive. Fishing for sea bass is already limited, and legal provisions specify the size classes that can be caught. Since these regulations are updated annually, they remain highly variable. For sea ranching to be viable, specific legal exceptions would be required.

Sea bass naturally form loose schools, enabling social association, and prefer habitats near hard substrates. This behavioural trait makes it possible to condition wild-caught sea bass in captivity to respond to a specific sound signal associated with feeding. Once conditioned, the fish can be released into the offshore wind farm, where the same signal and supplementary feeding are used to reinforce the behaviour. Over time, wild sea bass are expected to mimic the conditioned fish, gradually expanding the school.

Stomach content analyses indicate that sea bass primarily consume prey associated with hard substrates, including crab, lobster, shrimp, squid, and small fish species. This natural feeding behaviour means that supplementary feeding can be minimized to the level of “giving some candy”, ensuring an extractive nitrogen and phosphorus balance when harvesting the fish. The automatic feeding and conditioning equipment can be housed within the wind turbine itself (V1), utilizing its large internal space, which can reach a diameter of up to nine meters. This setup eliminates any obstruction to maintenance vessel access. Harvesting market-ready sea bass can be achieved through passive fishing methods, either inside or outside the offshore wind farm.

S13 - Artificial reefs for on-site herding of specific species (incl. erosion protection layers)

The placement of artificial reefs to support the managed stocks, where specific target species are considered private property, is the responsibility of the farmer. These artificial structures serve multiple functions, including providing nutrition, protection, habitat, and reproductive opportunities. Successful examples can be found in Japanese literature, where large-scale artificial reef deployment has supported scallop populations, and in Norway, where similar structures have benefited lobster populations.

In the Belgian context, the authors see potential applications primarily for sea bass, European lobster (*Homarus gammarus*), edible crab (*Cancer pagurus)* and possibly red crawfish (*Palinurus elephas*). Once the target species have established themselves within the artificial reefs, they can be harvested using passive fishing techniques inside the wind farm or through traditional fishing methods outside the wind farm.

3.4.3. Population support measures (S14, S15, S16, S17)

S14 - Oyster recovery through extensive bottom culture

Biogenic reef formers, particularly the flat oyster, are receiving significant national and international attention due to the numerous ecosystem services they provide. Extensive knowledge has already been gathered on the European flat oyster, and large-scale restoration under the protection of offshore wind farms in the PEZ is strongly recommended.

Adult European flat oysters (from the Atlantic population) are placed in underwater tables with a hard substrate (B3). This type of farming has minimal impact on the seabed, closely mimicking natural oyster populations and the ecological communities associated with oyster reefs. As these flat oysters reproduce over time, their offspring may settle within the reef or colonize other protected areas where bottom fishing is restricted, contributing to long-term reef restoration and biodiversity enhancement.

S15 - Restoration of biogenic reefs by introducing juveniles

For population-supporting measures, large-scale restoration or creation of natural habitats can be implemented to enhance ecosystem productivity. In Europe, including Belgium, it is widely recognized that the biogenic reefs of flat oysters, which have historically disappeared, will not naturally regenerate just by banning seabed-disturbing activities in areas where these reefs once existed.

Significant knowledge is available about the flat oyster species and its reproduction, as it is a commercially farmed shellfish species bred in European hatcheries (feasible – code green). One promising technique being tested across Europe, including in Belgium (e.g., Belreef project), is the remote setting method, where competent larvae from hatcheries are allowed to settle on substrates near the location where reef restoration activity takes place. This approach offers a cost-effective and efficient way to seed artificial reefs or natural substrates with flat oyster spat on a large scale. The erosion protection layer of wind turbines is an ideal surface for this technique, with the stones being seeded with oyster larvae.

While this technique holds potential, similar methods can be applied to restore other biogenic reefs, but further research is needed to optimize and expand these applications (difficult to achieve – code yellow).

S16 - Increasing ecosystem productivity through complex erosion protection layers

Enhancing the complexity of the erosion protection layer can not only support bioreef formers but also generally increase biodiversity, which in turn can boost the food supply for target species. The structure of the protective layer can be made more bio receptive by carefully mixing large and small stones in specific proportions to maintain the stability of the structure. Additionally, stacking stones into vertical formations can create more surface area for colonizing organisms.

This approach would provide increased shelter for various marine species, including commercially valuable ones like lobster, sea bass, and cod (*Gadus morhua*), which are attracted to these habitats. However, further research is needed to optimize these techniques and fully assess their effectiveness.

S17 - Restoration of non-biogenic reefs

In addition to biogenic reefs, the presence of natural hard substrates like gravel and boulders can also significantly contribute to increasing biodiversity. Gravel beds naturally occur near the "Hinder Banken" and play a crucial role as spawning grounds for species like herring and sand eels, as well as breeding and nursery grounds for many other fish species and invertebrates. The fauna found in these gravel beds is quite unique and does not occur in soft sandy sediments. These habitats are primarily inhabited by sessile and/or long-lived species, such as *Pomatoceros triqueter*, *Sabellaria spinulosa*, *Haliclona oculata*, *Flustra foliacea*, *Alcyonium digitalatum*, *Sertularia cupressina*, *Buccinum undatum* and *Ostrea edulis*.

Unfortunately, some gravel beds have been lost due to extraction activities, while others have been damaged by bottom-disturbing fishing methods like bottom trawling. Restoring gravel communities could lead to an increase in productivity and biodiversity, including the resurgence of commercially valuable species. This restoration can be achieved by adding gravel and boulders to areas where gravel beds once existed. However, these areas must be protected from bottom-disturbing fishing activities to allow sessile organisms to colonize the gravel beds and enable the development of the specific fauna and flora typical of gravel bed habitats.

4. Recommendations

4.1. Recommendations for government

4.1.1. Legal adjustments

The tender procedure is crucial for successfully integrating aquaculture into OWFs. Through this procedure, the government can impose specific conditions on bidders to align with its priorities—such as increasing energy independence, enhancing food security, and supporting the development of the blue economy. In addition to the electricity "strike price," shared space for aquaculture should be included as a significant criterion in the evaluation process, influencing the final score during contract awards.

Conditions relating to food production and nature restoration could be added as non-price criteria or pre-qualification criteria, making it clear from the onset what is expected from the bidders. The Netherlands already offer excellent examples of such holistic tender procedures, with projects like Holland West, Borssele, and Ijmuiden, setting a high standard. Similarly, in Germany, environmental compensation is required, such as creating an oyster reef at a location within the wind farm area (e.g., Borkum reef).

To further support the integration of aquaculture, regulatory frameworks and permitting processes must be simplified. Complex and burdensome regulations are a significant barrier for aquaculture farms and the multiple use of offshore wind spaces. Streamlining permitting processes and offering clear guidance and regulatory compliance support could help overcome these challenges and encourage investment in integrated aquaculture and wind energy projects. A "one-stop-shop" approach could further expedite procedures.

Harmonizing regulations for multi-use at the European level is also essential. Promoting communication and data sharing between licensing authorities across countries would create a level playing field, benefiting the offshore industry as a whole. Belgium could play a supporting role in driving this process forward.

The alignment of aquaculture activities with the long-term operational durations of offshore wind farms (typically 20 years) presents a challenge. To ensure continuity for aquaculture operators, it will be essential to establish mechanisms that guarantee the right to exploit these areas, even if the OWF is decommissioned. One possible solution is the implementation of a rotation system. Under this system, active aquaculture operators would always be offered a suitable location within the OWF zone, helping to maintain the activity while also supporting bottom health by preventing long term accumulation of waste products.

Regarding the legislative framework around the removal of artificial structures, particularly for nature restoration or creation purposes, it is crucial to clarify whether exceptions can be made for artificial reefs or other structures that have demonstrable, permanent benefits to marine ecosystems. These structures could be considered as population support measures, and their removal could be reconsidered if they continue to provide significant ecological value.

An amendment to legislation on the landing obligation for bycatch of sole (Solea solea) is necessary to support the intensive cultivation of sole in bottom cages. Currently, only a very small fraction of juvenile sole from bycatch (estimated at fewer than 40,000 fish annually, less than 0.1% of the total bycatch) would be needed to sustain the aquaculture activity—representing . Such an amendment would help facilitate the development of sole farming without significantly affecting the wild populations.

Sea ranching also requires careful consideration of several legal and policy issues. The private ownership of fish populations, a key aspect of sea ranching, does not currently align with the principles of the Common Fisheries Policy. Furthermore, there is a need to evaluate whether existing fishing quotas and limitations on the harvest of specific size classes (e.g., sea bass) would impact the legality and feasibility of sea ranching activities. Adjusting these policies could create a more supportive environment for sea ranching, ensuring that these activities can be carried out without conflicting with existing regulations.

4.1.2. Support for technological development

There is a clear need for an offshore test platform located within or near OWFs to address the challenges faced by aquaculture systems in the dynamic and energetic conditions of the North Sea. The harsh weather conditions, particularly storms, often cause damage to aquaculture prototypes, highlighting that current commercial systems are not yet robust enough to withstand these conditions on a large scale.

While the “Blue Accelerator” provides a testing space in Oostende, it is not fully representative of offshore conditions and lacks the capability to optimize integration with OWFs or support the cultivation of a wide variety of target species. Therefore, a more suitable offshore test platform is necessary to advance research and development in offshore aquaculture.

Looking to successful examples in Germany and the Netherlands, we see that test platforms can be specifically designed for both offshore aquaculture research and integration with offshore wind farms. These platforms could serve as important sites for testing and optimizing aquaculture systems under real-world conditions.

Over the long term, fully integrated multi-purpose platforms (either fixed or floating) could provide an ideal solution. These platforms, resembling "energy islands," would offer various services including energy storage, processing facilities, docking units, and staff housing. Such platforms could support the cultivation of different species in tanks, similar to land-based aquaculture operations, allowing for scalable and sustainable growth in offshore aquaculture.

.4.1.3. Financial support measures

Certain forms of aquaculture discussed in this work may be eligible for support through ecological trading schemes. Specifically, population-supporting measures could qualify for carbon, nitrogen, or biodiversity credits. This could provide an additional funding mechanism for nature restoration and creation efforts within offshore wind farms. However, to ensure transparency and credibility, it is essential that such funding methods are officially accredited. The government must play a key role in regulating these funding sources to prevent misuse or greenwashing.

Additionally, financial compensation made available by offshore wind farms through the environmental compensation fund should be directed toward supporting nature restoration initiatives within OWFs. By strategically allocating these funds, the ecological benefits of aquaculture activities can be maximized, ensuring a balanced approach between economic development and marine conservation.

4.1.4. Coordination

We recommend that different stakeholders—including OWF operators, fisheries, the aquaculture sector, and the nature restoration sector—collaborate to develop a good practice guide. This guide should include technical guidelines for the integrated design of aquaculture and/or nature restoration within OWFs. To ensure fair and balanced development, the process should be supervised by the regulatory authority. This oversight will help prevent any power imbalances between stakeholders that could hinder the creation of an effective and sustainable integrated model.

4.2. Recommendations for OWF stakeholders

OWFs can take simple preparatory steps to integrate aquaculture, even if it is not initially included in the tender process. This should be done in consultation with relevant stakeholders. Some interventions may require authorization from MUMM, modifications to existing permits, or entirely new permit applications. Recommended facilities include:

- Anchor points: Installing anchor points for testing intensive aquaculture systems and for sea ranching feeding and conditioning systems.
- Artificial structures: Introducing structures to support commercial target species or endangered species.
- Scour protection layer adjustments:
    - Using suitable substrates to encourage the development of *Sabellaria* reefs by installing filter layers.

    - Adding complexity to enhance habitats for commercially or ecologically valuable species.
    - Mimicking natural gravel bed structures to support biodiversity.
- Preseeded substrate introduction on erosion protection layers:
    - Substrate with oyster spat via remote setting to establish flat oyster populations and/or support natural populations in historically significant oyster bed areas.
    - Substrate with other habitat-forming species, such as the Honeycomb worm and Ross worm (*Sabellaria alveolate* and *S. spinulosa)*.
- Restoration Efforts:
    - Restoring natural gravel beds between turbines.
    - Reintroducing oyster beds where they previously existed.

These measures can promote biodiversity, enhance ecosystem services, and contribute to sustainable aquaculture within OWFs.

4.3. Recommendation for applied scientific research

Most offshore aquaculture techniques remain in the experimental phase, requiring further research in collaboration with the industry to assess their technical and economic feasibility at a commercial scale. The lack of commercial experience with integrated systems, as well as the absence of standardized safety and construction guidelines, leads to unknown risks and high insurance premiums. Therefore, targeted research funding is necessary for automation, the development of multi-purpose vessels, access to green electricity at sea, and support for both intensive cultivation and large-scale habitat restoration.

Automation is crucial for scaling up offshore aquaculture projects. This includes automating the maintenance of farming systems ; enabling automatic adaptation of aquaculture structures to changing hydrodynamic conditions, and in function of the target species' growth and seasonal biofouling ; and developing innovative monitoring systems to enhance operational safety.

The development of multi-purpose vessels is another key area of research. Inspired by modular shipbuilding in the military sector, vessels could be designed for flexible use across different industries. A single ship could be adapted for tasks such as turbine maintenance, mussel harvesting, and aquaculture operations. While this concept has already gained traction in the wind energy sector, it should be expanded to support aquaculture as well.

Access to green electricity at sea is essential for several aquaculture scenarios, as well as for the operation of the electric vessels of the different industries on site. Ensuring a reliable supply of offshore renewable energy would support the automation of aquaculture systems and improve overall efficiency.

Finally, further research is needed to develop large-scale, cost-effective seeding techniques for habitat-forming species, as well as to advance methods for their intensive culture.

5. Conclusion

The expansion of offshore energy production presents a unique opportunity for the aquaculture sector to explore offshore waters and leverage existing mature offshore technology. However, integrating these two sectors remains a challenge, and the synergies often discussed in the literature rarely materialize in practice. A crucial factor in determining the success of aquaculture in OWFs is the tender procedure, which has the power to either encourage or hinder future developments in intensive farming, sea ranching, and population support.

Currently, the tender process does not reflect the importance of local food production as a non-price criterion or a pre-qualification condition. This omission effectively prevents the development of a commercial offshore aquaculture sector within the Belgian North Sea. This is a significant disappointment for the aquaculture sector as well as for stakeholders involved in marine conservation and restoration. No conditions have been included in the tender framework regarding food production, nature-inclusive measures that could support commercial stocks, or nature restoration efforts that would enhance the ecosystem and, in turn, benefit commercial fisheries.

The authors strongly advocate for future tenders to embrace a model that integrates energy production, food production, and nature restoration within OFWs, similar to the Dutch approach. The current procedures outlined in the Royal Tender Decree of June 3, 2024, impose constraints that make it highly unlikely for OWFs to incorporate aquaculture or nature restoration into their projects. Without explicit inclusion of food production and/or nature restoration as award criteria, the potential for meaningful synergy between these sectors will remain untapped.

Among the various aquaculture methods, bottom farming emerges as a particularly promising approach. It presents lower risks of damage to OWF infrastructure compared to floating systems and includes a range of technologies, from relatively simple shellfish and crustacean farming to more complex flatfish farming. This scalability allows for a gradual accumulation of knowledge and expertise, which is essential for long-term success. Given these advantages, the authors argue that priority should be given to licensing and supporting bottom farming systems. Because this method can also be implemented in existing wind farms, it represents an opportunity for short-term progress in integrating aquaculture into OWFs.

Passive fishing plays a crucial role in our proposals. Although enthusiasm within the fishing industry is still in its early stages, the authors firmly believe that passive fishing can become a vital part of the future of Belgian fisheries. Several studies highlight the complementarity of passive fishing with coastal fishing, and with the European Union's plan to phase out bottom trawling in the medium term, the need for alternative methods is becoming increasingly clear. However, the fishing fleet is not yet prepared for this transition. Many projects led by ILVO will need to provide answers regarding the economic and technical feasibility of this shift, which has been met with scepticism. A structured consultation between OWF operators, fishermen, and aquaculture farmers will be necessary to define the social, technical, and economic measures required to diversify the sector while ensuring access to production and harvesting in offshore wind farms.

The coming years will be a period of expansion and transition for the offshore green energy sector. Integrating wind energy with food production and nature restoration presents significant challenges. The authors have identified two key concepts that will enable this integration in the near future: co-design and large-scale implementation.

All stakeholders acknowledge the importance of co-design, but its urgency is not sufficiently recognized. Given that wind farm construction and potential turbine modifications are planned years in advance, it is essential to prioritize co-design now. Early coordination between energy developers, aquaculture operators, and fisheries will be critical to ensuring successful multi-use integration. In addition, the authors believe that the development of an offshore aquaculture sector integrated with OWFs will only be viable if approached on a large scale. Due to the high risks, substantial investment requirements, and significant operational costs, achieving scale is one of the most important factors in making offshore aquaculture economically feasible. Two primary strategies could help achieve this necessary scale: the establishment of marine parks and the creation of multi-use platforms, either fixed or floating. These large-scale approaches would not only enhance the profitability of offshore aquaculture but also strengthen synergies between renewable energy, food production, and marine ecosystem restoration.

The concept of mariparks, as defined in the glossary, is not new, and successful examples exist worldwide. In the Netherlands (Borssele), space is expertly divided to ensure that all activities are accommodated without interfering with each other. The frequent use of space is the most straightforward integration approach and the easiest to implement. With a well-structured policy and close collaboration between wind farm operators and aquaculture growers, a practical and efficient plan can be developed. Certain services, such as licensing, insurance, and government financial support, will need to be centrally managed, and the role of government support in this framework should be carefully examined.

A second approach that could facilitate large-scale development is the use of multi-use platforms. Although this concept is more challenging, it is also highly innovative. Such platforms offer the potential for synergies beyond mere spatial integration. For example, the planned energy island (Princess Elizabeth island) could be designed to support aquaculture activities (and related research) not as an additional feature but as an integral part of the energy island itself. Floating or fixed renewable energy islands can provide essential support to aquaculture by enabling long-term staff presence in the vicinity of aquaculture zones and offering storage, processing, and research facilities, such as platforms for drones, remote monitoring, and ecological studies. The structure of the island could serve multiple functions, including anchoring aquaculture systems, mooring work vessels, acting as an observation and monitoring station, or serving as a real-life test site for automation systems. This integration would allow transport, monitoring, and personnel costs to be shared among platform users, making offshore operations more efficient. Moreover, such platforms would reduce weather-related limitations by significantly extending the time window available for maintenance and harvesting operations.

Technological innovation is essential to make this integration possible and should be actively encouraged. Automation, advanced monitoring systems, and reliable long-term weather forecasting will play an increasingly important role. Given the growing local energy demand—partly driven by the electrification of vessels operating within offshore wind parks—the development of a localized electrical network is imperative. Furthermore, the authors stress the necessity of designing innovative, multi-purpose modular vessels that can be adapted for maintenance, harvesting, repairs, research, and routine operations related to OWFs and fisheries.

Legal adjustments required to promote the integration of aquaculture activities in offshore wind farms have been underexplored in this study. However, key areas that require attention include (i) facilitating private ownership and exploitation of commercial stocks (sea ranching), (ii) allowing the use of bycatch for further breeding (intensive flatfish farming), (iii) granting aquaculture exploitation licenses, (iv) providing exception rules to maintain specific and long-term effective population-support structures when the OWF’s permits expire, (v) permitting the controlled cultivation of exotic species that cannot reproduce, and (vi) establishing a clear and precise definition of extractive aquaculture. Addressing these legal aspects will be crucial to unlocking the full potential of offshore aquaculture integration within OWFs.