Optimizing Shellfish Aquaculture for Multi-Use Spaces Within Offshore Wind Farms in the Dutch North Sea

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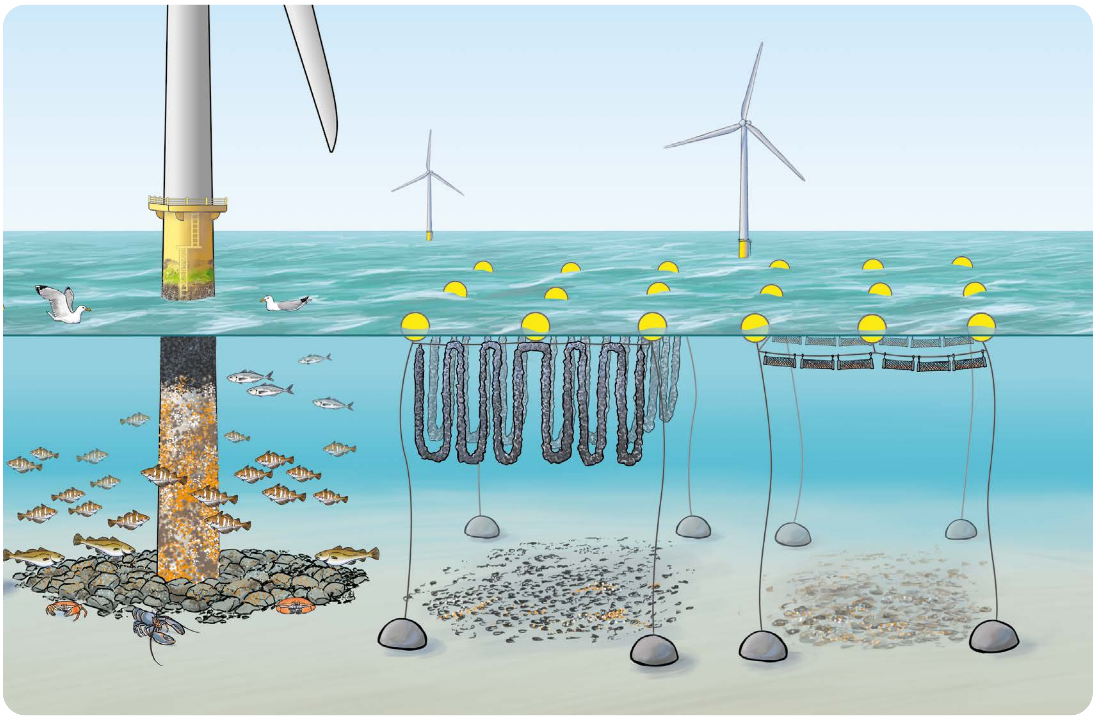

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Disclaimer

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Executive Summary

Wind energy in the Dutch North Sea is rapidly expanding. These areas create trawling- and shipping-free zones that can possibly be used for food production and nature enhancement. Shellfish aquaculture has the potential to contribute to both of these goals. The North Sea Foundation (NSF) is a Dutch NGO that works towards achieving "a clean and healthy North Sea that is used sustainably" (North Sea Foundation, 2016). They are interested in whether shellfish aquaculture within wind farms can truly be sustainable and if so, what steps are needed to implement multi-use. Therefore the main research question of this advisory report is, "What is the optimal method for implementing shellfish aquaculture amidst offshore wind farms that safely combines sustainable food production and enhancement of wild shellfish beds, and what can the North Sea Foundation do to help achieve this?"

There are two native species of reef-building shellfish that are currently cultivated in the Dutch North Sea: Blue mussels and European flat oysters. Both species can be cultivated offshore using variations of a longline system where mussel ropes or oyster cages are suspended vertically from a central horizontal line. The main horizontal line should be submerged in the water column to prevent gear from breaking loose and hitting wind turbines or cables. Ideally, shellfish aquaculture can help with nature enhancement by creating structural complexity and hard substrate. As a result, shellfish farms may serve as a foraging ground, nursery, and shelter for a diverse community of marine organisms. Aquaculture can also aid in the enhancement of wild shellfish beds by increasing the local population density of breeding shellfish and consequently the number of larvae in the North Sea. These wild shellfish beds provide their own ecosystem services including habitat provision, coastal protection, and increased biodiversity. Certain best practices are required, however, to ensure that shellfish aquaculture can meet

these nature-enhancement goals and act as part of a healthy ecosystem. This study resulted in suggested best practices for sustainable, nature-enhancing offshore shellfish aquaculture and actions that the North Sea Foundation can take to ensure sustainability going forward.

The suggested best practices include:

- Use diploid flat oysters and blue mussels.
- Don't harvest an entire farm at once in order to maintain more consistent habitat provision.
- The scale of the farm should not exceed the local carrying capacity.
- Use seed capture installations or hatchery seed instead of seed dredging.

Actions that NSF can take to implement sustainable offshore shellfish aquaculture include:

- Push to include multi-use planning in the tender criteria for wind farm permits and publish area
- passports earlier in the process. Include nature enhancement in area passport design.
- Facilitate pilot projects to test feasibility, build a business case, and monitor ecological impacts
- of offshore aquaculture before increasing the scale.
- Leverage government support for biodiversity and sustainable food to set up subsidies for
- additional hatcheries research.
- Communicate with policymakers to increase awareness of the criteria for what constitutes
- "sustainable" within the shellfish industry, and clarify within aquaculture policies.
- Encourage continued research to refine carrying capacity models, and assess hydrodynamic
- effects of shellfish and wind farms.

NSF should prioritize advocating for multi-users, as they are resolute in wanting to secure space for other nature development projects. They should also work with a knowledge institute partner to continue research regarding the ecological effects of shellfish farms such as carrying capacity and hydrological changes, and increased bird populations in wind farms. Based on these results, NSF needs to decide if offshore shellfish aquaculture meets their definition of sustainability. If so, they also need to determine how much effort is reasonable to invest in interventions aimed at encouraging shellfish farmers to move offshore, or if their time and resources may be better used on other projects.

Table 1. - Abbreviations for terminology used within the paper (in order of appearance).

Term	Abbreviation
The North Sea Foundation	NSF
Non-governmental organization	NGO
European Union	EU
United Nations	UN
Sustainable Offshore Nature-enhancing Aquaculture (In Dutch: Duurzame Offshore Natuurversterkende Aquacultuur)	DONA
Science, Business and Policy	SBP
Gigawatts	GW
Mussel seed capture device (in Dutch: mosselzaadinvanginstallatie)	MZI
Netherlands Enterprise Agency (in Dutch: Rijksdienst voor Onderne-mend)	RVO
Wageningen University & Research	WUR
Royal Institute for Sea Research	NIOZ
Bureau Waardenburg	BuWa
Native Oyster Restoration Alliance	NORA
Marine Research Institute Netherlands	MARIN
European Marine Fisheries and Aquaculture Fund	EMFAF
National Strategy on Spatial Planning and the Environment (in Dutch: Nationale Omgevingsvisie)	NOVI
Multi-Use offshore platforms demoNstrators for boostIng cost-effec-Tive and Eco-friendly proDuction	UNITED
Hectare	ha
Tonne (metric)	t
Year	y

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1. Introduction and Background

1.1 Context

Throughout the North Sea multiple countries, industries, and ecosystems vie for space and resources which makes spatial planning a challenging balance of various interests (Jansen et al., 2016; Jentoft & Knol, 2014). In an effort to decrease greenhouse gas emissions there is demand for an increase in renewable energy production and therefore an increase in offshore wind farms (Michler-Cieluch & Krause, 2008; North Sea Consultation, 2020; Weiss et al., 2020). Additionally, with expanding populations there is an increased demand for food, some of which can be produced in the North Sea through fisheries and aquaculture (Michler-Cieluch & Krause, 2008; Weiss et al., 2020). Besides these major sectors, there is also demand for space for shipping, sand extraction, oil and gas, defense exercises, and recreational boating. Lastly, there is also a push for nature enhancement and conservation to lessen the effects of human activities and climate change on marine ecosystems (Theuerkauf et al., 2022). As a result of all of these demands, governance in the North Sea is a complicated process of compromises.

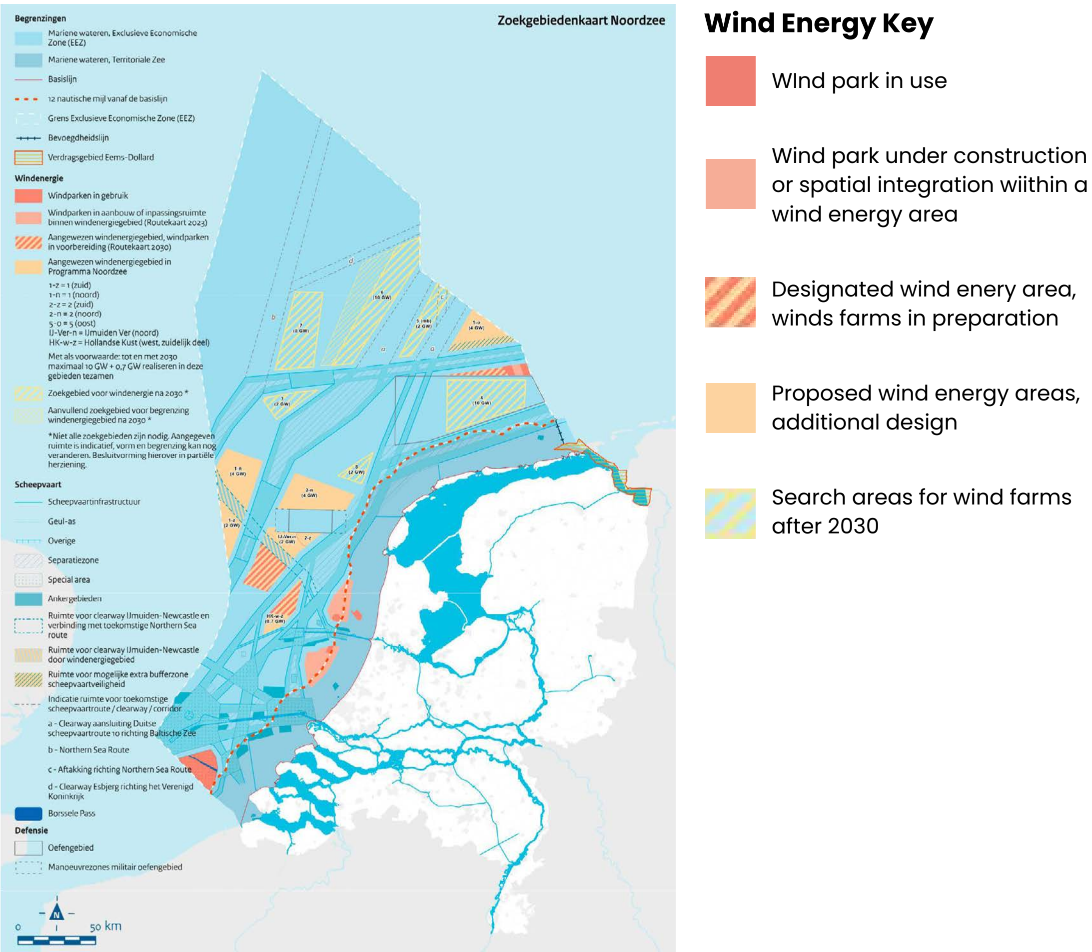


Figure 1. - Map of current and planned wind farms in the Dutch North Sea (Ministry of Infrastructure and Water Management, Ministry of Agriculture, Nature, and Food Safety, Ministry of Economic Affairs and Climate Policy, et al., 2022)

Due to the limited space within the North Sea, multi-use areas such as a combined wind farm and aquaculture areas are attractive for marine spatial planning (Palmer et al., 2021). Currently there are seven active wind farms in the Dutch North Sea producing approximately 2.5 gigawatts (GW) of power annually (Ministry of Economic Affairs and Climate Policy, 2021; Ministry of General Affairs, 2021). Within the context of European Union climate goals, offshore wind farms are set to expand to cover over 2.8%, or approximately 1600 km2 of the Dutch North Sea and produce 21 GW of wind energy annually by 2030 (Michler-Cieluch & Krause, 2008; Ministry of General Affairs, 2021; North Sea Consultation, 2020; Rijkswaterstaat & Ministry of Economic Affairs and Climate Policy, 2022). Building offshore wind farms creates trawl fishing and shipping-free zones which could allow for benthic ecosystem recovery and potentially also be used for offshore aquaculture (European Commission, 2012). Around 200 years ago, shellfish reefs primarily consisting of European flat oysters covered about 20% of the Dutch North Sea floor, but have all but disappeared due to overfishing and disease (Christianen et al., 2018; Sas et al., 2016). Offshore shellfish aquaculture can potentially help support recovery of wild shellfish populations and provide increased structural complexity by following sustainable shellfish aquaculture practices (Carranza & Zu Ermgassen, 2020; Theuerkauf et al., 2022). Carranza and Zu Ermgassen (2020) define sustainability within shellfish aquaculture as “related to the long-term maintenance (or improvement) of wild stocks and their habitats”. The presence of cultivated shellfish increases the local population density, which can support reproduction and thus produce larvae needed to increase wild stocks (Carranza & Zu Ermgassen, 2020; Theuerkauf et al., 2022). These benefits are not inherent, however, and sustainable best practices must be followed. Concerns have also been raised regarding the effects of shellfish aquaculture on the local planktonic community and ecological carrying capacity due to their filter feeding, as well as the hydrodynamic effects that aquaculture gear may have and what ecological changes that may cause (Mascorda Cabre et al., 2021; McLachlan & Defeo, 2018). Due to these uncertainties, this study addresses the ecological effects of offshore shellfish aquaculture and suggests best practices to help increase positive effects and avoid negative effects associated with implementation.

In order to implement these sustainable aquaculture techniques and best practices, one must also consider governance and spatial planning within the Dutch North Sea. Currently, spatial planning in the Dutch North Sea is laid out in the North Sea Agreement. This document is an agreement between the Dutch government and North Sea stakeholders regarding priorities and management strategies within the North Sea (North Sea Consultation, 2020). This agreement states that multi-use is a “guiding principle” to resolve competition for space between parties. While statements in support of multi-use between aquaculture and wind farms have been made, there is not a clear process for licensing and installing aquaculture farms or other multi-use activities within wind farms (Netherlands Enterprise Agency, 2022a; North Sea Consultation, 2020). Some policy aspects that need to be addressed before aquaculture-wind farm multi-use can be implemented include permitting of space within wind farms for multi-use, regulations to ensure that aquaculture is carried out in a sustainable manner, possible subsidies for aquaculture farmers to transition offshore if practicing nature-enhancing aquaculture. The result of this study synthesizes these policy topics into suggested sustainable aquaculture best practices, as well as interventions that can be taken to implement offshore shellfish aquaculture. These suggestions are tailored towards The North Sea Foundation (NSF), a Dutch non-governmental organization (NGO) that advocates for sustainable use of the North Sea, and their goals of sustainable food and nature enhancement.

1.2 Goals and research questions

The goal of this project is to evaluate opportunities for combining offshore wind farms, shellfish aquaculture and wild shellfish bed enhancement in the Dutch North Sea in order to create multi-use spaces that incorporate wind energy production, sustainable food production, and nature enhancement. I have researched various types of shellfish aquaculture including species, farming methods, types of gear and how each would affect the end goals of sustainable food production and nature enhancement. For the purposes of this report, a full life cycle analysis was not considered when assessing sustainability. A full life cycle analysis including the environmental impacts of materials manufacturing, production, and distribution should be addressed in the future in order to fully compare the sustainability of offshore farmed shellfish versus other potential protein sources. During this project I focused more on the ecological impacts of shellfish farming. Using the North Sea Foundation's criteria for sustainability (see section 1.3.1) I have provided recommendations for optimal methods of shellfish aquaculture within wind farms that would meet The North Sea Foundation's goals of sustainable food, space for nature, nature-friendly energy, and clean seas (North Sea Foundation, 2016). Additionally I analyzed the current governance of these areas, and made suggestions for actions that can be taken to facilitate the transition into the recommended multi-use approach.

Main research question: What is the optimal method for implementing shellfish aquaculture amidst offshore wind farms that safely combines sustainable food production and enhancement of wild shellfish beds and what can the North Sea Foundation do to help achieve this?

Sub questions:

Scientific questions:
1. What shellfish species, gear types and configurations are feasible and which can provide the best outcome in terms of safe operation, sustainable food production, and nature enhancement?
2. What are potential effects of shellfish farms on local ecosystems and biodiversity?

Policy questions:

1. What actors are involved in the licensing and management of space within offshore wind farms and how would they impact such a project?
2. What current policies affect possibilities for placing aquaculture farms among offshore wind farms?
3. What resources and interventions are needed to sustainably implement shellfish aquaculture/wind farm multi-use and make it financially feasible for shellfish farmers?

1.2.1 Research methods

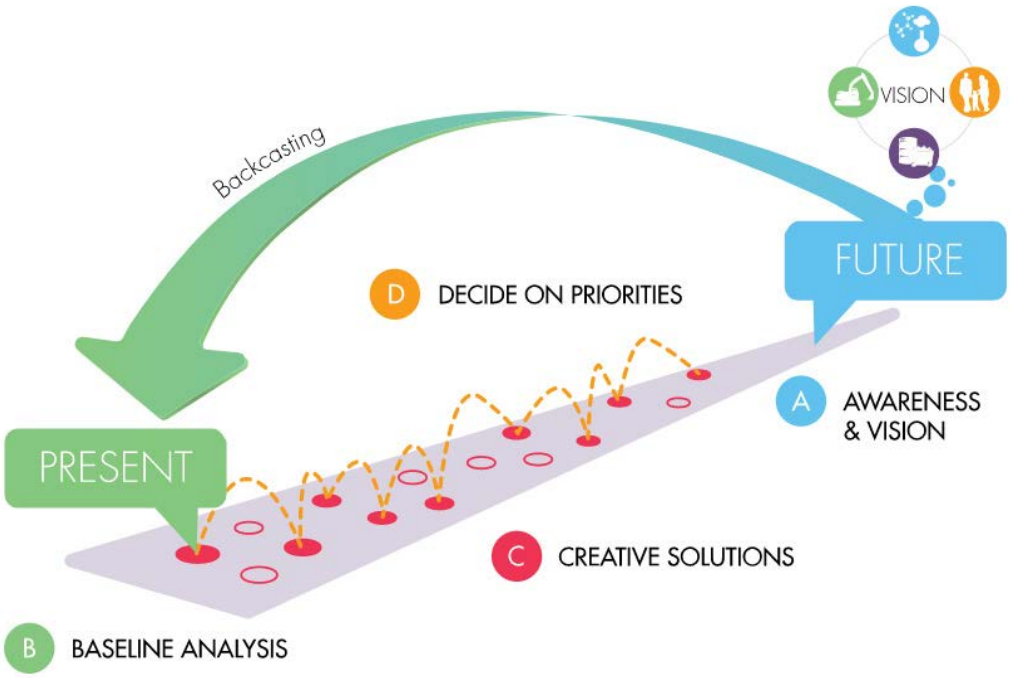


Figure 2. The Natural Step framework used to approach this project (The Natural Step International, 2015)

When approaching this research question I used the Natural Step framework (see figure 2 above) (The Natural Step International, 2015). This framework involves first determining what the ultimate goal is once this project is completed. In this case, what does sustainable, nature-enhancing aquaculture look like in an ideal scenario? Then I examined the present situation to determine what discrepancies exist between the two. Lastly, I brainstormed solutions to help bring the present situation closer to the ideal future state where shellfish aquaculture is implemented in a way that produces sustainable food, does not have negative ecological effects, and contributes to shellfish bed recovery. The aim for the final advice is to provide the North Sea Foundation with a suggested prioritization of these steps in order to potentially move forward towards sustainable offshore aquaculture multi-use.

This study has been conducted through a combination of scientific literature review, policy analysis, internet searches, and interviews. Scientific papers were primarily found using Google Scholar. Where possible, research conducted in the Dutch North Sea was prioritized. Due to a lack of published results from pilot studies being done in the Dutch North Sea on offshore aquaculture, wild shellfish bed enhancement, and the connection between these two topics, examples of similar projects from other countries were also consulted. In the case of policy analysis, legal documents and government websites were consulted to assess the political and legal framework around aquaculture and wind farm multi-use. Finally, to gain more insight into the social factors contributing to this topic, the knowledge and opinions of involved stakeholders were consulted through internet searches, email conversations, and virtual interviews. I also had the opportunity to attend the Shellfish Conference held in Zeeland in March where stakeholders in the shellfish industry presented on their work as well as the outlook of the industry going forward. In addition to the presentations in the program, conversations with other attendees also provided valuable insight.

1.3 Formal framework

1.3.1 Internship organization

The organization offering this internship is the North Sea Foundation (NSF). NSF is a non-governmental organization (NGO) that advocates for "protection and sustainable use of the North Sea" (North Sea Foundation, 2016). Their work falls under four broad categories including sustainable food, nature-friendly energy, room for nature, and clean sea. The mission of the North Sea Foundation is to, "attain a healthy ecosystem that is resilient and adaptable to external influences. In our opinion, North Sea nature should always be the starting point for sustainable use. We stand up for the North Sea and work together with other parties on solutions to present and future challenges on the North Sea" (L. Planthof, personal communication, May 11, 2022). Their primary methods of working towards this goal include providing science-based advice for various stakeholders in order to encourage sustainable practices and influence policy in the North Sea. They also facilitate dialogue between actors in order to identify and pursue sustainability solutions. In addition to providing advice and fostering discussion, NSF stays actively involved with research, monitoring, and pilot projects in order to provide insight on sustainable practices and data collection, and ensure that data is put to good use. Through all their work, NSF maintains close connections with other nature NGOs, particularly those who also work around the North Sea, as well as government ministries, and research institutes. They are also part of groups such as the North Sea Consultation (see section 3.3.2, North Sea Consultation) and the Community of Practice forum which helps establish the North Sea Foundation as a leading voice for nature conservation and sustainable use in the North Sea.

This internship project is part of the Duurzame Offshore Natuurversterkende Aquacultuur (DONA) project (in English: Sustainable Offshore Nature-enhancing Aquaculture), which is a collaboration between the sustainable food and nature-friendly energy teams within the North Sea Foundation. Linda Planthof, Heleen Vollers, and Renate Olie have been working on this project prior to the start of this internship. The DONA team is in the process of finalizing a position paper detailing the criteria for "sustainability" as it relates to offshore aquaculture (North Sea Foundation, 2022).

These criteria include:

- It has no significant negative impact on the ecosystem
- It does not negatively affect the water quality
- It respects the space for nature
- It only uses sustainable procured source materials
- It is operationally safe
- It is produced by companies with a demonstrable sustainability policy
- It complies with legal regulations and licensing requirements
- It is accepted among all stakeholders
- It fits within the possibilities of the area passport

Expanding on that position paper, this project has explored sustainable methods specifically for shellfish aquaculture and developed suggested steps to move the project forward. These recommendations can then serve as input for the DONA project's future steps and be incorporated into the project after the internship. Future goals of the DONA project include building a solutions toolbox and hosting an innovation lab meeting with relevant stakeholders and experts.

1.3.2 Educational framework

This internship took place within the context of the Science, Business & Policy track at the University of Groningen. The intention was to apply business and/or policy aspects to a project from each student's primary scientific discipline. In this case, my background is in marine biology. The final product of this internship is an advice report that integrates approximately 50% scientific and 50% policy analysis. The internship took place over the course of 26 weeks starting on January 10, 2022 and ending on July 8, 2022. Throughout this time I have had multiple supervisors from Stichting Do Noordzee and the University of Groningen with varying roles as described in table 2 below.

Table 2. - Project advisors along with their titles and role in the project.

Name	Institute	Function	Role in supervision
Linda Planthof	North Sea Foundation	Project leader, sustainable food	Daily supervisor
Laura Govers	University of Groningen	Examiner, marine biology Master's degree program	Science supervisor
Karin de Boer	University of Groningen, Science Business and Policy Master's track	Lecturer	SBP supervisor
Heleen Vollers	North Sea Foundation	Senior project leader, nature friendly energy	Offshore wind expert

1.4 Reading guide

Following this introduction, chapter 2 describes shellfish aquaculture methods and how they contribute to nature enhancement. This begins in section 2.2.1 with a description of reef-building shellfish that are used for aquaculture in the Netherlands. These species include blue mussels, European flat oysters, and Pacific oysters. Then cultivation methods are described in section 2.2.2 including traditional bottom growing methods, and off-bottom methods. With each method, the appropriate environmental conditions are described including a determination of whether that technique would be suitable for offshore aquaculture. Then section 2.2.3 includes farm design factors that can help to increase shellfish production and decrease environmental impacts. The last section relating to aquaculture methods (2.2.4) is a synthesis of environmental, policy, and logistical conditions that are required for offshore shellfish aquaculture. These criteria can be used to assess the viability of a wind farm site for this type of multi-use. Lastly, section 2.3 discusses the ecological impacts of shellfish aquaculture such as increased biodiversity, habitat provision, passive recovery of shellfish beds, planktonic community changes, and the effect on ecological carrying capacity. Additionally, two factors regarding reproduction and larval dispersal are discussed that would affect the nature enhancement potential of shellfish aquaculture.

Chapter 3 transitions into discussing wind farm multi-use, starting off with some background information on this topic within the Dutch North Sea in sections 3.1 and 3.2. Next, section 3.3 contains an actor analysis including actors involved in shellfish aquaculture multi-use within wind farms. The actors are divided into sections including private industry, governmental bodies - both national and international, and scientific experts and nature organizations. Following that, section 3.4 is a summary of current European and Dutch national policies that affect the process of implementing multi-use and express priorities related to offshore shellfish aquaculture. To end this chapter, section 3.5 is a summary of the current bottlenecks preventing shellfish aquaculture from being implemented within offshore wind farms.

Chapters 4 and 5 contain integration and final advice, starting with a multiple criteria analysis (section 4.1) which states the current readiness and support for offshore mussel aquaculture versus flat oyster aquaculture. Then in section 5.1, the most sustainable aquaculture techniques are described for when offshore shellfish aquaculture is ready to be implemented. These techniques include what species should be cultivated, where to place the farm, how to harvest, importance of the carrying capacity, how to source sustainable seed, and what research still needs to take place to ensure sustainability. Following this, in section 5.2 there are recommendations for interventions that can help to facilitate the implementation of shellfish multi-use within wind farms. This has not been done yet, so certain actions should be taken to include multi-use earlier in the wind farm design process, continue with pilot projects, improve the business case for offshore shellfish aquaculture, and inform government officials as well as the wider public to generate support for multi-use. Lastly, this advice is combined with the North Sea Foundation's goals and strengths in section 5.3 in order to suggest which actions should be top priority following this report.

2. Shellfish Aquaculture and Nature Enhancement

In order to determine whether shellfish aquaculture can be implemented offshore in a way that meets NSF's criteria for sustainability, it is essential to first understand what methods may be used and what effect those methods would have on the environment. Fundamental to this question is deciding which shellfish species will be cultivated. Therefore, this chapter first describes the species that this study focuses on and the methods that are used to cultivate those species. Additional considerations for the layout of aquaculture farms and the necessary environmental conditions for shellfish farming are also included. Lastly, this chapter describes the known ecological impacts of shellfish farming, and what considerations must be taken into account to maximize the nature enhancement potential. Overall, this section provides the basis for the determination of sustainable shellfish aquaculture best practices which are suggested later in section 5.1.

2.1 Background

Oysters (order Ostreoidea) and mussels (order Mytilida) are two taxonomic orders of sessile bivalve mollusks (Naturalis, 2018). Both undergo a planktonic stage as larvae where they float through the water column (Goulletquer, 2022a, 2022b; Walles et al., 2016). Then when they grow to a certain size (approximately 300 μm for flat oysters and 250-320 μm for blue mussels), they settle on a hard substrate and remain sessile (Maathuis et al., 2020; Martel et al., 2014). At the end of their planktonic stage, studies have indicated that these larvae may be prompted to settle when they detect a suitable substrate, potentially through sound or chemical signals (Diederich, 2005; Lillis et al., 2013; Medy Ompi, 2010; Mesías-Gansbiller et al., 2013). The exact mechanism through which shellfish larvae metamorphose out of their planktonic stage and settle in a specific location is still not fully understood. One trend that has been observed is that both European oysters and blue mussel larvae settle preferentially on conspecific shells (Medy Ompi, 2010; Potet et al., 2021). As a result, over time groupings of oysters and mussels build larger reef formations (Walles et al., 2016). Those reefs can then be used by other marine organisms as space for shelter, food, and reproduction (Fitzsimons et al., 2020; Theuerkauf et al., 2022; Toone et al., 2021). In addition to creating structure, these congregations of shellfish are efficient water filters. Each animal draws in water and filters out microscopic

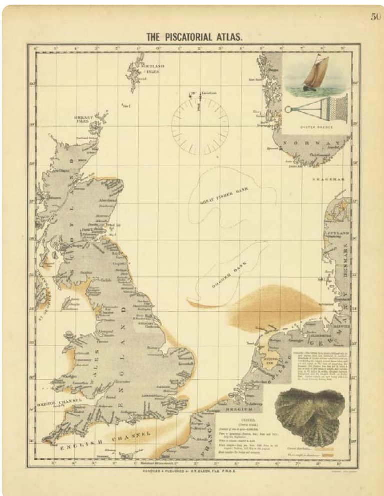


Figure 3. Historical map of European flat oyster reefs in the North Sea. Orange areas represent the presence of reefs (Olsen, 1883)

organic matter like phytoplankton which it then consumes (Tucker et al., 2008). A single blue mussel can filter up to 55 liters of water per day while a single flat oyster can filter up to 240 liters of water per day (Native Oyster Restoration Alliance (NORA), n.d.-b; Smith, 2022).

In the early 1800s, shellfish reefs once covered approximately 20%, or up to 114,400 km2, of the seafloor in the Dutch North Sea (see figure 3 above) (van den Wijngaard, 2018). By the beginning of the 20th century, intense fishing of the European flat oyster (*Ostrea edulis*) as well as bottom trawl fishing had eliminated those reefs leaving behind a predominantly soft sediment system (Hayer et al., 2019; Smaal et al., 2015). Without shellfish reefs, the associated ecosystem services, such as those mentioned above, were also lost. Within the Dutch North Sea, the blue mussel (*Mytilus edulis*), European flat oyster (*Ostrea edulis*) and Pacific Oyster (*Crassostrea gigas*) are the cultivated shellfish species which also have the capacity to build complex habitats like oyster reefs or mussel beds. Besides these species, there are also non-reef building shellfish including clams (*Arctica islandica*), cockles (*Cerastoderma edule*), and scallops (*Pecten maximus*) (Ecomare, 2017; Naturalis, 2018).

Shellfish also have cultural value in the Netherlands, as shellfish fishing and aquaculture have been taking place for at least 7000 years (Van Ginkel, 1990). Around the 1860s fishing decreased and cultivation began to increase as overfishing reduced wild populations (Netherlands Oyster Association, n.d.; Van Ginkel, 1990). With the transition to cultivation, Zeeland became the epicenter of shellfish production in the Netherlands. Today shellfish in the Dutch North Sea are primarily grown in Grevelingen and Oosterschelde, with mussels also being frequently cultivated in the Wadden Sea (NaturalHolland, 2014). The town of Yerseke in particular has named itself, "Zeeland's premiere mussel and oyster village" (Zeeland Visit, n.d.). Yerseke is the home of the historical oyster pits, where collected oysters are placed in clean seawater to clear themselves of sand before they are sold (Netherlands Oyster Association, n.d.). This rich history is embedded in the community and continues to drive the economy through tourism, gastronomy, and export of shellfish (Van Ginkel, 1990; Zeeland Visit, 2020; Zeker Zeeuws, 2018).

2.2 Aquaculture methods

2.2.1 Shellfish species

Within the Netherlands, there are many types of bivalve shellfish that are both harvested and cultivated for food. The two most significant types of cultivated shellfish in terms of annual sales are mussels and oysters. In 2019, mussels represented the biggest aquaculture product produced in the Netherlands, totaling €46 million in nominal value, and 38,000 tonnes produced (European Market Observatory for Fisheries and Aquaculture (EUMOFA), 2020). In comparison, oysters generated €7 million in nominal value and 3,000 tonnes of product (European Market Observatory for Fisheries and Aquaculture (EUMOFA), 2020). Mussels and oysters are also the only two types of shellfish that form shellfish reefs (Fitzsimons et al., 2020; van den Wijngaard, 2018). Other shellfish species burrow within the sediment, which means that while they still provide ecosystem services like food provision and water filtration, they do not create the added habitat benefits offered by epibenthic shellfish (Andriana, 2021; van der Schatte Olivier et al., 2020). Due to the benefits of shellfish reefs, the species that were initially considered for sustainable, nature-enhancing shellfish aquaculture are blue mussels, European flat oysters, and Pacific oysters (see figure 4). Pacific oysters were eventually removed from consideration (see Pacific oysters below for details).

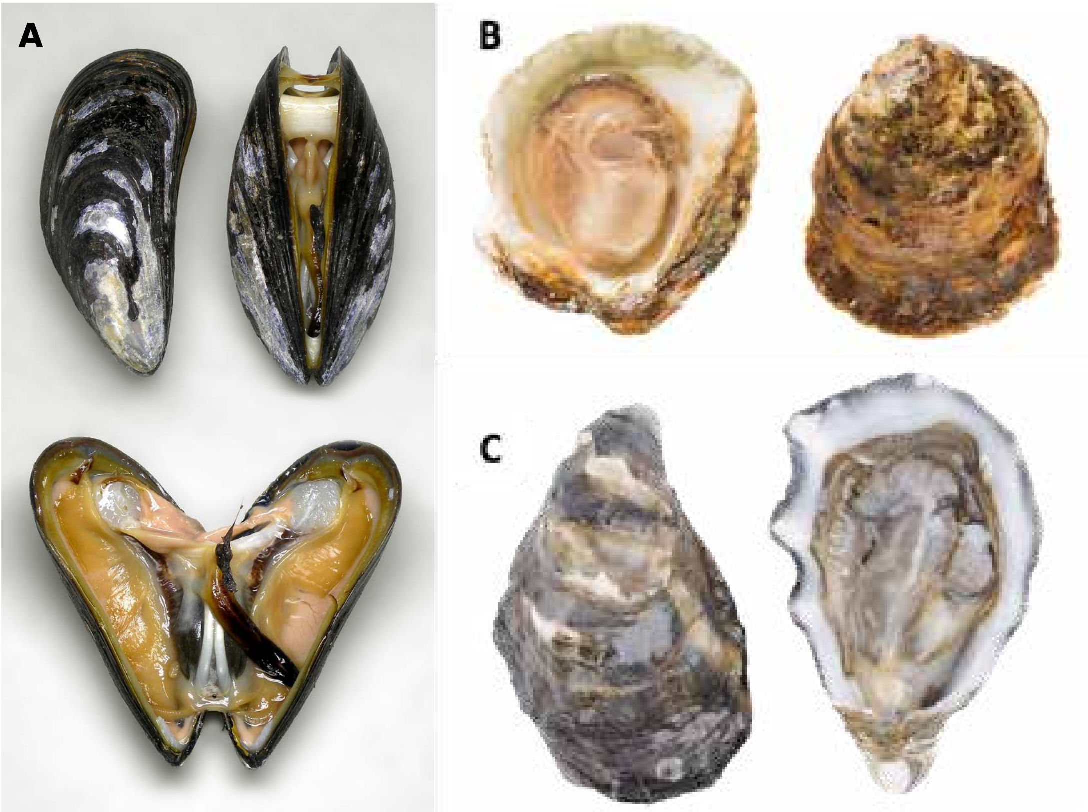


Figure 4. Reef forming shellfish species discussed in this report. A. Blue mussels (Mytilus edulis), B. European flat oysters (Ostrea edulis), C. Pacific oysters (Crassostrea Gigas) (Precy, 2022; TopPNG, 2019; Zenz, 2006)

Blue mussels

The primary mussel species that lives in the Dutch North Sea is *Mytilus edulis* also known as the blue mussel. The blue mussel has a wide geographic range due to the fact that it can withstand a wide range of environmental conditions such as salinity and temperature (Goulletquer, 2022a). Mussels typically grow from spat to market size adults (~40 mm) in less than 2 years (Goulletquer, 2022a). A distinguishing feature of mussels is that they attach to hard substrate using byssus threads. These threads are constantly being formed to replace damaged threads as needed, so mussels can be moved and re-attached to new substrates throughout the growing process (Smeathers & Vincent, 1979). This is a key property of mussels that allows them to be moved between spat collectors and ropes throughout their growing cycle which facilitates culturing methods. It should be noted that byssal thread formation is estimated to make up 8-10% of the available energy of a mussel (Roberts et al., 2021). As such, moving mussels between ropes as little as possible will allow them to focus their energy on growth and result in higher farm yields.

European flat oysters
There are two species of oysters that live in the Dutch North Sea. The native species, the European flat oyster (*Ostrea edulis*) and the introduced oyster species, the Pacific oyster (*Crassostrea gigas*). Flat oysters tend to occur in subtidal areas, where Pacific oysters are in shallow subtidal and intertidal areas (Stagličić et al., 2020). Following the previously mentioned decline in flat oyster populations, recovery has been hindered due to a parasite called *Bonamia ostrea* (Culloty et al., 2004; Sas et al., 2020). *B. ostrea* was first discovered in the Netherlands in 1980 and continues to impair flat oyster cultivation and restoration (Culloty et al., 2004; Van Banning, 1991). During this time, Pacific oysters became the more commonly cultivated oyster species in the Netherlands (Christianen et al., 2018; Drinkwaard, 1998). When healthy, flat oysters take 3-6 years to reach a market size of 40-110 grams. This long development period and challenges obtaining seed make them difficult to cultivate. Despite this difficulty, these oysters are considered a delicacy and earn a price at market that can be up to 3-5 times higher than that of Pacific oysters so they continue to be cultivated (Dutch Oyster Association, 2019; Goulletquer, 2022b; Qualimer, 2016). Both types of oysters get a higher price than blue mussels, for example between 2008-2018 blue mussels averaged around €1.50/kg, Pacific oysters around €3/kg, and flat oysters around €6/kg (Joint Research Centre, 2021).

The Food and Agriculture Organization of the United Nations estimates that approximately 250 tonnes of European flat oysters and 3000 tonnes of Pacific oysters are produced in the Netherlands annually (van der Heijden, 2022). Despite these differences, both types of oysters share some basic characteristics. Each type of oyster has a pelagic phase in their early life which means they are floating within the water column (Goulletquer, 2022b; Helm, 2006). Following this period they settle on a hard substrate and afix themselves with a small amount of cement. Unlike mussels, oysters only attach themselves to their substrate once and will not reattach if moved. As a reef-building organism, oyster larvae preferentially settle on oyster shells (Vasquez et al., 2013). Because the goal of aquaculture is to produce single oysters rather than reefs, hatcheries will provide pelagic oyster larvae with ground up oyster shells known as microcultch on which to settle (Wallace et al., 2008). When the larvae attach to the fine ground shells they can be easily separated from one another and grown into individual seed oysters. Once the seed oysters are large enough, they are placed within cultivation plots to grow through various methods, both on the sea floor and suspended in the water column (Wallace et al., 2008).

Pacific oysters

Since its introduction to the Dutch North Sea in 1964 the Pacific oyster has continued to thrive (Christianen et al., 2018). Today the Pacific oyster represents the primary oyster species that is cultivated in the Netherlands, as more seed is available, they are more resistant to the *Bonamia* disease that has affected flat oysters, and they mature faster - approximately 3 years to market size of 70-100 grams live weight (Christianen et al., 2018; Dutch Oyster Association, 2019). At present, Pacific oysters are mainly grown in more sheltered nearshore areas along the Dutch coast. Therefore, offshore cultivation would be a novel approach for Pacific oysters, as well as for flat oysters and blue mussels. While the Pacific oyster and the flat oyster share a lot of similarities, the Pacific oyster is larger and faster growing than the native flat oyster (Christianen et al., 2018; Goulletquer, 2022b; Helm, 2006). Due to the non-native status of Pacific oysters, policies such as the North Sea Program (see description below) state explicit support for the cultivation of native flat oysters and blue mussels, but not Pacific oysters (Ministry of Infrastructure and Water Management, Ministry of Agriculture, Nature, and Food Safety, Ministry of Economic Affairs and Climate Policy, et al., 2022). The North Sea Foundation is also in favor of the cultivation of only native species, so Pacific oysters will not be considered in the remainder of this report.

2.2.2 Cultivation methods

There are many different methods that can be used to cultivate blue mussels and flat oysters. Within each method there are also many different kinds of gear that can be used, and ways that the farms can be designed. In order to implement offshore shellfish aquaculture, we must assess which methods are suitable for offshore cultivation. This section therefore discusses available cultivation methods, first for blue mussels and then for flat oysters, and assesses whether each would work for offshore shellfish aquaculture.

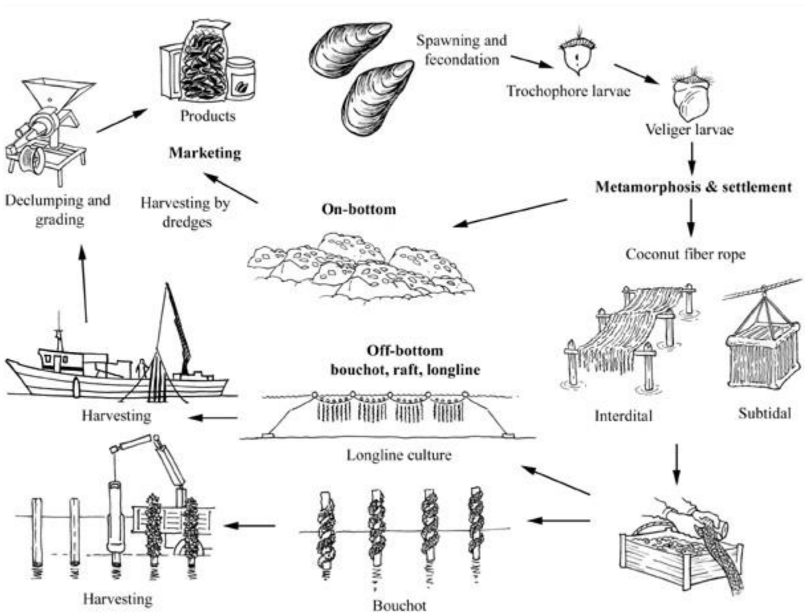


Figure 5. Blue mussel aquaculture cycle diagram (Goulletquer, 2022a)

Mussels

Bottom culture

In bottom culture, mussel seed is trawled from natural settlement areas or collected with mussel seed capture devices, and then spread out in an area where growing conditions are known to be good. The mussels are also spaced out to ensure that they have enough room to grow which also makes the harvesting process easier and reduces mortality due to predation (Avdelas et al., 2021). This method is not suitable for offshore wind farms because the water is an average of 40 meters deep, making it difficult to impossible for farmers to reach the plot and harvest the mussels (Toodesh et al., 2021). Additionally, dredging mussels or mussel seed from the bottom would negatively affect potential reef formation which is not the desired outcome of this project (Piñeiro-Corbeira et al., 2018; Sampaio et al., 2022).

Off-bottom culture

Off-bottom culture is defined by the use of aquaculture gear to prevent the mussels from resting directly on the seafloor.

- Longline
    - A longline is hung horizontally with buoys and held in place by anchors at either end of the line. From that main line, ropes or socks of mussels are suspended vertically (Avdelas et al., 2021). Ropes are often stocked at higher density when the mussels are young, so they may have to be collected and thinned during the course of growth to prevent overcrowding. Recent studies in Norway and Denmark have shown promising results from using rope nets in a grid pattern instead of traditional longlines which only hang vertically (Smart Farm, 2018; Taylor et al., 2019). The increased surface area for mussels to attach to (as compared to traditional ropes) can lead to increased yields. Despite higher initial investment, these net systems require less maintenance which would be particularly beneficial offshore. It must be noted that mesh surrounding longlines or nets can help reduce loss of mussels, but if it is too fine, the mussels can experience reduced access to food and thus decreased growth rates (Taylor et al., 2019). Exactly which mesh size will provide the best results depends on the carrying capacity at the farm location.
    - This technique is suitable for offshore wind farm sites. The mussels are suspended vertically from the top of the water column so that they are easily accessible by boat. Additionally, a longline could be placed below the water surface so that the system will not be subject to the harshest conditions (Feng et al., 2021).
- Raft
    - Raft culture is similar to longline, but instead of suspending the vertical ropes or socks from a line, they are suspended from a floating platform. Water depth >8 meters is required for this technique (Avdelas et al., 2021).
    - This technique is not ideal for offshore wind farm sites. While it is suitable for sites with deep water, it is more vulnerable to damage in turbulent

conditions than longlines (Buck, 2007). As a result, rafts would be a less suitable method than longlines in the open North Sea.

- Bouchot
  - In this method, vertical pilings are driven into the seabed. Ropes are then wrapped around the pilings and mussels grow on the ropes. Mesh is also placed around to prevent predation and mussels falling off the rope (Avdelas et al., 2021)
  - Bouchot culture is best used in intertidal areas, so this approach is not suitable for wind farm multi-use.

In summary, while there are many techniques that are used for mussel aquaculture, most are intended for use in intertidal or shallow subtidal areas. The method that is most suitable for offshore mussel cultivation at this time is the submerged longline design. Methods for flat oyster aquaculture are further discussed below.

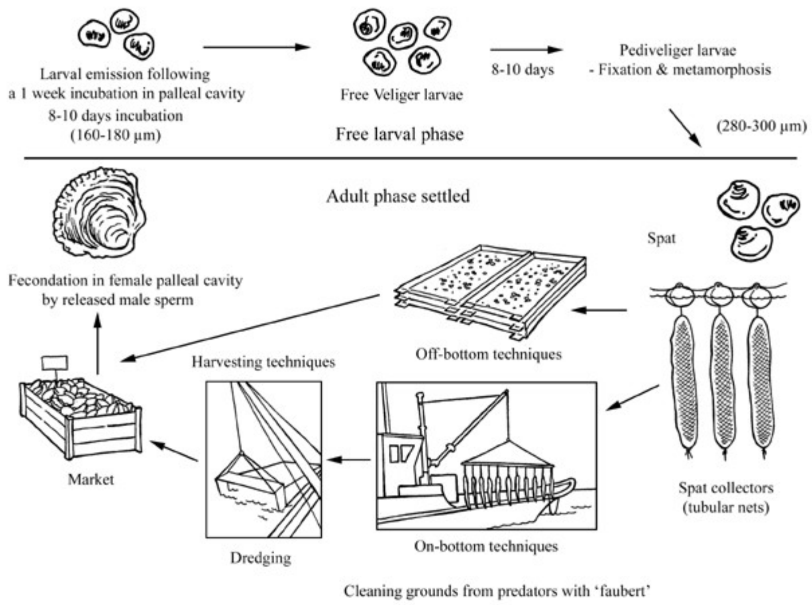


Figure 6. European flat oyster aquaculture cycle (Goulletquer, 2022b).

Oysters

While mussels and oysters share some morphological and life cycle similarities, the methods used to cultivate them are quite different. In this section the methods used to cultivate oysters will be described in order to differentiate between techniques used for the two species.

Bottom culture

Bottom culture yields oysters that are the closest to native, non-cultured oysters (Lu, 2015). Unlike wild oysters, bottom culture oysters are separated to yield single oysters rather than settling on surfaces in clumps. This method forms robust shells. It is not known exactly why, but hypothesized that it could be because they get more minerals from the mud or maybe because they are rolled around due to turbulence as they are not confined in a bag or cage. Risks of this method include burial in sediment leading to suffocation, and higher rates of predation, primarily by oyster drills (Lu, 2015). Bottom culture is not suitable for offshore wind farms because of the deep water and dynamic conditions.

Off-bottom cultures

The term "off-bottom culture" describes techniques where the oysters are physically separated from the seafloor. This includes methods where the oysters are floating in the water column or at the surface, but also methods where oysters are contained in bags or cages near the seafloor. In general, off-bottom culture produced better yields in comparison to bottom culture because the oysters are more protected from unfavorable bottom conditions and predators. The downsides are that off-bottom culture requires additional equipment which costs money and farmers have to spend time removing fouling organisms (Fitridge et al., 2012). Also, shells can become brittle, so methods to periodically reposition the oysters are used to help strengthen the shells and improve their shape (Lu, 2015). Listed below are the different strategies for off-bottom oyster culture and a determination of whether this technique should be considered for offshore cultivation.

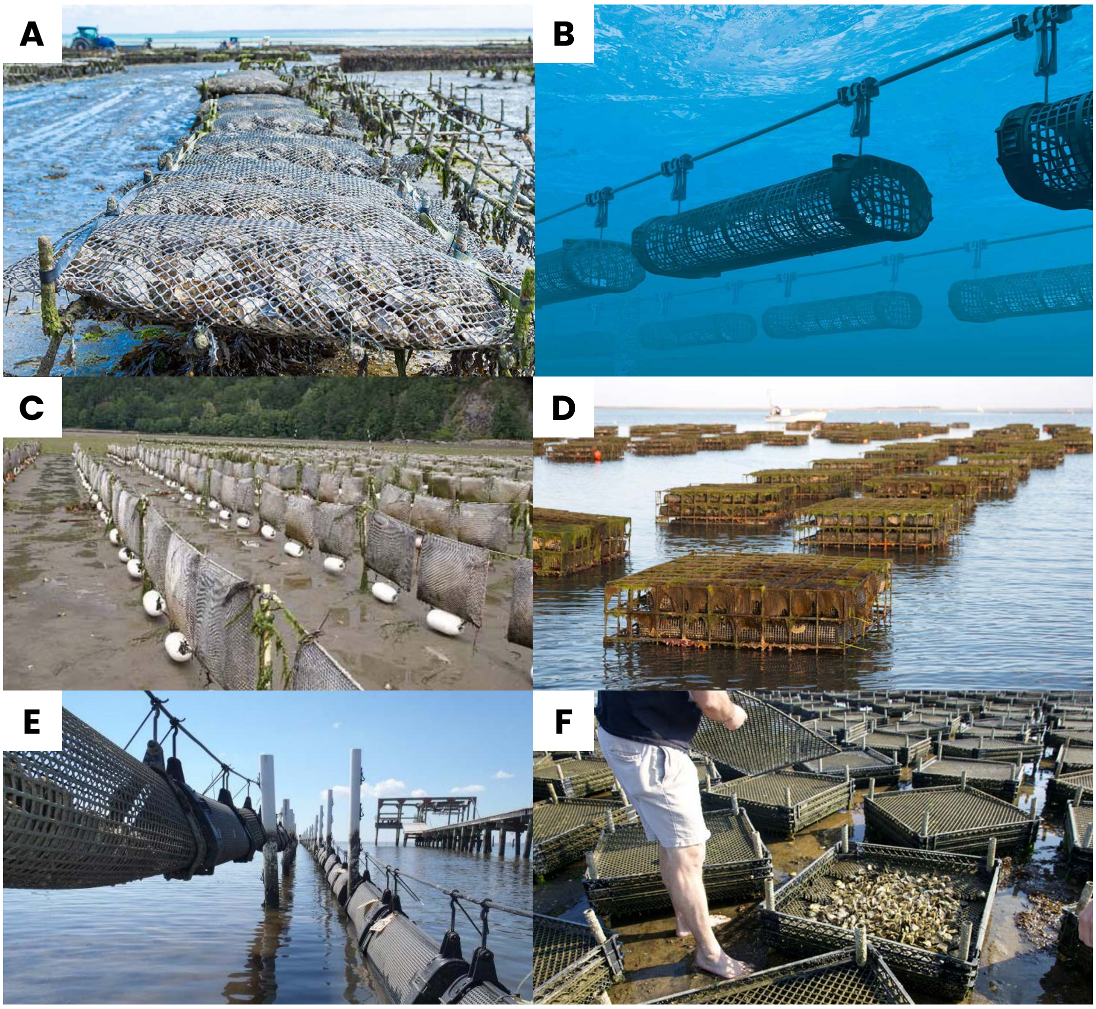


Figure 7. Off-bottom oyster cultivation methods. A. rack and bag, B. submerged longline, C. suspended, D. cages, E. adjustable longline, F. trays (Lu, 2015; SEAPA, 2021; Shutterstock, n.d.; W. Walton et al., 2012)

- Rack and bag
  - Steel rebar racks are pushed into the bottom sediment, creating a surface about 50 cm off of the sediment (see figure 7A). Mesh oyster bags are then fixed to the racks with zip ties or another securing strategy to prevent the bags from floating away at high tide (Doiron, 2008; Lu, 2015).
  - This method is only suitable for intertidal culture and thus will not be suitable for use offshore.
- Suspended
  - Oyster bags are attached to a longline on one end and the other end is attached to a floating buoy (see figure 7C). As the tide goes up and down the bag is moved around which naturally tumbles the oysters to strengthen their shells (Lu, 2015).
  - This method is intended for intertidal or shallow areas with calm conditions. The rough conditions at the surface in an open environment like offshore wind farms is too dynamic for this farm construction.
- Long line
  - Lantern nets, cages, or bags hang from a longline that can be pulled up for maintenance (Lu, 2015). The line can be set at the surface, or submerged beneath the surface in the case of rougher conditions (see figure 7B). Oysters are placed in the desired container at densities which allow for them to grow and still have room in the container (Hood et al., 2020).
  - SEAPA and BST are two companies which produce commonly used systems with cages on longlines (BST, 2006; SEAPA, 2021). The cages can be attached to the line individually, grouped in stacks, or stacked within metal frames. The metal frames make it easier to access individual baskets if needed, but require larger boats and cranes due to the added weight (B. Foret, personal communication, April 19, 2022). In other methods, cages/bags are allowed to fall dry periodically to remove fouling organisms. This is not an option if the longline is deployed in a subtidal area, so an offshore longline would need to be washed periodically to remove fouling organisms and allow for water flow through the cage (B. Foret, personal communication, April 19, 2022).
  - This method is suitable for offshore conditions if the longline is submerged below the surface. Trials are being conducted to determine what adjustments will be needed to implement this technique offshore (see section 4.1.5 for more information about the technology readiness level). Currently, results have shown that there are still issues with cages breaking loose due to harsh weather, so further trials are needed to develop a reliable method that withstands storm conditions.

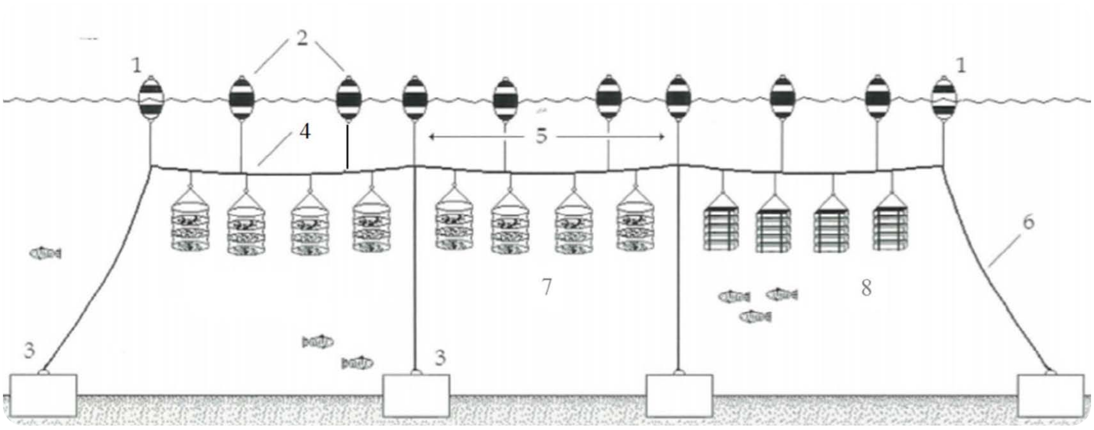


Figure 8. Submerged longline oyster aquaculture diagram from Tamburini et al. (2019). Numbers indicate "1, head-buoys; 2, buoys; 3, anchoring blocks; 4, floating system; 5, span; 6, mooring; 7, baskets for oyster fattening; 8, trays for oyster prefattening" (Tamburini et al., 2019). This method is currently considered the best for offshore, as the submerged design keeps the cages in the calmer water below the surface.

- Floating
  - Different types of bags, floats, and equipment can be used, but all floating systems sit at the top of the water (see figure 9 below). The oysters stay wet and the wave action tumbles them, which is a routine practice in aquaculture to strengthen the shells and deepen the cup of the oysters. Fouling occurs on the side of the bag that is in the water, so gear is periodically flipped over to remove fouling by drying the bag and exposing it to the sun (Lu, 2015). While flipping the bags is not inherently difficult, this necessary maintenance would be expensive in an offshore setting due to transportation costs. One advantage of floating methods is that there are many different configuration options and gear suppliers, so it is very customizable (B. Walton et al., 2012).
    - Examples include: OysterGro system, Taylor floats (Lu, 2015), Go Deep International (Walton et al., 2012) (see figure X)
  - Floating cage option
    - Vinyl coated wire cage that houses mesh oyster bags (see figure 9D/E). Cage is floated with two large air-filled pontoons under one side of the cage, and it can be flipped onto the pontoon side periodically to get rid of fouling on the cage as well as on the oysters. Floats can be filled with water to sink the cages below the surface during a storm (Walton et al., 2012)
    - Need two people to flip for anti-fouling due to size and weight of the cage, so this method requires more labor but also provides more protection than single bags.
  - Floating gear methods are best suited for calmer areas, or ones with occasional bad weather. A US-based resource suggests a hurricane plan for floating farms in waters deeper than 8 ft/2.44 m, which is to lower the longline on one side of the bag so that bags are suspended in the water

column. This implies that with rough North Sea storm conditions, and difficulty accessing offshore farms, submerged culture might be a safer choice than floating (Walton, 2012).

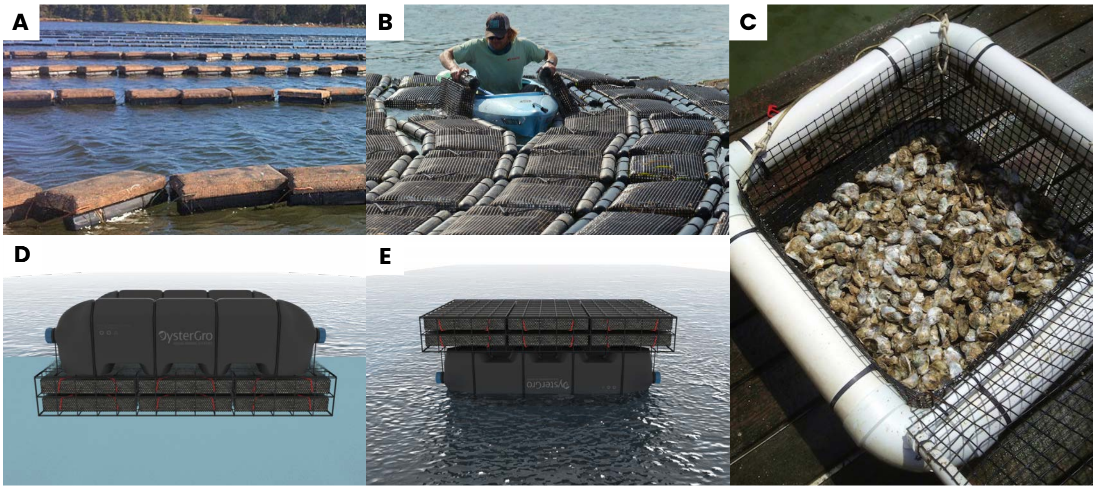


Figure 9. Floating oyster cultivation methods. A. Go Deep bags with floats on bottom, B. bags with floats on the sides, C. Taylor float, D. floating cage with bags in the water, E. floating cage in drying mode with bags out of the water (Capt. Tom's Oyster Floats, 2019; Freidah, 2021; Go Deep, 2015; OysterGro, 2020)

- Cages
    - Cages rest on the bottom and house mesh bags of oysters (see figure 7D). This is still considered an off-bottom method because oysters are housed within bags and held above the sediment. The cage method protects the oysters from predation by keeping them from touching the bottom and keeping the bags from floating away. This only works if the bottom is sturdy so that the cage doesn't sink into the sediment (Lu, 2015).
    - Not suitable for offshore wind farms because the water is too deep. In this case, placing cages on the seafloor would make them extremely difficult for farmers to monitor and harvest, so other methods are preferred. Additionally, the seafloor is dynamic with large sandwaves which vary in size and move up to 10 meters per year which would create a high risk of cage burial and resulting loss of oysters (Toodesh et al., 2021).
- Tray culture
    - Similar to cages, trays are set on or near the bottom (see figure 7F). The walls of the tray are a mesh material like that of oyster bags, so oysters can be laid directly inside and trays can be stacked on top of one another (Lu, 2015).
    - As previously mentioned, gear that rests on the bottom is not suitable for offshore wind farm multi-use aquaculture.

2.2.3 Farm configurations

Along with aquaculture methods, it is important to consider how farms should be configured to safely operate within wind farms, avoid negative environmental effects, and maximize shellfish growth. All of the aquaculture methods mentioned above are highly customizable depending on the site conditions, resource availability, and preferences of individual growers. Each new site requires trial and error to figure out what the best arrangement is given the combination of relevant factors such as environmental conditions, size of the available area, budget, and competences of the shellfish farmers.

In the case of wind farm multi-use, there are some additional considerations that limit the configuration possibilities and size of aquaculture farms. Current policy states that there is a 50 meter safety zone around wind turbines and 500

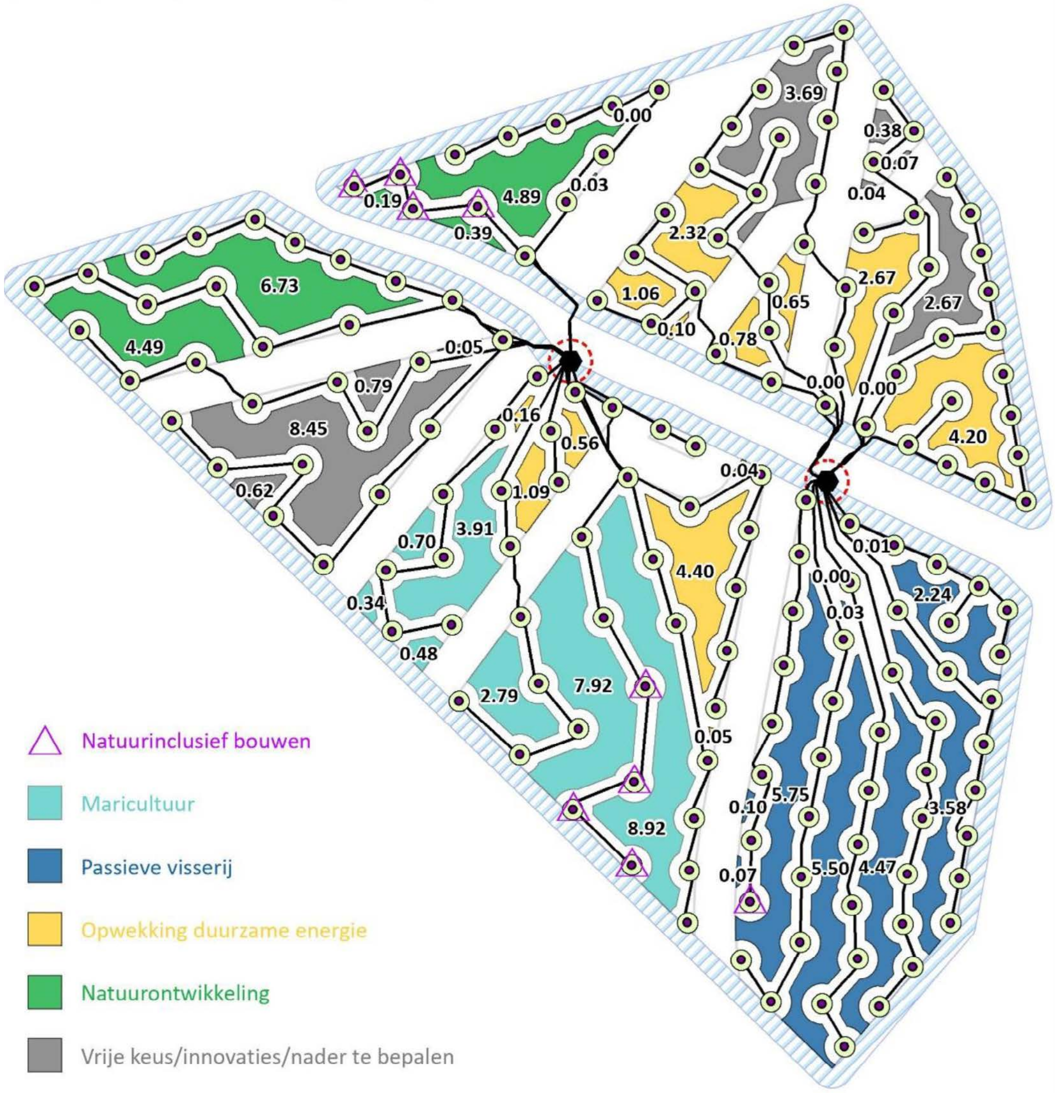


Figure 10. Area passport of Borssele wind farm (North Sea Counter, 2021). Shellfish aquaculture is included under "maricultuur" which is Dutch for mariculture. Areas designated as mariculture also allow for finfish and seaweed farms.

meters around transformer stations where vessels, including multi-users, should not enter (Rijkswaterstaat, 2018). These areas are to be marked in area passport maps such as the one below (figure 10) along with safety zones around cables which run along the seafloor. The only area passport that has been published so far is for Borssele wind farm. This map shows seven sections that are dedicated for aquaculture multi-use, ranging in size from 0.34-8.92 hectares in area (North Sea Counter, 2021). Shellfish farmers will have to adjust their methods in order to maximize production within the allotted space they are given, taking into account area as well as shape of the parcel. This method of building the wind farm first and then figuring out how to accommodate multi-use places the logistical burden on the potential multi-users rather than asking the wind farm to make accommodations.

In addition to the shape and size of the area allotted for multi-use there are other factors that must be considered when designing a shellfish farm in order to maximize yield and minimize any negative environmental impacts. One such factor is the angle of the longlines relative to the prominent direction of water flow. Current velocities are slowed down within shellfish farms to varying degrees based on the angle relative to water flow, density of the farm, and spacing of the gear (Mascorda Cabre et al., 2021). Reduced water flows then increase farm residence times which means that less food is coming into the farm for the shellfish, and their waste products are not being carried away as efficiently (Kim et al., 2020). Studies have shown that farms that are positioned at a 45-50 degree angle to the prominent direction of water flow have less impact from drag and thus have better water flow and better overall farm performance (Mascorda Cabre et al., 2021). The effect of farm angle and shape is particularly notable in areas that are dominated by tidal flows, as the water tends to move in a more consistent direction (Petersen et al., 2019).

2.2.4 Site selection criteria

When looking for an aquaculture or pilot project site there are many factors that need to be considered including social and political, logistical, and environmental conditions (Brouwers et al., 2021). Tables 3 and 4 below summarize a variety of these factors to consider as well as environmental conditions that are ideal for the growth of shellfish. Additionally, figures 11 and 12 show the result of a study evaluating suitability for flat oyster and mussels cultivation respectively within current and potential future wind farm sites (van den Bogaart et al., 2019).

Based on the information in table 3 flat oysters typically grow well in water with a higher salinity, higher current velocities, and lower suspended particulate matter compared to blue mussels. Overall, the environmental conditions under which the two species perform best are quite similar but the upper and lower limits of their ideal growing conditions vary. These environmental conditions are then used to make a suitability map in figures 11 and 12 which take into account salinity, current velocity, chlorophyll a, and suspended particulate matter (van den Bogaart et al., 2019). This data suggests that the ideal locations for growing shellfish based on those environmental conditions are in the southern Dutch North Sea where the Hollandse Kust and Borssele wind farm sites are located (see figure 15). Ijmuiden Ver, Nederwiek, and Lagelander wind farms are also positioned just north of those sites and are predicted to be more suitable for mussel cultivation than oyster cultivation. Hollandse Kust zuid, noord, and west are set to be commissioned in that order in the coming 4 years (Ministry of General Affairs, 2021). Depending on the realized timing of wind farm construction and multi-use initiatives, these sites could be a good starting point for incorporating multi-use given their high environmental suitability. In the long term, the sites that are being explored for wind farms after 2030 are north of the Wadden Islands (see figure 1), but this area is designated as "less suitable" for flat oysters and "suitable" or "less suitable" for mussels according to van den Bogaart et al. (2019).

Table 3. Environmental conditions needed for offshore flat oyster and blue mussel farms. "Feasible" indicates conditions under which shellfish can survive whereas "ideal" indicates conditions where growth and survival are optimal. These values also consider necessary conditions for aquaculture gear (Davaasuren et al., 2013; Goseberg et al., 2017; Leavitt, 2019; A. Smaal et al., 2017; von Thenen et al., 2020).

	Flat oysters		**Blue mussels**	
Suitability level	Feasible	Ideal	Feasible	Ideal
Chlorophyll a (μg l⁻¹)	<1.68	>1.68	>2	>3
Oxygen (mg l⁻¹)	>1.5	>3.5	4	>4
Current velocity (m s⁻¹)	<0.25	0.25-0.8	>0.05	>0.1
Bathymetry (m)	**50-79**	**10-50**	50-80	20-50
Temperature (°C)	3-6, 25-30	7-25	20-29	5-20
Salinity (‰)	20-25	25-35	15-18	18-30
Suspended particulate matter (mg/l)	<4, 60-180	4-60	<10, >90	10-90

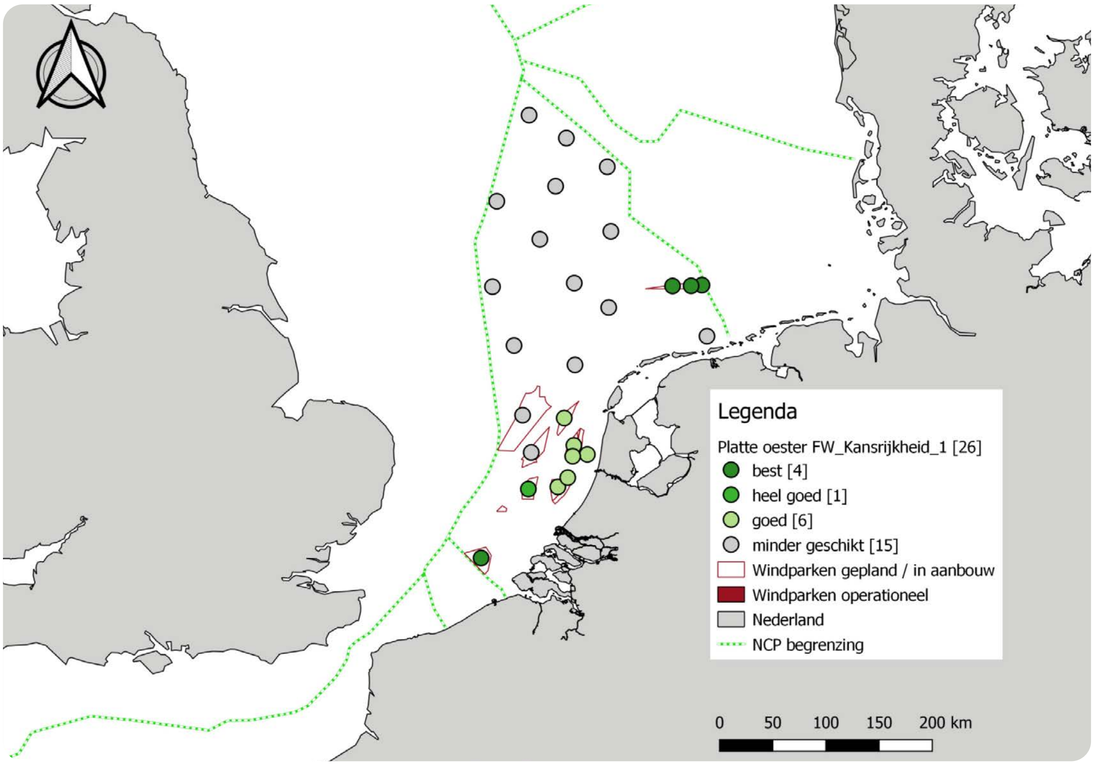


Figure 11. Suitability map for flat oyster cultivation in the Dutch North Sea considering salinity, flow velocity, chlorophyll a, and suspended particulate matter (van den Bogaart et al., 2019)

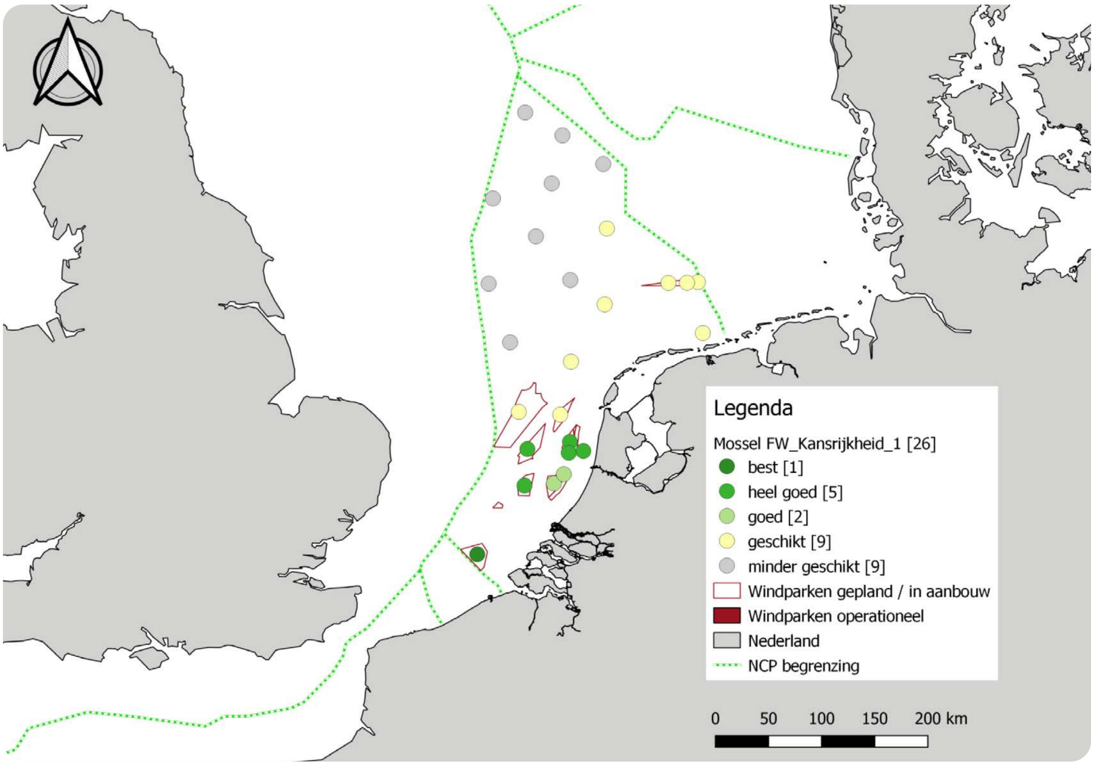


Figure 12. Suitability map for blue mussel cultivation in the Dutch North Sea considering salinity, flow velocity, chlorophyll a, and suspended particulate matter (van den Bogaart et al., 2019)

In addition to environmental conditions, it is important to take into account the policy and logistical contexts of a site, as this greatly influences how it will function for a given type of multi-use. In terms of policy, the multi-user must do some prior research to understand what permits are required and what steps would be needed to acquire these permits. Without permits, it is not possible to move forward. The other important factor here is "level of alignment/cooperation with pilot location stakeholders" (Brouwers et al., 2021). With wind farm multi-use, it is important for multi-users and wind farms to work together in order to both operate efficiently and safely within the same area. Multi-users may want to meet with wind farm operators of a few sites to determine which company may be most favorable to work with and most open to their form of multi-use. Along with the political factors, logistical considerations like distance from port, plot size, and grid conditions are essential to determining feasibility and potential profitability of a site. All of these factors must be taken into consideration when laying out a prospective business plan in order to accurately account for all costs and profits. As a result, these factors should be taken into account when choosing a location in order to pick the one with the most favorable balance for a prospective multi-user.

Policy Considerations
• Status of any required permits • Status of potentially required demarcation measures and/or other security measures • Level of alignment/cooperation with pilot location stakeholders • Governance of the pilot locations
Logistical Considerations
• Availability of required area • Port locations in the vicinity • Distance and time from your preferred port • Facilities in your preferred port • Sufficient trained personnel • Maximum size to your multi-use area • Potential for future scale-up and expansion • Grid conditions • Onshore based (support) facilities • Connectivity (e.g. 4G) for any remote monitoring requirements

Table 4. Pilot location policy and logistical considerations for multi-users as listed by (Brouwers et al., 2021)

There are some additional factors not included in the tables that can still affect the quality of a site for nature-enhancing aquaculture. For example, the type of substrate on the seafloor is something that should be noted. Settlement of larvae on the seafloor is most likely if there is gravel, shells, live shellfish, or other hard substrate on which the larvae can settle (Brouwers et al., 2021; Commito et al., 2014; A. Smaal et al., 2017). In cases like this, interventions may also be possible to improve conditions for the given purpose. Overall, these environmental, policy, and logistical considerations indicate that not all wind farm sites in the North Sea would work equally well for offshore shellfish aquaculture multi-use. It is also unlikely that any site will fit all desired conditions perfectly. When choosing a pilot project site or a future farm site all of these factors from tables 3 and 4 should be considered in order to weigh the benefits and drawbacks of each site and consider whether interventions can be taken to improve the drawbacks.

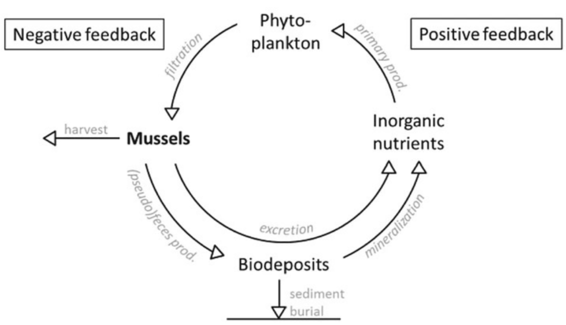
2.3 Ecological impacts of shellfish farming

Adding a large shellfish farm within a wind farm likely has environmental impacts, so it is critical to consider the positive and negative impacts of this multi-use activity before it is installed. In terms of positive impacts, both mussel longlines and oyster aquaculture gear have been shown to increase biodiversity in the surrounding area (Mascorda Cabre et al., 2021; Sheehan et al., 2019; Tallman & Forrester, 2007; van der Schatte Olivier et al., 2020). Aquaculture installations create structural complexity which provides refuge for fish and other mobile marine organisms, especially in soft bottom systems like the Dutch North Sea. Additionally, the hard surface of the shellfish as well as the aquaculture gear provide an area for sessile organisms such as tunicates, barnacles, anthozoans, hydrozoans and macroalgae (Markert et al., 2009; Mascorda Cabre et al., 2021; van der Schatte Olivier et al., 2020). These sessile organisms as well as the shellfish themselves also act as a food source for mobile organisms, attracting them to the area and increasing biodiversity (Barrett et al., 2022; Sheehan et al., 2019).

Shellfish aquaculture farms can also attract a variety of birds which feed on shellfish (Barrett et al., 2019; Callier et al., 2018). While providing a food source for birds may be neutral or positive in some cases, this would be a negative effect within wind farms, as there is a risk for bird collisions with wind turbines. Birds as well as other mobile organisms including marine mammals, have also been shown to be repelled from aquaculture sites by maintenance activities due to noise and pollution from boat exhaust (Callier et al., 2018; Varennes et al., 2013). Not all farm maintenance is bad, however, as removal of fouling organisms deposits them on the seafloor thus attracting animals to feed on them (Callier et al., 2018). As a result, farms can act as attractants or repellants depending on the nature and frequency of maintenance and how much food is ultimately available from the farm.

Another significant contribution of shellfish aquaculture is in assisting the recovery of natural shellfish beds. Increasing the local population density of mussels or oysters has the potential to increase reproduction and release more larvae into the water column to increase wild populations (Norrie et al., 2020). Adult shellfish can also be lost from the aquaculture farm and deposited on the seafloor, especially in mussel longline farms where the shellfish are directly exposed to the water column (Sardenne et al., 2019). This “fall-off” provides food for benthic organisms like crabs and lobsters while the shells add hard substrate for larval settlement (Mann & Powell, 2007). Both of these factors contribute to increased biodiversity.

Shellfish aquaculture also has an impact on the planktonic communities around them through their filter feeding process which can be positive or negative. In general, shellfish filter water and consume plankton which decreases the amount of plankton in the water over time (Hulot et al., 2020). Then the shellfish digest their food and ultimately excrete waste products which add nutrients back into the water and stimulate the growth of phytoplankton (see figure 13) (Mascorda Cabre et al., 2021). The balance between positive and negative feedback depends on the size of the farm and the surrounding environmental conditions including the rate of water flow through the farm and the amount of available nutrients in the water (Jansen et al., 2019; Mascorda Cabre et al., 2021). Plankton forms the basis of the marine food chain, so the availability of plankton has major implications for the ecological carrying capacity of the area (Mascorda Cabre et al., 2021). The term ecological carrying capacity refers to the amount of use that an ecosystem can withstand before it undergoes major changes which are often irreversible (McLachlan & Defeo, 2018). In the case of shellfish aquaculture, exceeding the carrying capacity primarily means depleting planktonic resources such that there is not enough food for other organisms that would typically live in that ecosystem. This capacity can be difficult to define, as it is different for each site and the degree of ecosystem change that is considered acceptable is often different according to different users (McLachlan & Defeo, 2018)



	System nutrient status	
	Rich	Poor/limited
Service	Eutrophication control by nutrient removal through filtration and harvest	Stimulation of primary production through nutrient regeneration (may in turn sustain higher filter feeding stock)
Impact	Benthic degradation through biodeposit accumulation	Competition with other filter-feeding species (exceeding carrying capacity)

Figure 13. Basic overview of the interactions between mussels, system nutrients, and primary production (Jansen et al., 2019). The same kind of cycle can also be applied to flat oysters.

Another factor that can have major impacts on the ecosystem carrying capacity is the hydrodynamic changes caused by the presence of aquaculture gear. Due to the restricted flow of water within the aquaculture farm, current velocities are decreased (Mascorda Cabre et al., 2021). To compensate for this disruption, current velocities below and to the side of the farm are increased as water is diverted around the gear. Water flow between the bottom of the farm and the seabed is maximized when the longlines or cages extend to 80% of the water column depth (Mascorda Cabre et al., 2021). These hydrodynamic changes lead to increased mixing within the water column and also the resuspension of the biodeposits from beneath the farms, stimulating an increase in primary productivity in the pelagic waters. Simultaneously, the reduced rate of flow through the farm increases residence times which leads to greater plankton depletion from filtration (Hulot et al., 2020). The balance between positive and negative feedback can be affected by the size of the farm, angle relative to water currents, density of shellfish within the farm, bathymetry, and sediment type beneath the farm, making carrying capacity a difficult but important factor to quantify (Jansen et al., 2019; Mascorda Cabre et al., 2021). The flow rates can also affect the distribution of biodeposits from the farm, which is important for determining the effect that shellfish farms can have on benthic biogeochemistry (Gadeken et al., 2021). Overall, shellfish aquaculture has the potential to provide helpful ecosystem benefits, but it is not without its potential risks as well. Each site must be evaluated before farm placement and monitored after in order to ensure that no significant negative ecological impacts are taking place.

2.3.1 Nature Enhancement Considerations

Nature enhancement in the case of shellfish aquaculture is primarily aimed at supporting wild shellfish bed recovery and regaining their associated ecosystem services as mentioned above (Markert et al., 2009; van den Wijngaard, 2018). The most significant contribution of aquaculture farms in this regard is facilitating reproduction and therefore increasing larval supply. It is important therefore to ensure that the shellfish being cultivated are capable of reproduction, as discussed below in Diploid vs Triploid Shellfish. Additionally, the placement of farms can have a significant impact on where larvae end up settling and how much this benefits reef restoration, which is discussed further in Spatfall and Connectivity.

Diploid vs Triploid Shellfish

Shellfish, like most animals, are naturally diploid organisms, meaning that they have two sets of chromosomes (Piferrer et al., 2009). In the 1980s, research began on how to breed triploid oysters so that they would not reproduce and potentially be more resistant to disease (Colsoul et al., 2021). It was ultimately found that ploidy did not affect disease resistance, but this modification still held value (Dégremont et al., 2015). Diploid oysters, as well as mussels, decrease in marketability during the summer due to a change in body mass composition associated with reproduction (Hollier, 2014; Nell, 2002; Wilson, 2008). Triploid oysters and mussels could therefore be harvested and sold year round, which is ideal for aquaculture businesses to maximize profit. Triploid mussel and flat oyster seed are still in development and not yet available at a commercial scale like with Pacific oysters (Adamson et al., 2018; Nell, 2002; Osterheld et al., 2021; Wilson, 2008). While this development may help aquaculture businesses, restoration efforts do not benefit from triploidy. Shellfish restoration projects typically aim to increase population numbers while maintaining genetic diversity, fitness, and disease resistance (Colsoul et al., 2021). As a result, reproduction is essential for creating larvae which will help sustain wild populations into the future, and continue the growth of shellfish reefs. Studies have shown that aquaculture farms can act as a source of larvae to support wild populations, so restoration efforts could be enhanced by the use of diploid shellfish in nearby aquaculture (Norrie et al., 2020).

Spatfall and Connectivity
In order for oyster or mussel larvae to settle and start to build reefs, two things are needed: an adequate supply of larvae which have been dispersed into a given area, and suitable hard substrate for them to settle on. At the moment, both of these are limiting factors in the Dutch North Sea (Colsoul et al., 2021; A. Smaal et al., 2015). Increasing the number of adult shellfish in the area by installing aquaculture farms can help to increase the number of larvae and thus improve the odds of settlement and survival (Norrie et al., 2020). Additionally, to facilitate the beginning stages of recovery, hard substrate can be placed in order to provide a foundation for the larvae to settle on. Previous restoration projects have used artificial reef structures and cages or bags of shellfish shells to provide that settlement surface (Colsoul et al., 2021; Spires, 2019; The Rich North Sea, 2021a). In order to place these hard substrates in areas where larvae will settle, studies have been conducted to model the probable location of spat fall - the time period when swimming larvae search for suitable substrate and transition into sessile spat (Kamermans et al., 2020). Within the Dutch North Sea, larvae are predicted to settle generally northeast from their release points (Figure 6) due to the surface currents running in the same direction (Kamermans et al., 2018, 2020; A. Smaal et al., 2015). Flat oysters have a pelagic phase of 10-30 days, while blue mussels can remain pelagic for 16-70 days (Coolen et al., 2020). As a result, blue mussel larvae can move considerably farther from their release point than flat oyster larvae (oyster dispersal zone pictured in figure 14). Considering these findings, offshore shellfish farms and reef restoration sites should be placed relative to each other so that spatfall from farms lands within the restoration area.

2.4 Summary

This chapter provided an introduction to the two native reef-building species in the Dutch North Sea, the European flat oyster and the blue mussel. Additionally, a small background was provided for the invasive, but also most commonly cultivated oyster species, the Pacific oyster, which will not be examined further in this report. Then after exploring all cultivation methods for mussels and flat oysters, it was concluded that submerged longline cultivation is the ideal offshore method for both species. Mussels are attached directly to the rope while oysters are placed in cages which are attached to the longline. In terms of farm layout, it is important to maintain the 50 meter radius around wind turbines and 500 meters around transformers. The angle of the farm relative to the current and the length of longlines relative to the water depth can also have impacts on how the water flows around the farm and thus the environmental impact created by the gear. Site selection criteria were also provided in order to consider the environmental, political, and logistical conditions that shellfish aquaculture multi-users need in order to be successful in using a certain location.

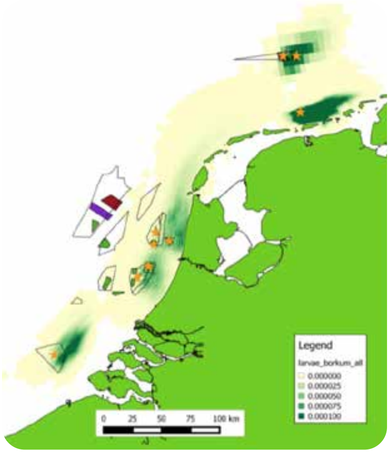


Figure 14. Simulation of flat oyster larval transport in the Dutch North Sea. Orange stars represent release points of larvae. Legend shows relative concentration of larvae with dark green as the highest concentration (Kamermans et al., 2020; A. Smaal et al., 2017). Blue mussels have a longer planktonic phase, so likely disperse further (Coolen et al., 2020)

The final section of this chapter investigated the ecological impacts of shellfish production. Shellfish farms can increase biodiversity by adding habitat and providing food, but human activity from maintenance can drive away mobile species. Farms can also help to produce more shellfish larvae in order to recover wild shellfish beds, but this is only possible if the shellfish used are capable of reproducing. Shellfish can also have an impact on planktonic communities through their filter feeding, and management is important to ensure that this does not exceed carrying capacity. Overall, this section shows that shellfish aquaculture can have environmental benefits such as increased biodiversity and larval subsidy for recovering reefs. These farms can also have negative impacts like attracting birds to wind farms and exceeding carrying capacity such that no algae is left for other organisms. As a result, sustainable management practices are essential to ensure that aquaculture farms take action to maximize their positive impacts and avoid negative impacts as much as possible.

3. Wind Farm multi-use

After investigating how to install offshore shellfish aquaculture, we next have to discuss where to install these farms. Given the lack of space in the Dutch North Sea, many actors are interested in exploring possibilities for multi-use within offshore wind farms. This proposition is much more complicated than it may sound, however, so this chapter explores the political context surrounding these multi-use spaces. After some initial introduction to the state of wind energy and multi-use in the Dutch North Sea, this chapter will outline the involved actors and their interests in this project. Additionally, all relevant policies from the European Union and the Dutch national government are summarized. This information then leads to an assessment of the bottlenecks that are currently preventing the implementation of offshore multi-use. The scientific feasibility analysis from chapter 2 and the social analysis from this chapter ultimately combine into an integrated analysis in chapter 4.

3.1 Wind energy in the Dutch North Sea

Wind energy is a key method by which countries throughout the European Union aim to reach climate goals set by the Paris Climate Accords as well as the European Green Deal (Netherlands Enterprise Agency, 2022). In particular, offshore wind energy has a higher capacity to produce renewable energy than onshore wind turbines due to the higher sustained winds over the ocean (Bilgili et al., 2011). As a result, offshore wind is set to expand dramatically in coming years. The EU, for example, aims to reach 300 gigawatts (GW) of annual offshore wind energy production by 2050, a more than tenfold increase from 2020 levels (Timmermans & Simson, 2020; WindEurope, 2021). As a member state of the EU, the Netherlands is also planning to significantly expand offshore wind energy production in coming years. Currently there are 7 active wind farms in the Dutch North Sea producing approximately 2.5 GW of power annually (Ministry of General Affairs, 2021; Ministry of Economic Affairs, 2021). New offshore wind farms are set to open in coming years with the goal of producing 21 GW of wind energy by 2030 (Michler-Cieluch & Krause, 2008; Ministry of General Affairs, 2021; North Sea Consultation, 2020; Rijkswaterstaat & Ministry of Economic Affairs and Climate Policy, 2022) (North Sea Consultation, 2020; Michler-Cieluch & Krause, 2008; Ministry of General Affairs, 2021).

Figure 15. Map of currently designated and newly designated wind farm areas in the Dutch North Sea (Rijkswaterstaat & Ministry of Economic Affairs and Climate Policy, 2022)

3.2 Multi-use wind farms

One way to solve the problem of limited space within the Dutch North Sea (as seen in figure 1) is to implement multi-use spaces. In particular, offshore wind farms offer an attractive multi-use opportunity because there is open space between wind turbines. Additionally, no dredging, shipping, or bottom trawl fishing is allowed which makes this an attractive space for nature enhancement activities such as facilitating wild shellfish reefs. Plus, if no fishing is allowed here then other industries should make use of this space so that other space can be left open for fishing. Due to the interest in multi-use, the government has decided to produce maps called "area passports" to designate different areas within the wind farm for different multi-use activities (see figure 10). There are areas for aquaculture, passive fisheries, nature development, solar energy, and areas left open for any usage as well as innovation projects. While multi-users can apply for a permit in any area, permit applications for the designated activity will be given priority (Ministry of Infrastructure and Water Management, Ministry of Agriculture, Nature, and Food Safety, Ministry of Economic Affairs and Climate Policy, et al., 2022). This process is theoretically developed, but only one area passport is currently published. Multi-use is still in its early stages, and many parties are working to figure out the best method for implementation. To further expand on the status of wind farm multi-use, the next sections will describe these actors as well as the current policies that are in place.

3.3 Actor analysis

Many actors are involved with wind farm multi-use including private industry companies, governmental bodies, scientific experts, and NGOs. Figure 16 below provides a visual summary of the actors in terms of their power and interest in this specific project. Three main groupings can be seen amongst the actors. The private industry actors are the most powerful and the most interested because they are the ones who run the businesses which are involved in this multi-use. Whether they are interested or not determines whether multi-use will take place or not, giving them a lot of power.

Additionally, changes in multi-use procedures affect their business so they are highly interested. Governmental bodies are typically high power but lower interest. These organizations have the power to create policies which could change the way that multi-use is permitted, funded, and managed. That gives the government great power. They are busy dealing with other projects, however, and currently have left implementation in the hands of private industry to decide, indicating lower interest. Lastly, the scientific experts and nature organizations are more interested in this topic than the government, but they are less powerful. These organizations spend a lot of time researching environmental conservation projects, sustainable food production, and offshore wind energy, so they are highly interested in the outcome of offshore wind farm multi-use. In terms of power, they rely on their ability to influence government officials in order to enact change, giving them lower power. Moving forward, experts and nature organizations could leverage governmental bodies to use their power and facilitate multi-use.

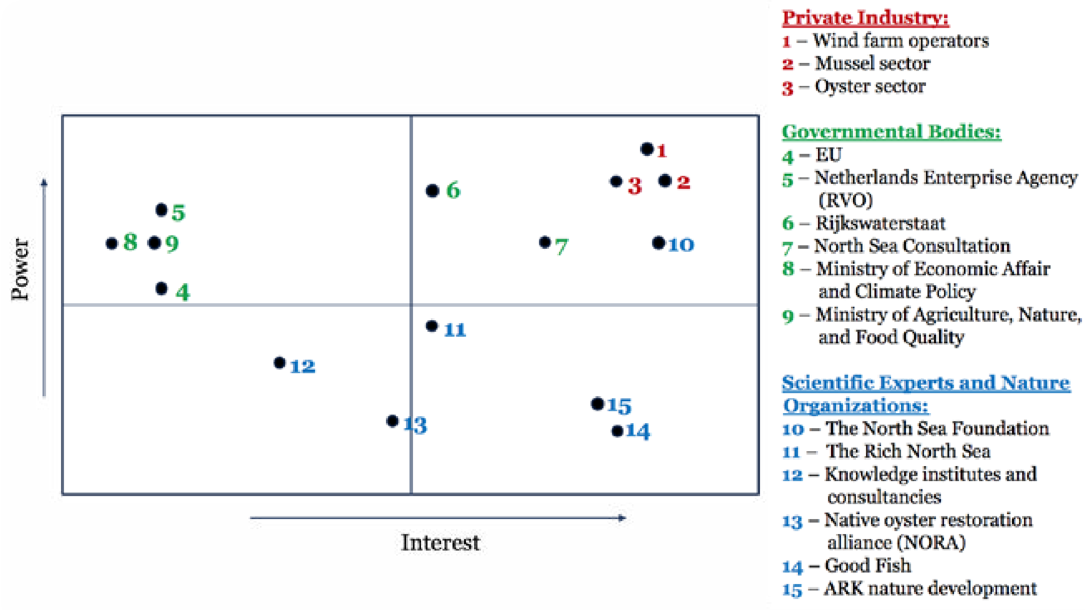


Figure 16. Plot of actor analysis based on power and interest of each actor

3.3.1 Private industry

Wind farm operators

Wind farms are one of the main actors in this project with high power and high interest. The primary interest of wind farms is maintaining operational wind turbines to generate maximum power, and to do so under safe working conditions at all times. The easiest way for wind farms to do this is to closely control and monitor everything that goes on in the area (L. Folkerts, personal communication, February 25, 2022). As a result, wind farms view aquaculture multi-use as a risk because it leads to unknown factors such as aquaculture gear and fishermen entering the farm.

During the policy formation process, it is probable that wind farms would be wary of these types of collaborations. Wind farms that are already operational will likely be the most resistant to policy changes that affect their procedures. While all wind farms except for Gemini are technically open for multi-use, the permitting process can be made long and expensive if there is not agreement between the multi-users and the wind farm operators on how procedures will be managed (Ministry of Infrastructure and Water Management, Ministry of Agriculture, Nature, and Food Safety, Ministry of Economic Affairs and Climate Policy, et al., 2022). Wind farms that are still in construction could potentially work with governmental bodies and prospective multi-users to create a layout that would prove satisfactory to all parties and allow for a more harmonious multi-use installation in these areas. As a result, future multi-use projects should focus on upcoming wind farms. The wind farms represent an important partner in any multi-use project, so getting them on board with aquaculture installations from the beginning stages of the construction process would help to set the stage for the future.

Mussel sector

Regarding shellfish aquaculture actors, this project will primarily focus on mussel and oyster farmers. There are other types of shellfish aquaculture in the Netherlands (cockles, clams, scallops) but these species are not reef forming and thus do not provide the same robust ecosystem services as mussel and oyster reefs (Fitzsimons et al., 2020). Within the mussel sector there are bottom growers and hanging culture growers. The Producers' Organization of Dutch Mussel Culture, the trade organization for bottom culture mussel growers, contains 89 member companies (Producers' Organization, n.d.). These companies constitute the majority of the mussel farming industry as approximately 95% of annual mussel production comes from bottom culture (Dutch Mussel Bureau, n.d.). There are significantly fewer hanging culture growers, with hanging culture representing approximately 5% of mussel production in the Netherlands each year (Dutch Mussel Bureau, n.d.). Offshore mussel aquaculture would need to be hanging culture, so any prospective offshore mussel growers would need to use or adapt to these techniques.

Mussels are the largest aquaculture product in the Netherlands with 44 thousand tonnes produced and 47 million euros in revenue in 2017. Oysters make up a much smaller market by comparison with 2000 tonnes produced in 2017, generating 17 million euros (European Market Observatory, 2020). Both mussel and oyster aquaculture companies are primarily based in Zeeland, with aquaculture plots in the Oesterschelde, Grevelingen, or Wadden Sea (Capelle, 2017). Most of these businesses are family owned and rooted in tradition (Dutch Mussel Bureau, n.d.; Dutch Oyster Association, n.d.). As a result, many are hesitant to take on an offshore aquaculture project, which requires high capital investment and high risk, without prior evidence that it will be profitable. A representative from the Producer's Organization of Dutch Mussel Culture, for example, has stated that members are interested in a pilot project to see whether offshore mussel culture could be profitable, but that they would like the pilot site to be very near shore (A. Risseeuw, personal communication, March 9, 2022). Areas very near shore are less risky in terms of costs and environmental conditions, and they

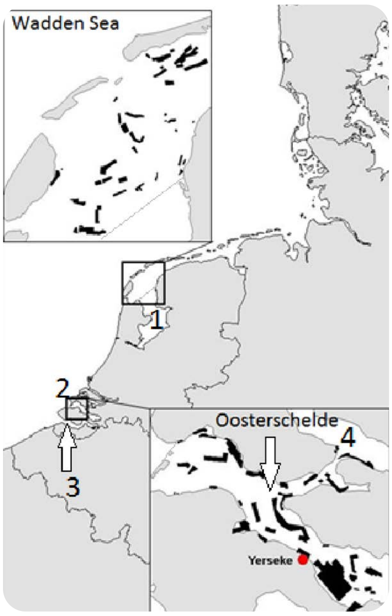


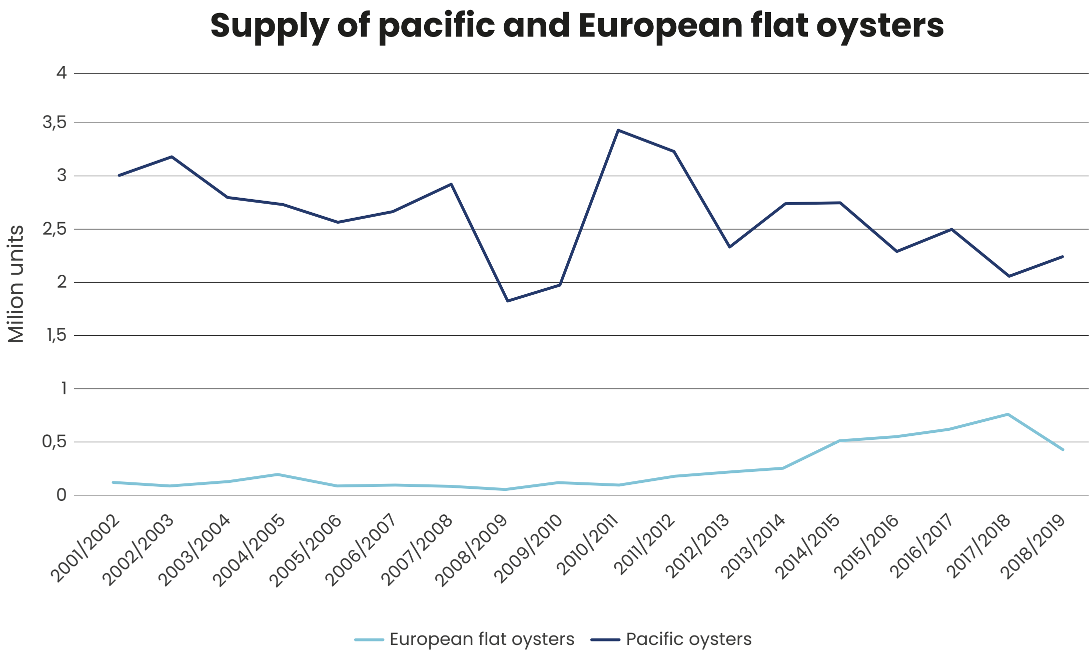
Figure 17. "Mussel culture plots (in black) in the Netherlands at the Wadden Sea and Oosterschelde, 1 = Zuiderzee (now: Lake IJssel), 2 = Voordelta, 3=Westerschelde, 4=Grevelingen" (Capelle, 2017)

don't involve the complicated multi-use aspects of a wind farm. These kinds of small steps indicate that the sector is not ready to jump right into building aquaculture farms within wind farms, but rather needs additional testing and research to determine the best next moves. One company that is currently taking steps to put aquaculture in offshore wind farms is the international offshore service provider, OOS. OOS recently announced intentions to launch a semi-submersible mussel farm in the Dutch North Sea (Balkenende, 2022). They have designed and will build the ship, while leaving the actual cultivation practice to Zeeland mussel farmers. This will be a primary pilot for offshore farming and will potentially help influence other farmers to consider this novel approach. In general the challenge for this project with regard to the mussel sector will still be proving that offshore wind farm multi-use will be profitable for their business. Supporting pilots such as this one which can help develop a successful business model will help persuade farmers to move offshore.

Oyster sector

The oyster industry shares many of the same characteristics as the mussel industry. Oyster aquaculture companies are also primarily based in Zeeland and are dominated by small, family owned businesses that have been around for generations. Currently there are about 30 oyster aquaculture companies operating in the Netherlands (Zeeland Visit, n.d.). These companies grow oysters in the Grevelingenmeer and the Oosterschelde, with 550 and 1550 hectares of aquaculture plots respectively in the two locations (van Beveren, 2021). Oyster yields in the Netherlands in 2018 consisted of 84% Pacific oysters and 16% flat oysters (van Oostenbrugge, 2021). While flat oysters make up a smaller market percentage, the supply of flat oysters has been slowly increasing over the last 20 years, where Pacific oysters have been slowly decreasing (van Oostenbrugge, 2021). One reason for this decline is Pacific oyster mortality caused by the Japanese oyster drill, an invasive species of snail that was introduced to the Netherlands in 2007 (Kamermans, 2017). In recent years farmers have been experimenting with growing oysters with a rack and bag method (see section 2.2.2 for a detailed description) to reduce predation, but this still represents a relatively small portion of oyster aquaculture (Kamermans, 2017; van Oostenbrugge, 2021).

Oyster farmers have high power and high interest in implementation of oyster farms within offshore wind farms. Without their cooperation, this project will not be able to move forward. Similar to the mussel industry, oyster farmers are not currently interested in entering into a wind farm multi-use project (J. de Rooij, personal communication, February 20, 2022). A majority of oyster aquaculture in the Netherlands uses on-shore bottom culture methods, so moving offshore would be a total change in business model, a large financial investment, and also higher risk. That being said, oyster growers have a wealth of knowledge on oysters and how they can be grown. One potential solution could be a collaboration between government and oyster growers to leverage industry knowledge without asking oyster growers to take on so much of the financial burden and risk.



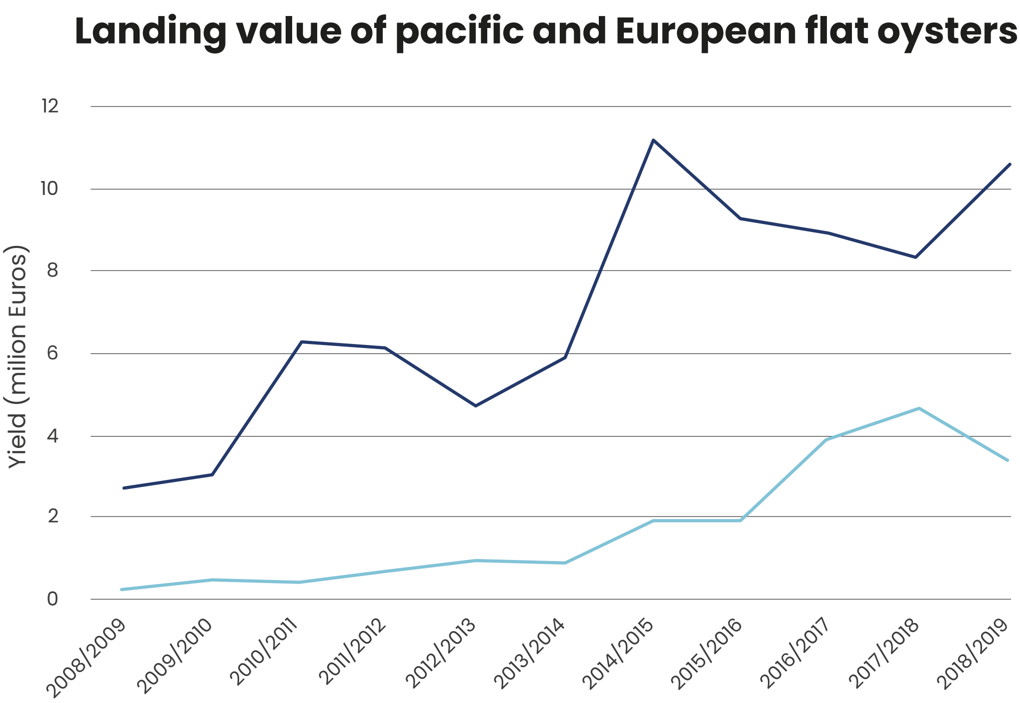


Figure 18. Annual supply and landing value of flat oysters versus Pacific oysters in the Netherlands. Based on data from (van Oostenbrugge, 2021).

3.3.2 Governmental bodies

European Union (EU)

The European Union is a political body that creates policies which apply to all of the Member States within the EU. Member States are then responsible for taking the EU policies and translating them into plans of action and legislation at the national level. Due to their larger scope, the EU has low interest in this project which is specific to the Netherlands. If a successful solution was found that allowed for aquaculture, wind, and nature restoration all in one space, then the EU might be more interested because it could be applied in other Member States as well. While they do not have high interest, they still have medium power given their role as an international governing body. The policies that they set affect what policies are put into place in the Netherlands, so their influence is indirect but notable.

Netherlands Enterprise Agency (RVO)
The Netherlands Enterprise Agency (RVO) is a government agency responsible for implementing the policies of the Ministry of Economic Affairs and Climate Policy (Netherlands Enterprise Agency, 2018). As a result, they are responsible for the tender process for offshore wind farms, as well as conducting site assessments and environmental impact assessments for future wind farm sites (Netherlands Enterprise Agency, 2020, 2022a). The RVO is also the agency in charge of administering grants such as the European Marine Fisheries and Aquaculture Fund (EMFAF), and the Horizon - Cluster 6 grant which covers food production, natural resources, and aquaculture among other related topics (Netherlands Enterprise Agency, 2021). Both of these grants could be used by organizations looking to implement sustainable shellfish aquaculture within wind farms. In relation to this project, the RVO has medium to low interest and medium power. They are not invested in this project specifically, but as the permitting organization and the organization in charge of awarding relevant grants they must be considered in the development process of offshore aquaculture techniques. Consulting with RVO along the way could help ensure that any solutions provided in this project would be possible to get permitted and potentially funded as well.

Rijkswaterstaat
Rijkswaterstaat is a Dutch government agency that is part of the Ministry for Infrastructure and Water Management. Their website states that their priorities are safety, mobility, and quality of life as well as balancing all of this with the health of the environment (Rijkswaterstaat, 2019a). In relation to this project, Rijkswaterstaat handles applications for permits for multi-use under the Water Act. They also conduct monitoring activities during the planning, construction, operation, and environmental impact of wind farms (Netherlands Enterprise Agency, 2022a). As part of the OSPAR convention, Rijkswaterstaat also participates in the Biological Diversity and Ecosystems, Human Activities, and Offshore Industry (OIC) working groups which together encompass the goals of this project (Rijkswaterstaat, n.d.). Safe offshore operation and monitoring of activities to ensure positive environmental impacts are essential in installing sustainable shellfish aquaculture in offshore wind farms. Overall, Rijkswaterstaat has medium-high power and medium interest in relation to this specific project, with the potential to increase that power and interest if they took on the project of offshore shellfish aquaculture more directly. Currently Rijkswaterstaat would be involved in offshore shellfish farming by monitoring the environmental impacts along with those of the wind farm. In the future, Rijkswaterstaat could also be a potential government

partner in supporting the nature-enhancement potential of offshore shellfish aquaculture, which would be in line with their previous nature enhancement projects (Rijkswaterstaat, 2019b).

North Sea Consultation

The North Sea Consultation (Noordzeeoverleg) is the group in charge of implementing the North Sea Agreement (see section 3.4.2 Netherlands policy for a description of the policy). This group consists of 15 stakeholders representing government ministries, food production and fisheries, nature, energy, and shipping (North Sea Consultation, 2021). Shellfishermen are indirectly represented under “Food Production and Fisheries”. Two of the three seats devoted to this sector are dedicated to cutter fishery producers’ organizations within the North Sea (Nooitgedagt, 2022; PO Urk, 2018). The third fisheries representative is NetVISwerk, an organization that represents small-scale fishermen in the Netherlands and Belgium (NetVISwerk, 2018). NetVISwerk deals with manual shellfish harvesters, but not with aquaculture businesses, so aquaculture is still left largely unrepresented in the North Sea Consultation. Additionally, aquaculture and fisheries often compete for space, so designating fisheries organizations to represent aquaculture is a conflict of interest. The North Sea Consultation has high interest and high power over this matter, as they are responsible for creating specific implementation plans for the various topics put forth in the North Sea Agreement. The North Sea Foundation is a member of the North Sea Consultation representing nature interests, so they have some ability to influence the actions of this implementation body.

Ministry of Economic Affairs and Climate Policy

In the National Water Plan, the Ministry of Economic Affairs and Climate Policy, along with the Ministry of Infrastructure and Environment were responsible for designating areas for wind farm development (Netherlands Enterprise Agency, 2022a). Overall their mission is to promote entrepreneurship and innovation while maintaining sustainability (Ministry of Economic Affairs and Climate Policy, 2011). Their role in this project is primarily in crafting policy that relates to wind farm establishment and operation. As a result, they have medium-high influence but low interest in the placement of shellfish aquaculture within wind farms.

Ministry of Agriculture, Nature and Food Quality

The ministry of Agriculture, Nature, and Food Quality is in charge of managing fisheries which also includes aquaculture (Spreij, 2022). As a result, they are also responsible for translating EU policy regarding aquaculture into Dutch national policies. Similar to the Ministry of Economic Affairs and Climate Policy, the Ministry of Agriculture, Nature and Food quality has medium-high influence over this project because they control aquaculture policies within the Netherlands. They also have medium-low interest because they do not necessarily have a preference for whether shellfish aquaculture is implemented within wind farms. The Ministry website states that they are interested in producing safe and affordable food that also contributes to the conservation and restoration of natural areas (Ministry of Agriculture, Nature, and Food Quality, 2017). With this goal in mind, sustainable, nature-enhancing shellfish would be an attractive proposal for them to take on. A coordinated effort between the Ministry of Agriculture, Nature and Food Quality and another government agency like Rijkswaterstaat or the Ministry of Economic Affairs and Climate Policy could potentially help to bridge the gap between wind-related actors and aquaculture-related actors.

3.3.3 Scientific experts and nature organizations

The North Sea Foundation

The North Sea Foundation is a non-governmental organization (NGO) which advocates for the "protection and sustainable use of the North Sea" (Stichting De Noordzee, n.d.). Their four main focus areas include sustainable food, nature-friendly energy, room for nature, and clean sea. The North Sea Foundation works towards these goals by arriving at a suggested course of action based on research, expert opinions, and conversations with stakeholders. The organization will then publish their position on a certain topic to spread awareness on the issue and influence policies being made. In this case, NSF has high interest and high influence. They are the organization requesting this study because shellfish aquaculture has been shown to have potential to provide sustainable food, and the Dutch government has expressed interest in implementing multi-use within wind farms. Given these promising indications, more research is needed to find the most sustainable, effective way to combine sustainable food and nature-friendly energy through shellfish aquaculture multi-use. With a more detailed review of best practices and suggestions for policy solutions, the North Sea Foundation can be a coordinating body for this multi-use implementation. As a result, final advice will be tailored to NSF in order to help them most effectively facilitate this transition.

The Rich North Sea

The Rich North Sea is a program that was formed by NSF and Natuur & Milieu. They are focused on a range of nature enhancement projects, including flat oyster reefs, within offshore wind farms in the North Sea. This goal is complementary to the current project, as one aim of the North Sea Foundation is for offshore shellfish aquaculture to support ongoing restoration efforts. The Rich North Sea, North Sea Foundation, and Natuur & Milieu all share an office in Utrecht which helps to facilitate communication. This close communication gives The Rich North Sea medium influence in this project, as these organizations work together frequently and value each other's input. Throughout this project, The Rich North Sea has been a helpful resource for the ecological implications of potential solutions. Ultimately they have medium interest in this project and could be a helpful partner in implementing offshore shellfish aquaculture since they already have knowledge of the processes involved in running shellfish-related projects in the same spaces. Their focus is primarily on European flat oysters right now, but their primary objective is nature conservation and restoration in the North Sea so they would still be interested in participating in a project focused on mussels or Pacific oysters if research showed that those would be beneficial.

Knowledge institutes and consultancies (WUR, WMR, NIOZ, BuWa, MARIN)
Knowledge institutes such as Wageningen University & Research (WUR), Wageningen Marine Research (WMR), the Royal Netherlands Institute for Sea Research (NIOZ), Bureau Waardenburg (BuWa), and Marine Research Institute Netherlands (MARIN) all play a role in scientific research and monitoring covering a wide range of topics including offshore wind and aquaculture (Bureau Waardenburg, 2017; MARIN, 2019; NIOZ, n.d.; Wageningen University & Research, 2017). The knowledge gained from their work informs all relevant parties about what conditions are necessary for shellfish to thrive in a certain area, and how different management decisions can impact the ecosystem in a variety of ways. Having more information about the interactions between shellfish aquaculture and the surrounding environment can also help organizations like the North Sea Foundation to determine what are the most sustainable practices and use that to inform future policy demands.

Native Oyster Restoration Alliance (NORA)
The Native Oyster Restoration Alliance (NORA) is an organization that brings together those who are working on European flat oyster restoration projects in order to facilitate the sharing of knowledge and development of ideas (Native Oyster Restoration Alliance (NORA), n.d.-a). There are two current projects that are affiliated with NORA which are working with flat oyster restoration in offshore wind farms. One is the Blauwind project being conducted by the Rich North Sea, and the other is a Belgian pilot called UNITED that is researching methods for combining flat oyster aquaculture and restoration in offshore wind farms (Native Oyster Restoration Alliance (NORA), 2022). NORA could prove to be a helpful partner in terms of maximizing the nature restoration potential of aquaculture installations and monitoring oyster bed recovery. Their members include scientists and experts from all around Europe who focus on oyster habitats and restoration, so they have particularly specialized knowledge which would prove useful. In regard to this project, they have medium interest and medium influence. Aquaculture is not exactly the focus of the Alliance, but they would likely be interested in at least staying informed about the project if flat oysters are involved. Because the goal of NORA is active restoration, they would likely push aquaculture to participate in more than just passive nature enhancement. Therefore, The North Sea Foundation will have to balance NORA’s desire for restoration with the shellfish industry’s desire to focus solely on food production in order to achieve the stated goal of nature-enhancing food production.

Good Fish
Good Fish is a Dutch NGO that works to ensure that fish that is caught, sold, and consumed in the Netherlands is sustainable (Good Fish, 2020c). One way they do this is through awareness, like with their VISwijzer tool (in English: Fish Index)(Good Fish, 2020a). This tool lists all the types of fish that are sold in the Netherlands and

gives them a score of how sustainable they are. This sustainability rating includes a breakdown by cultivation method and an explanation of why the rating was given. Good Fish also works with restaurants and stores that sell fish to assess their sustainability and potentially gain recognition as a sustainable fish supplier. Concerning shellfish, Good Fish has a project called TOP Mussel which aims to increase the popularity of this sustainable food source among young adults thereby expanding the market (Good Fish, 2020b). Informational campaigns and market research are two strengths of Good Fish that would be very useful in this project. Overall Good Fish has high interest in the production of sustainable food, and low influence over whether shellfish aquaculture is conducted in offshore wind farms. This combination will make them a more valuable partner in the implementation phase of offshore shellfish farming as their strength lies in informing the public about the sustainability of the product and analyzing how the market affects the consumption of sustainable seafood products. Both of these will be valuable in the case of offshore shellfish, and are not inherently strengths of the North Sea Foundation.

ARK Nature Development

ARK is an NGO based in the Netherlands that focuses on rewilding (ARK, 2014). Their objective is to restore ecosystems to a place where natural processes are able to take place without the need for human intervention. While they are interested in supporting natural ecosystems, they also recognize the socio-economic value of nature, and work together with organizations from industries such as water management, urban planning, and offshore energy (ARK, 2014). One such relevant project was recently announced which involves a collaboration with Ørsted to incorporate nature rewilding into offshore wind farm sites and also create a Marine Field Lab (Roggema, 2022). New restoration methods will be tested in this field site with the intention of scaling up those which are successful. The restoration methods being tested include methods for stimulating shellfish reef formation, as ARK sees these reefs as vital for biodiversity and increased population densities of marine animals in the North Sea . (Roggema, 2022; van den Wijngaard, 2016). Due to their interest in offshore re-wilding and shellfish reef restoration, ARK has medium-high interest in the project at hand. They are involved with offshore shellfish within wind farms, but do not currently work with aquaculture for food production. Their research regarding biodiversity effects of oyster restoration could be helpful in informing nature-enhancement projects such as sustainable aquaculture. Since they do not work with aquaculture, their influence over this project is low, as they do not hold influence over the key processes of implementing shellfish aquaculture.

3.4 Current policy concerning multi-use

Like with the involved actors, it is important to have an overview of the relevant policies from the EU and Dutch national government which shape the current procedures surrounding aquaculture and multi-use. In general, policies on both levels either directly or indirectly support shellfish aquaculture. Most policies show indirect support by promoting multi-use, sustainable aquaculture, and/or sustainable food production (see figure 19 below). Only one policy explicitly states support for offshore shellfish aquaculture multi-use which is the North Sea Program 2022-2027. In this section, the EU policies are described first which set regulations and strategies for all EU member states. It is then up to the member states to determine how they put those policies into practice. The national regulations are more directly related to final implementation of multi-use in the Dutch North Sea as these policies determine procedures within the Netherlands specifically.

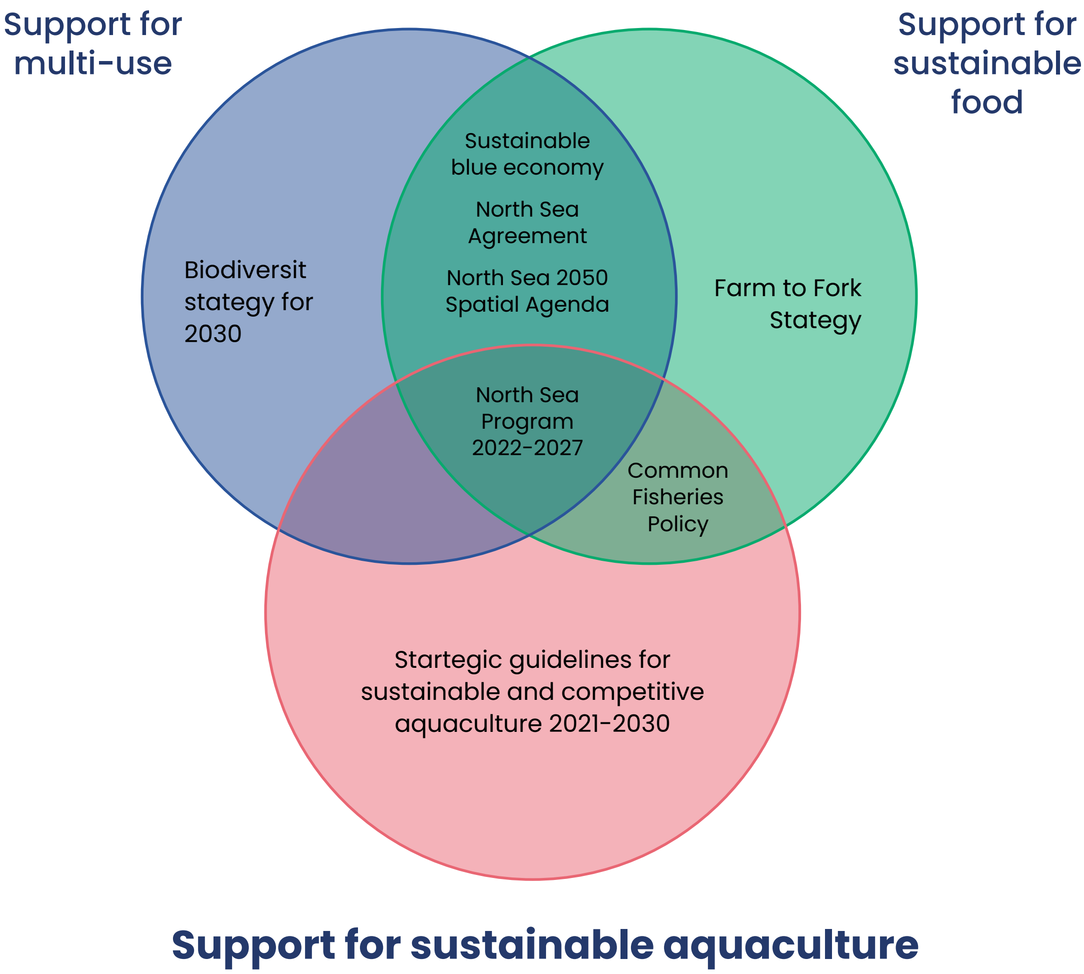


Figure 19. Venn diagram showing the focus of EU and Dutch policies as it relates to offshore multi-use shellfish aquaculture. Asterisk indicates European Union policies. Those without are Dutch national policies.

3.4.1 EU policy

Common Fisheries Policy

The Common Fisheries Policy (CFP) is the European Union's primary legislation regulating the fishing industry (Directorate-General for Maritime Affairs and Fisheries, n.d.). The CFP was originally drafted as part of the Common Agricultural Policy with the goal to, "preserve fish stocks, protect the marine environment, ensure the economic viability of EU fleets and provide consumers with quality food" (Breuer, 2021b). The latest version of the CFP was published in 2013 with additional focus on environmental, economic, and social sustainability of fisheries and aquaculture (Directorate-General for Maritime Affairs and Fisheries, n.d.; Breuer, 2021b). Additionally, the intention is set to promote the development of sustainable aquaculture techniques in order to provide sustainable food to meet growing demand, as well as to create jobs (European Parliament & European Council, 2013). As part of this policy, the strategic guidelines for sustainable and competitive aquaculture (described in more detail below) were formed to provide more specific direction for the aquaculture sector.

Strategic guidelines for sustainable and competitive aquaculture 2021-2030
These guidelines were laid out by the EU with the primary goals being for the European aquaculture sector to be more resilient, competitive, innovative, and sustainable, as well as to make consumers more aware of aquaculture products (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021). These goals are also in line with those of the Integrated Maritime Policy of the European Union which establishes the priorities of sustainability, innovation, economic development, and increased awareness of maritime sectors (Breuer, 2021a). Originally, strategic guidelines for aquaculture were issued in 2013, based on which Member States developed Multi-annual National Strategic Plans (MNSPs). The revised guidelines suggest access to space and clear administrative structure as two methods to increase the resilience and competitiveness of aquaculture (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021). To promote innovation, the guidelines suggest supporting research and aiding in the sharing of results with industry end-users as well as with other Member States. To improve sustainability, the Commission recommends setting environmental regulations and enforcement procedures to curb negative impacts of aquaculture, and encouraging aquaculture of low trophic level organisms and those that provide ecosystem services (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021). Given that reef-building bivalve shellfish are lower trophic level organisms that contribute significantly to the provision of ecosystem services, this guideline indicates support for shellfish aquaculture though this is not explicitly stated. Lastly, to improve consumer awareness of aquaculture, the suggestion is to improve trademarks, run information campaigns, and promote EU aquaculture products as locally sourced food (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021). In order to assist with achieving the developments discussed here, the European Climate, Infrastructure and Environment Executive Agency (CINEA) is in the process of creating an EU Aquaculture Assistance Mechanism to consolidate relevant information and best practices (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021). A tender was issued in November of 2021 for the development of this tool, so progress is being made towards realizing this resource, but it is not currently available (European Climate, Infrastructure and Environment Executive Agency (CINEA), 2021).

Green Deal

The EU Green Deal was originally presented in 2019 and represents a large set of proposals with the ultimate goal of achieving carbon neutrality in Europe by 2050 (Directorate-General for Communication, 2022). Along with climate, the Green Deal covers major themes such as agriculture, industry, and environment and oceans. This advice report largely focuses on the "environment and oceans" theme, where there are more specific goals such as promoting biodiversity, sustainable food production, and sustainable economic growth of marine industries (Directorate-General for Communication, n.d.). The Green Deal also frames the strategies below including the Farm to Fork Strategy, sustainable blue economy approach, and biodiversity strategy for 2030.

Farm to Fork Strategy

The Farm to Fork Strategy aims to create food systems that are sustainable and healthy. Under this strategy, the designation of "sustainable" implies that a food source has neutral or positive environmental impacts, mitigates climate change, supports biodiversity, and/or ensures access to safe, nutritious food (Directorate-General for Health and Food Safety, n.d.). Under the Farm to Fork Strategy, shellfish aquaculture has the potential to be a poster child of sustainable food production given its capacity to filter water, create habitat, and provide a high-protein food source. Informational campaigns promoting shellfish consumption can point to the Farm to Fork criteria as an indication of the positive environmental effects of shellfish aquaculture. A legislative framework for sustainable food systems (FSFS) is currently being drafted and the goal is for it to be implemented by 2023 (Directorate-General for Health and Food Safety, 2022). This framework would detail measures to facilitate the transition to more sustainable food production including standardizing measures within the EU, incorporating sustainability measures into all food-related policies, and implementing food labeling guidelines to make it easier for consumers to choose healthy and sustainable products (Directorate-General for Health and Food Safety, 2022). This labeling policy could also help the shellfish industry to more clearly indicate the environmental benefits of their products.

Sustainable blue economy

The sustainable blue economy approach within the EU is an action plan for marine industries to work towards Green Deal objectives and also contribute to economic growth. Key topics under this plan include decarbonization, circular economy, biodiversity, climate adaptation, and sustainable food (European Commission, 2021b). To achieve decarbonization, the Commission sets the goal of producing a quarter of the Union's electricity through offshore renewables by 2050 (European Commission, 2021a) (Transforming the EU's Blue Economy for a Sustainable Future, 2021). At present, offshore wind energy is the primary method of offshore renewable energy, but thermal, wave, and tidal energy are also being developed. Marine spatial planning is also emphasized, with a focus on multi-use as a useful method for reducing conflicts between users (Transforming the EU's Blue Economy for a Sustainable Future, 2021). Additionally, the sustainable blue economy approach pledges to promote use of funding for energy efficient ships (European Commission, 2021a). This availability of funding could be an opportunity for shellfish farmers who currently operate onshore to switch to a new boat that is suitable for offshore farming. The European Maritime Fisheries and Aquaculture Fund also supports this policy as an additional funding stream for sustainable marine projects such as offshore aquaculture. These sustainable aquaculture projects ideally foster biodiversity, another priority for the blue economy (European Commission, 2021a). Artificial reefs and seabed habitat restoration are listed as two ways to improve biodiversity as well as solutions for fighting eutrophication. Shellfish aquaculture can act in all of these regards by providing structure through aquaculture gear, supporting wild shellfish bed recovery, and improving water quality through the filter feeding of shellfish. The European Commission pledges in this policy to promote local initiatives that create jobs and help preserve marine resources (Transforming the EU's Blue Economy for a Sustainable Future, 2021). Additionally, another priority is sustainable food production. The communication from the Commission states that aquaculture, and especially low-trophic level, organic aquaculture, is a sustainable source of food that can also contribute valuable environmental impacts. In order to support sustainable food the Commission also sets the intention to create a consistent guideline for labeling of sustainable seafood so that consumers can make informed purchasing decisions. Lastly, the sustainable blue economy communication states that the EU will create a program called InvestEU to connect small businesses with investors to reduce costs and facilitate new innovations entering the market. This financial assistance could be transformative for budding industries like offshore aquaculture and multi-use projects in general, as the costs of working offshore can be prohibitive for small businesses like the family-owned shellfishing businesses in the Netherlands.

Biodiversity strategy for 2030

The EU biodiversity strategy for 2030 lays out a series of goals to protect and restore nature, enable transformative change, and support biodiversity globally (European Commission & Directorate-General for Environment, 2021; Directorate-General for Environment, n.d.). Of these goals, the two that are most relevant to this project are restoring nature and enabling transformative change. The strategy states that restoring marine ecosystems, especially those that serve as nurseries for marine life, is an important step to recovering marine biodiversity. Additionally, there is support for multi-use that allows for both renewable energy and biodiversity restoration (European Commission & Directorate-General for Environment, 2021). Shellfish aquaculture can help support shellfish enhancement efforts, and both aquaculture and reef recovery provide habitat that can help increase biodiversity. The European Commission also lays out tools to support businesses in having a positive impact on biodiversity. There is an online platform as part of the EU Business for Biodiversity initiative with tools and resources in order to increase awareness and facilitate "nature-based solutions" (European Commission

& Directorate-General for Environment, 2021). The Commission also sets the intention to create a classification system of business activities that contribute to biodiversity, and to shape the financial system so that it incentivizes this type of activity. This type of classification could help shellfish farmers to market their brand as supporting biodiversity in order to appeal to environmentally conscious consumers. Lastly, the biodiversity strategy lays out an intention to create a Biodiversity Partnership program to increase communication and flow of information between research, industry, and government (European Commission & Directorate-General for Environment, 2021). This program is now operational under the name "Biodiversa+". The Biodiversa+ website pledges to support capacity building activities as well as promote nature-based solutions in the private sector (Biodiversa+, 2021). Both of these goals would align well with the expansion of shellfish aquaculture into offshore wind farms, so Biodiversa+ could be a helpful ally in this project. In general, the EU biodiversity policy would support shellfish activity within offshore wind farms, and the available resources could help to encourage wind farms to participate in this transition as well.

European Maritime Fisheries and Aquaculture Fund (EMFAF)

The European Maritime Fisheries and Aquaculture Fund (EMFAF) is the renewed version of a previous initiative called the European Maritime Fisheries Fund (EMFF) and is designed to help fulfill the goals set out in the Common Fisheries Policy and the Green Deal (Directorate-General for Maritime Affairs and Fisheries, 2021). EMFF was originally approved to run from 2014-2020 (Directorate-General for Maritime Affairs and Fisheries, 2015) and EMFAF picked up where that fund left off to run from 2021-2027 (Directorate-General for Maritime Affairs and Fisheries, 2021). Like the EMFF, the new EMFAF aims to support sustainable fishing and aquaculture methods and economic development in coastal communities. EMFAF also intends to focus on lowering carbon emissions, protecting biodiversity, producing safe seafood, preserving the economic viability of small-scale fishing, improving skills and working conditions within the seafood sector, and promoting international cooperation towards a sustainable blue economy. The European Commission directly controls 15% of the total budget, while the other 85% is divided between Member States to fund National programs. Within the Netherlands, the Ministry of Agriculture, Nature, and Food Quality is considered the national authority of the EMFAF, while the Netherlands Enterprise Agency (RVO) is in charge of evaluating proposals for EMFAF funding (EMFAF, 2022; Netherlands Enterprise Agency, 2022b). Projects can receive up to 100% funding depending on the extent to which the project will help reach the goals of the EMFAF and Common Fisheries Policy, but full funding is not guaranteed (EMFAF, 2021).

3.4.2 Netherlands policy

National Strategy on Spatial Planning and the Environment (NOVI - Nationale Omgevingsvisie)

The National Strategy on Spatial Planning and the Environment (NOVI) is a national strategy for adapting to climate change and maintaining a good living environment into the future (Ministry of the Interior and Kingdom Relations, 2020). This policy focuses on four broad priorities which are: "Space for climate adaptation and energy transition, sustainable economic growth potential, strong and healthy cities and regions, and future-proof development of rural areas" (Ministry of the Interior and Kingdom Relations, 2020). The combination of environmental and economic concerns across these themes sets the tone for other relevant government documents that were published more recently, including the National Water Program which also contains the North Sea Program (Ministry of Infrastructure and Water Management, Ministry of Agriculture, Nature, and Food Safety, & Ministry of the Interior and Kingdom Relations, 2022; Ministry of Infrastructure and Water Management, Ministry of Agriculture, Nature, and Food Safety, Ministry of Economic Affairs and Climate Policy, et al., 2022). NOVI also sets out a list of 21 matters of national interests, 13 of which are then incorporated into the North Sea Program 2022-2027.

Those interests include:

- Strengthen international relations
- Maintain and develop mobility infrastructure
- Ensure national security and provide space for military activities
- Limiting climate change
- Realization of reliable, affordable and safe energy supply, which will be low in CO2 , by 2050
- Safeguarding the main infrastructure for the transport of substances via pipelines
- Achieving a future-proof, circular economy
- Ensuring flood risk management and climate resilience
- Ensuring good water quality
- Realization and maintenance of high-quality digital connectivity
- Preserving and enhancing cultural heritage and scenic and natural qualities of (inter)national
- importance
- Improving and protecting biodiversity
- Develop sustainable fisheries

National Water Program 2022-2027

The National Water Program 2022-2027 (hereinafter "National Water Program") then takes these national interests into consideration while detailing policies and management strategies to mitigate flood risk and maintain good water quality in the face of climate change (Ministry of Infrastructure and Water Management, Ministry of Agriculture, Nature, and Food Safety, & Ministry of the Interior and

Kingdom Relations, 2022). The National Water Program also acts as the legal basis under which wind farms and multi-use projects are permitted in the North Sea. Included in this policy is the North Sea Program 2022-2027 which is described below.

North Sea Program 2022-2027
The North Sea Program 2022-2027 (hereinafter "North Sea Program") is an appendix to the National Water Program that discusses in more detail the policies and management measures that will apply to this area. The vision put forth for the future of the North Sea is of a system that has improved ecosystem health and continued heavy usage as well as spatial planning that balances energy, food, and nature transitions. In order to achieve this goal, the North Sea Program proposes sustainability changes that can be made to existing industries and work towards a "Sustainable Blue Economy" (Ministry of Infrastructure and Water Management, Ministry of Agriculture, Nature, and Food Safety, Ministry of Economic Affairs and Climate Policy, et al., 2022).

In regards to this project specifically, the North Sea Program states continued support for aquaculture within offshore wind farms, specifically including flat oysters and mussels. Pacific oysters are not mentioned, and emphasis is placed multiple times on use of native species. It is recognized that while Luchterduinen, Princess Amalia, and Egmond aan Zee were opened for passage and shared use as of April 2018, no shared use has taken place. As such, the North Sea Program sets the goal of realizing large-scale experimentation of sustainable offshore food production. Borselle, and Hollandse Kust Noord and Zuid will be the first sites considered for such experimentation, with the intention that positive results could lead to more specific plans for shared use in future wind farms.

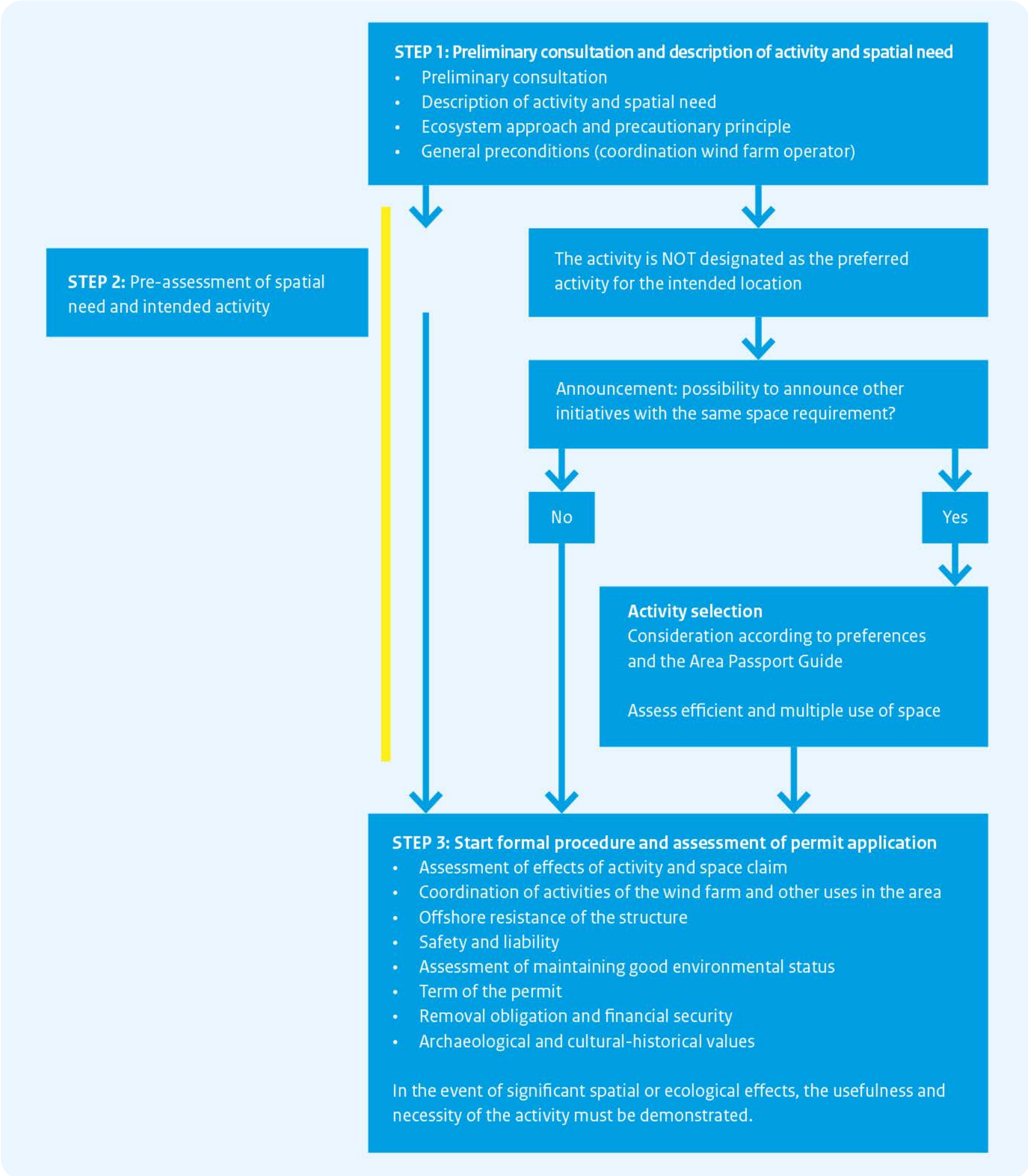


Figure 20. Steps of the assessment framework for multi-use within wind farms in the Dutch North Sea. Taken from the North Sea Program 2022-2027 (Ministry of Infrastructure and Water Management, Ministry of Agriculture, Nature, and Food Safety, Ministry of Economic Affairs and Climate Policy, et al., 2022)

North Sea 2050 Spatial Agenda

The North Sea 2050 Spatial Agenda is a document published in 2014 by the Ministry of Infrastructure and the environment which details a future vision for sustainable use of the North Sea (Ministry of Infrastructure and Environment, 2014; North Sea Counter, 2014). This vision is described in five themes including: "Building with North Sea nature; Energy transition at sea; Multiple use of space; Connection between land and sea; and Accessibility/shipping" (Ministry of Infrastructure and Environment, 2014). Within these themes the North Sea 2050 Spatial Agenda supports multi-use, activities which improve water quality and add hard substrate, contributions from wind farms towards improved biodiversity, and the provision of sustainable food. All of these goals indicate support for the current project of nature-enhancing shellfish aquaculture within wind farms. While the North Sea 2050 Spatial Agenda is more of a goal for the future and less of an explicit policy in itself, this is a promising indication that the National Government supports the project at hand and will continue to do so until at least 2050.

North Sea Agreement

The North Sea Agreement is an agreement between the Dutch national government and stakeholders which establishes priorities and intentions regarding management of the North Sea (North Sea Counter, 2020). The agreement aims to support the nature, energy, and food transitions towards sustainable practices, and to balance the interests of different stakeholders (North Sea Consultation, 2020). As a result, multi-use is supported as a means to accommodate the various stakeholders within the limited space in the Dutch North Sea. Currently, when multi-use is discussed it involves conducting other activities within wind farms. In order to facilitate this type of multi-use, the North Sea Agreement sets the intention to create area passports for each wind farm. The area passport will designate certain areas for certain activities in an attempt to simplify the site selection process for multi-use.

The North Sea Agreement also outlines a few points of common ground on which the various stakeholders agree. One such point is that a transition fund should be set up to support the nature, energy, and food transitions within the North Sea, as funding is needed to support the various industries as they change practices. In particular, the Agreement mentions using transition funds in order to update Dutch fishing boats to more sustainable alternatives (North Sea Consultation, 2020). This funding could potentially also be accessed by shellfish farmers looking to move offshore, as they need to buy boats that are capable of handling the more extreme offshore conditions. In general there are many mentions of transitioning to sustainable fisheries without any mention of how aquaculture would fit into that new system. Whether aquaculture is included in fisheries or not is a point that will need to be clarified moving forward. In addition to a transition fund, the North Sea Agreement also states that adaptive management and continued monitoring of the Dutch North Sea are essential, as there is still a lot that is unknown about how the food and energy transitions will affect natural ecosystems. Finally, the agreement establishes the North Sea Consultation as a permanent body which will dictate the implementation of the North Sea Agreement. Policy agreements such as this one which include strong support for multi-use, blue economy, sustainable food, and nature enhancement indicate theoretical support for shellfish aquaculture multi-use within offshore wind farms. If prospective multi-users can leverage their position at the intersection of these goals, then there may be government funding and support that could be offered to transition offshore.

Water Act
The Water Act (in Dutch: Waterwet) is the Dutch policy under which activities in the North Sea are permitted. This law contains regulations aimed at protecting water quality, limiting flood risks, and maintaining the "fulfillment of social functions by water systems" (Rijkswaterstaat, 2012). Passed in 2009, the Water Act combined eight older laws concerning water management into one policy (Ministry of Infrastructure and Water Management & Directorate-General for Water, 2008; Rijkswaterstaat, 2012). This policy does not contain specific references to offshore aquaculture or multi-use within wind farms, because these topics were not as widely discussed at the time of publication. The most important implications for this project are that Rijkswaterstaat is the permitting authority for activities within the North Sea, and any activities including aquaculture must not negatively impact water quality and safety.

Nature Conservation Act
Those applying for Water Act permits for activities within the North Sea most often also have to apply for a Nature Conservation Act permit from the Ministry of Agriculture, Nature, and Food Quality (Ministry of the Interior and Kingdom Relations, 2021). This act is intended to ensure that activities within the North Sea do not have negative environmental impacts, especially in Natura 2000 areas. In relation to this project, this can include the transport of shellfish larvae into conservation areas which raises concerns over spread of diseases or non-native species.

3.5 Current bottlenecks

With all of the policies mentioned above that support offshore shellfish aquaculture multi-use in different ways, there still is no aquaculture multi-use happening within the Dutch North Sea. To address why this is, this section contains an analysis of what factors are still preventing multi-use. This analysis can then be used in order to identify what steps should be taken to alleviate these bottlenecks and more towards implementation.

One bottleneck that is discouraging shellfish farmers from pursuing offshore aquaculture is that offshore operations would not be profitable under current conditions. Transportation to the offshore site, investment in a boat that is suitable for the rougher conditions, and higher insurance premiums all drive up costs significantly compared to onshore farming (Avdelas et al., 2021; J. de Rooij, personal communication, February 20, 2022). Meanwhile the price of shellfish remains quite low, and the scale of offshore farms is limited by the ecological carrying capacity, limiting potential profits (Avdelas et al., 2021; Smaal & van Duren, 2019). In order to address this bottleneck, interventions to increase profits and decrease costs will need to be taken unless there is a significant innovation or change in business model.

The long and difficult permitting process can also serve as a deterrent for implementation as well as pilot projects or research studies within wind farms.

Prospective multi-users are not able to apply for permits until the wind farm construction is complete and the area passport has been published (North Sea Foundation, personal communication, May 19, 2022). This timeline leads to a significant delay for multi-users and puts them in a position of lower priority as compared to the wind farms. When they apply for the permits, offshore shellfish aquaculture operations will need to obtain a Water Act permit as well as a Nature Conservation Act permit. Nature Conservation Act permits can require applicants to prove that there is no negative impact of their proposed activity. This can be especially difficult for offshore aquaculture given that it is a very new industry and not much research has been published (Rimco Slagter, personal communication, March 30, 2022). As there are a few pilot projects in operation now, more data will likely become available in the next few years, but for now the limited information leads prospective multi-users to need to commission their own environmental studies.

Another issue concerning multi-use is the uncertainty surrounding ownership and responsibility in the wind farm area. Under previous policies, wind farm operators had exclusive rights to the space between wind turbines. Now the government retains the right to lease out the area between turbines to multi-users, but established wind farms still have a lot of influence over what users are allowed to enter for multi-use. This balance of power between government, wind farm operators, and multi-users creates uncertainty regarding who is in charge of coordinating a response in case of emergencies, or deals with maintenance issues. Currently wind farm operators contract out their maintenance to a third party company, but this has not been discussed as a possibility for shellfish farmers. While this would streamline the operations in the area as a whole, using contractors to manage the farm is a major shift in business operations for the shellfish industry. Ultimately the most successful shellfish aquaculture business may function more like a wind farm operator than an onshore shellfish farmer, but these types of companies do not currently exist.

Lastly, there are scientific questions regarding the environmental conditions and impacts that have yet to be answered. In particular, wind turbines and aquaculture gear have been shown to increase turbulence and mixing but the effects of this are not yet known. This mixing can have major impacts on the marine food web, so the impacts are important to determine before launching large scale aquaculture offshore. This can also affect the carrying capacity of the site itself. Carrying capacity is an important factor in determining what scale of aquaculture can be sustainably implemented in a certain area. Developing a tool to effectively define the carrying capacity within a multi-use site would also help for aquaculture producers to calculate their potential yield and more easily determine whether they can earn a profit.

3.6 Summary

This section has shown that many different actors say that they support the idea of offshore shellfish aquaculture multi-use. European and Dutch policies also state this same support, but multi-use is not yet in practice. A main bottleneck preventing implementation is that offshore shellfish aquaculture is not currently profitable, so there is little interest from shellfish farmers. Wind farm operators, as the other party involved in multi-use, are also wary of the increased risk and unclear regulations surrounding multi-use installations. Additionally, of the parties that support multi-use, no single organization is taking the lead in identifying and enacting interventions which could alleviate the current bottlenecks. Identifying the current framework and the areas where there are still issues provides a good starting point for next steps.

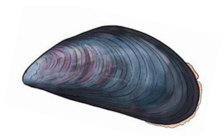
4. Integration

Given the scientific analysis in chapter 2 and the policy analysis in chapter 3, this section integrates these two to provide an overview of problems and opportunities in offshore shellfish aquaculture. Specifically the differences between mussels and flat oysters are laid out clearly in a multiple criteria analysis throughout section 4.1.

4.1 Multiple criteria analysis (MCA)

This multiple criteria analysis compares factors regarding environmental impact, technological readiness, and societal support between blue mussel longline and flat oyster submerged cage longline aquaculture. This comparison helps to show that currently blue mussel aquaculture is a more feasible choice with a higher technology readiness level and availability of seed, and a lower concern regarding disease. Mussel aquaculture and the resulting nature-enhancement would present biodiversity and habitat benefits to the Dutch North Sea, though to a lesser extent than with the flat oyster. Shellfish aquaculture multi-use within wind farms is not ready to be implemented immediately. If flat oyster hatchery techniques can improve to provide a reliable supply of disease-free seed and technology readiness levels for offshore oyster aquaculture continue to improve, then flat oysters would become the optimal multi-use species. There are many more factors than what is included in this table, and aspects like farm design and size can be just as important, if not more important, as the species being cultured. Modeling the effects of a certain farm design on the local carrying capacity and considering any safety risks are necessary steps before multi-use can begin. Once a farm is operational, regular monitoring to evaluate actual environmental effects can help to refine models and inform future shellfish aquaculture multi-use planning.

Table 5. Multiple criteria analysis between blue mussel and European flat oyster aquaculture

Assessment Criteria	Blue mussels 	European flat oysters 
Safety	Medium-low	Medium-low
Food yield	37.5 t/ha/y	3.85 - 40 t/ha/y
Biodiversity impacts (aquaculture)	Medium	Medium-low
Biodiversity impacts (shellfish beds)	Medium	High
Habitat value	Medium	High
Availability of seed	Medium-high	Low
Offshore cultivation technology readiness	6-7/10	5-6/10
Stakeholder support	Medium	Medium
Disease concerns	Low	High

4.1.1 Safety

While neither mussel nor oyster aquaculture is inherently dangerous, there are risks that have yet to be addressed for offshore operation, especially within wind farms. For example, boats could collide with aquaculture gear, wind turbines, cables, or other boats and lead to injuries as well as property damage (van den Burg et al., 2017). Careful equipment maintenance and employee training are two effective measures to increase safety in these regards. In the recent solutions workshop, it was also brought up that further distance from shore makes search and rescue operations harder to conduct, and that the Rijkswaterstaat may be needed for these offshore searches (North Sea Foundation, personal communication, May 19, 2022). Due to the inherent risks involved in working offshore, it is essential that aquaculture and wind farm operators work together to create risk management and emergency action plans. These plans could also be further refined during pilot projects, as issues may present themselves at a smaller scale which can then be addressed before scaling up to commercial multi-use projects. Comparatively mussel and oyster aquaculture present similar safety risks as the primary concerns come from sharing space with the wind farm and the offshore location. At present oyster aquaculture has slightly higher safety risks as the UNITED pilot reports issues with oyster baskets dislodging from the longline system (Strothotte et al., 2022). This issue is required to be resolved before oyster aquaculture can take place within wind farms, so implementation will not take place until this safety concern is resolved.

4.1.2 Food yield

In the Netherlands, mussels are primarily cultured on the seafloor. As a result, there are not a lot of studies that show the yield for longline mussels grown in the Dutch North Sea. A 2017 study, however, created a model based on Borssele wind farm environmental conditions and Wadden Sea mussel seed availability (van den Burg et al., 2017). This model concluded that a longline farm in Borssele wind farm would produce approximately 37.5 tons of edible market size mussels per hectare per year (t/ha/y) (van den Burg et al., 2017). To provide some context, estimates for productivity of longline mussel farms in the western Baltic Sea include 40.96-94.15 t/ha/y in Denmark (Bergström et al., 2020; Taylor et al., 2019), and 1-51 t/ha/y (Buer et al., 2020) in Germany. While these estimates represent a wide range, it shows that van den Burg et al.'s model yielded a reasonable production level for a longline mussel farm.

The total yield of oysters was calculated starting with the estimate that 50-100 kg/ha of 5-6 mm spat are used for bottom culture (Towers, 2010). While this is a different cultivation technique, it was the only estimate that was available, as flat oysters are not widely cultivated at present. Then the following equation was used from a recent study: Wet weight (g) = $0.1013 \times X^{3.2693}$, where X is the size of the oyster in centemeters (Nielsen & Petersen, 2019). Using this formula with a starting spat size of 0.5 - 0.6 cm gives a wet weight of 0.01-0.02 g for each oyster spat. Adults are estimated to weigh approximately 80 g at harvest (Kamermans et al., 2020; Nielsen & Petersen, 2019) which represents a growth of 4000-8000 times their original weight. So when the starting weight of 50-100 kg of spat is multiplied by 4000-8000 which is the amount those spat are expected to grow, that gives a yield range of 200-800 t/ha/y. Adults are typically harvested after 3 years, at which point Towers (2010) gives a survival rate of approximately 5%. Factoring in survival rate brings the final estimate to a net annual yield of 10-40 t/ha. Additionally, a paper describing yields in France gave estimates of 3.85, 4.78, and 8.04 t/ha/y for different bays and estuaries (Buestel et al., 2009). These additional data points indicate that the calculations made above may be a high estimate, but not unreasonable. Combining the earlier calculation with these estimates gives a range of 3.85 - 40 t/ha/y.

These food production levels indicate that there is not a significant difference between yield from blue mussels and yield from European flat oysters. The fact that production rates on Danish farms can be more than double the estimate for the Netherlands from van den Burg et al. (2017) indicates that there is potential for higher yields with mussels, but this would need to be tested to confirm.

4.1.3 Habitat Value and Biodiversity

Preliminary results from a recent study by Sheehan et al. (2019) indicate that mussel longlines act as fish aggregation devices, increasing the density and diversity of fish around mussel farms. Additionally, when mussels fall off of longline ropes, they increase the structural complexity of the seafloor, thereby acting as a shelter and food source for other benthic organisms such as crabs and lobster (Mascorda Cabre et al., 2021; Sheehan et al., 2019). Fall-off serves as a natural method through which aquaculture increases the local habitat value by increasing the complexity and diversity of the surrounding environment. As a result, nature enhancement through shellfish reef formation is essentially built into mussel aquaculture by default. Oyster aquaculture gear similarly adds hard substrate and structural complexity that otherwise would not exist in a sandy bottom area (Tallman & Forrester, 2007). Fish communities around oyster cages have been shown to have equal or higher biodiversity compared to those associated with artificial reef structures. The cage technique used for growing oysters improves pelagic diversity, but it does not inherently contribute to benthic habitat formation like mussel longline aquaculture does because oysters are contained inside the cages rather than exposed to the open water. In this sense, wild population enhancement is essential for maximum added habitat value from oyster aquaculture.

In terms of the shellfish beds that would hopefully be supported by these aquaculture farms, flat oyster beds have been shown to have higher species diversity and richness than mussel beds (Markert et al., 2009). This difference is likely due to the increased structural complexity of oyster reefs as compared to mussel beds. Oysters orient themselves more vertically and thus create taller structures than the more horizontally oriented mussels (Markert et al., 2009). Additionally, European flat oysters reefs have been shown to have increased structural complexity, as well as the resulting higher species richness, when compared to Pacific oyster reefs (Guy et al., 2018). Another factor that may contribute to higher diversity among oyster reefs is the permanent configuration of these reefs as compared to mussel beds. Mussels are able to attach and detach themselves using their byssus threads, where oysters settle once and remain in that place (Guy et al., 2018). A more stable structure allows organisms to settle over time and create a rich habitat within the oyster reef. Fortunately, oysters have been found to be able to settle on mussel shells and vice versa, so any type of shell substrate can facilitate shellfish reef formation of one or both species (Markert et al., 2009)

4.1.4 Availability of seed

Limited availability of flat oyster seed could prove to be a limiting factor for expansion of flat oyster aquaculture and the resulting nature enhancement (Colsoul et al., 2021). Throughout the EU there are restrictions preventing the import of seed, adult oysters, or even shells from countries where the Bonamia parasite (see disease concerns) has been found, in an attempt to prevent the spread of Bonamia to uninfected areas (Sas et al., 2020). The Dutch North Sea is generally considered to be an infected area, although previous restoration projects have still used Bonamia-free oysters in order to increase the odds of survival (Sas et al., 2020; The Rich North Sea, n.d.). Putting restrictions on where flat oysters can be sourced from further limits the possibilities of obtaining enough seed to support both aquaculture and restoration. Within the Netherlands, there is a group of experts researching hatchery methods called Flat Oyster Breading and Research Netherlands (KOPON) (The Rich North Sea, n.d.). Advances in local flat oyster hatcheries could help solve the shortage of seed while providing Bonamia-free oysters and reducing the risk of importing novel diseases from other areas. While hatchery techniques are still being optimized in the Netherlands, there are companies abroad that have shown promising reliability. Orkney Hatchery in Scotland has said that they are confident that they will be able to scale up hatchery production, going from 10 million spat this year to 150 million in the next few years (O. Wynn-Jones, personal communication, April 12, 2022). Their goal is to produce sufficient supply to support commercial operations. More hatcheries will need to follow suit in order to produce enough for large scale aquaculture plus restoration and research projects throughout Europe, but progress is being made.

Mussel seed in Europe has long been obtained from wild beds using bottom dredging techniques (Capelle, 2017). This method leads to disturbance of the sea floor which is bad for natural shellfish bed formation as well as development of other benthic fauna. As a result, in recent years there has been a shift towards mussel seed capture devices (MZIs based on the Dutch term "mosselzaadinvanginstallaties") with the goal of eventually phasing out bottom seed fishing (Schouten, 2020). These MZIs have proven effective, but this technique still leaves the mussel industry vulnerable to natural fluctuations in seed availability (Ministry of Agriculture, Nature, and Food Safety, 2020). Hatchery techniques are also available, but not as commonly used in the Netherlands at present (Kamermans, 2008). The possibility of upscaling hatchery operations would allow for a more stable supply of mussel seed in the future, especially in the case of offshore aquaculture expansion. For the time being, MZIs provide a fairly reliable yield, but fluctuations will become more of a problem as the industry expands.

4.1.5 Offshore cultivation technology readiness

Blue mussel offshore longline aquaculture in the Dutch North Sea has a technology readiness level (TRL) between 6 and 7. As figure 21 shows, a TRL between 6 and 7 indicates that the technology has been demonstrated in a relevant environment, but a prototype has not yet been tested in the intended operational environment (TWI Ltd, 2020). Blue mussel longline aquaculture has been successfully implemented by Offshore Shellfish Ltd in Lyme Bay off the coast of southern England. This represents a successful demonstration of the technology, but the intended operational environment for this project is wind farms in the Dutch North Sea. These wind farms have more dynamic conditions as well as additional logistical and safety concerns compared to Lyme Bay. Another example of mussel longline aquaculture in offshore wind farms is the UNITED pilot in the northern German North Sea which has determined the TRL for their project to be 5 (Strothotte et al., 2022). The Dutch North Sea where this project is focused has comparatively milder environmental conditions, particularly because the German

UNITED site is quite far offshore (45 nautical miles or 80 kilometers) (FINO3, 2019). Therefore the TRL of offshore mussel cultivation in the Dutch North Sea has been determined to be at least a 6. Therefore, based on figure 21, mussel aquaculture is at the end of the development stage and beginning deployment trials.

Flat oyster offshore longline aquaculture using SEAPA cages (see section 2.2.2 on off-bottom oyster cultivation methods) has a TRL of 5-6. As of 2020, the Belgian UNITED pilot, which is testing methods for flat oyster aquaculture and restoration within offshore wind farms, placed the TRL at 5 which indicates it is "validated in [a] relevant environment" (Serafy et al., 2020; TWI Ltd, 2020). Since then, oyster longlines have been installed and operational in a nearshore area, but offshore attempts have encountered issues (Strothotte et al., 2022). The primary issue has been loss of baskets due to the harsh conditions, which represents a loss of product as well as a safety hazard. Once these issues are solved then this technology will be at TRL 6, and the ultimate goal of the UNITED project is to reach TRL 7 by the end of the project (Strothotte et al., 2022). In summary, flat oyster aquaculture is still currently in the development stage slightly behind the stage of mussel aquaculture, and has the goal of reaching deployment in the next few years.

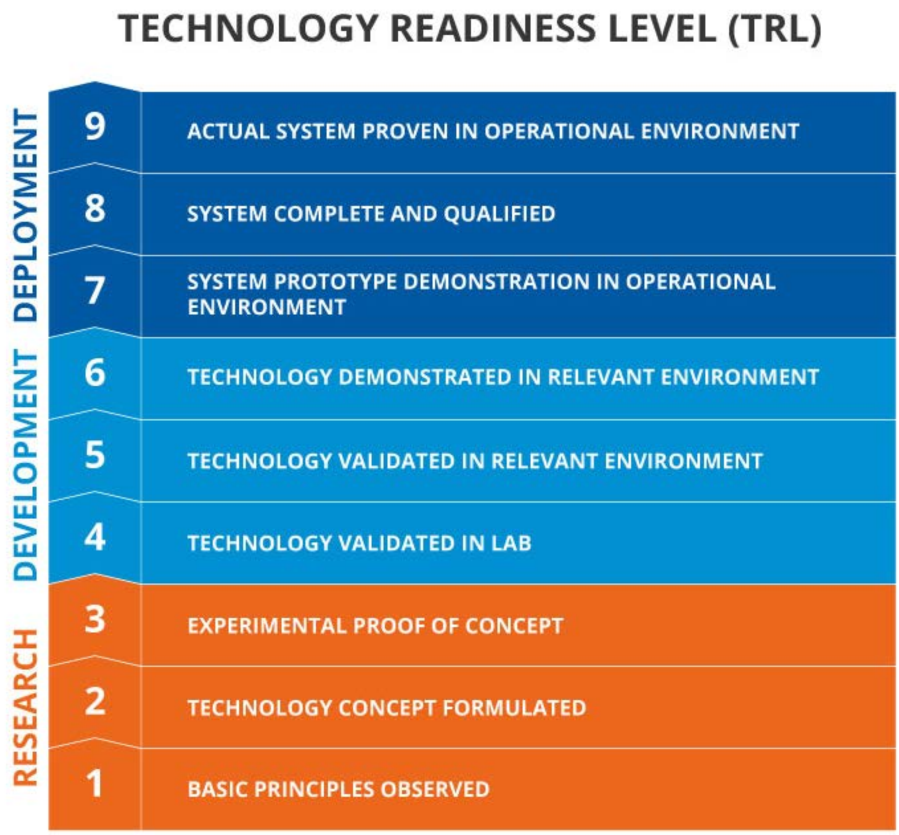


Figure 21. Technology Readiness Level scale (TWI Ltd, 2020)

4.1.6 Stakeholder support

Stakeholder support is a complex criteria to quantify. Both mussel and oyster aquaculture in offshore wind farms involve stakeholders who are interested in food production, nature enhancement, and marine spatial planning in addition to shellfish farmers who are interested in the business case of offshore aquaculture. In terms of food production, earlier calculations have shown that food yields could be roughly similar, but that exact numbers require calculations based on the specific site in use. Therefore, government officials interested in increasing food production would view mussels and oysters equally. Marine spatial planning officials are also satisfied, as any multi-use helps to alleviate the need for space within the North Sea.

Where the two types of aquaculture differ is in terms of nature enhancement and business case. There is a lot of support from the national government, the EU, and nature NGOs for European flat oyster restoration or enhancement projects. As mentioned previously, flat oysters are a native species that has declined greatly around the 1970s and 80s due to overfishing and the introduction of Bonamiosis. A lot of effort from multiple stakeholders is being put into recovering their population levels, regaining the ecosystem services provided by flat oyster reefs, and growing oysters as a sustainable source of food. That being said, there are farmers who grow flat oysters, but only in combination with Pacific oysters. As a result, there is limited support from oyster growers because offshore flat oyster farming would be a significant departure from their current business model. Mussels farmers on the other hand have experience with mussels and the technology of offshore longlines is well developed and tested. There is still some resistance to moving into wind farms given the extra logistical and administrative complications, but they are closer to being able to make this transition than oyster farmers are. While farmers may be more ready to make the transition, there is less support from government and NGOs as mussels are seen only as a food source and not as a conservation priority. In the end there is a similar level of stakeholder support between offshore mussel and flat oyster aquaculture, as they each have their strengths and weaknesses. Knowing which stakeholders are already on board can help know who to turn to for support and who still needs to be convinced in order for the project to move forward.

4.1.7 Disease concerns

Mussels are affected by predators, but not as much by disease/parasites, although there are illnesses/infections that can occur (Brenner, 2019; Thieltges, 2006). That being said, there are still regulations in the EU to control the movement of live shellfish in order to avoid inadvertently introducing novel diseases or parasites into other areas (Kamermans et al., 2020). These regulations are in place primarily to control the threat that diseases pose to flat oyster restoration efforts. In flat oysters, the primary disease concern is the parasite *Bonamia ostreae* which causes the disease Bonamiosis (Sas et al., 2020; Vera et al., 2019).

Bonamiosis attacks the immune system which leads to inflammation and high mortality rates (da Silva et al., 2005; Engelsma et al., 2010; Sas et al., 2020; The Rich North Sea, n.d.). Along with overfishing, Bonamiosis is often cited as one of the main causes of flat oyster population decline in the 1970s and 80s as well as the lack of recovery over time (Centro Tecnológico del Mar - Fundación CETMAR, 2015; Engelsma et al., 2010). Bonamiosis has not been observed in blue mussels, and they have also been shown not to be vectors of the disease (Culloty et al., 2004; Figueras & Fernández Robledo, 1994). The prevalence of lethal diseases in flat oysters makes them a more difficult species to cultivate both scientifically and legally, so in terms of this criteria blue mussels would be the preferred species for offshore multi-use aquaculture.

5. Advice

This chapter contains the final advice. The advice is broken down into two sections, first describing the offshore shellfish aquaculture methods that have been identified as the most sustainable and nature-enhancing. While not included in this study, a full life cycle analysis including the environmental impacts of materials manufacturing, production, and distribution should be addressed in the future. The techniques suggested in section 5.1 address the ways that shellfish aquaculture can be most sustainable, but a life cycle analysis would help compare the sustainability of offshore farmed shellfish versus other potential protein sources. Then section 5.2 describes interventions that can be used in order to implement offshore shellfish aquaculture multi-use.

5.1 Sustainable offshore aquaculture techniques

Throughout this project, the goal was to identify shellfish aquaculture methods that are sustainable, safe, and nature-enhancing and can be implemented within offshore wind farms.

The North Sea Foundation definition of sustainable aquaculture includes:

- It has no significant negative impact on the ecosystem
- It does not negatively affect the water quality
- It respects the space for nature
- It only uses sustainable procured source materials
- It is operationally safe
- It is produced by companies with a demonstrable sustainability policy
- It complies with legal regulations and licensing requirements
- It is accepted among all stakeholders
- It fits within the possibilities of the area passport

These criteria will be used below to formulate recommendations for sustainable methods. While these suggestions can help to make aquaculture more sustainable, many of them also make the aquaculture less profitable. Before implementation the additional costs of these measures would need to be addressed.

5.1.1 Species choice

The optimal shellfish species for maximizing nature enhancement potential of aquaculture are the European flat oyster and the blue mussel. These two are reef forming species which maximizes habitat value and resulting biodiversity increase. Additionally, both are native, which avoids any potential negative impacts of invasive species such as the Pacific oyster. Based on the multiple criteria analysis in section 4.1 above, blue mussels aquaculture has a higher TRL and is more likely to be ready to farm offshore in the near future. In natural reefs, however, flat oysters provide more complex and permanent reef structures making their restoration important for the biodiversity of the Dutch North Sea. Additionally, their wide historical distribution suggests that they have potential for successful nature-enhancement. While each species has its strengths and weaknesses, it is important to continue using both within the greater aquaculture industry. This diversity can help prevent novel diseases that affect a single species, such as the impact of *Bonamia* on flat oysters in the 1970s. Furthermore, in the case of a decline in one species, the other can continue to act as a native reef-builder and provide some amount of hard substrate. It is also essential that the shellfish used in aquaculture are diploid. A key way that shellfish aquaculture can be nature-enhancing is to serve as a natural larval supplement to recovering shellfish reefs. Sterile triploid and tetraploid shellfish have been bred because they can be harvested year-round, but this negates a large part of their capacity to create habitat and foster biodiversity.

5.1.2 Farm placement

In order for shellfish aquaculture to best facilitate the formation of shellfish reefs throughout the Dutch North Sea, it would be optimal to create a network of multiple aquaculture farms and reef restoration sites. Larvae from aquaculture farms have been demonstrated to settle outside of the aquaculture area and act as a larval subsidy for recovering reefs (Norrie et al., 2020). As discussed in section 2.3.1, Spatfall and Connectivity, models have indicated that larvae released from within wind farm sites would generally drift northeast following the coastline of the Netherlands (Smaal et al., 2017). Some larvae stay within the windfarm and many settle outside. To maximize the effect of the larvae released by the diploid shellfish within the multi-use aquaculture farms, it would be ideal to place restoration sites and/or seed capture installations in the areas with maximum predicted spatfall. This arrangement could also be taken into account when formatting the area passports by placing designated aquaculture plots upstream of areas that are designated for nature development.

5.1.3 Harvesting schedule

Shellfish should not be harvested all at once in order to provide more consistent ecosystem services on a farm level. One way shellfish aquaculture contributes to nature enhancement is by creating habitat and foraging ground for mobile marine organisms, thereby increasing biodiversity (see section 2.3). More mature aquaculture installations are better able to provide these ecosystem services as the shellfish are larger and the associated sessile organisms are more established. As a result, if an entire shellfish farm is harvested at the same time, then the ecosystem services developed over time would be lost. By maintaining different age classes throughout the farm, there will consistently be some more mature lines or cages providing structural complexity and supporting local biodiversity. While better for nature enhancement, harvesting more frequently will likely increase transportation costs for aquaculture businesses. Combining harvesting with maintenance of existing lines or installation of new lines during the same trip would help to mitigate this increase.

5.1.4 Carrying capacity

To follow the NSF sustainability criteria "it has no significant negative impact on the ecosystem [and] it respects the space for nature", the scale of aquaculture farms must remain below the ecosystem carrying capacity. As mentioned above in section 2.3, carrying capacity is the amount of use that an ecosystem can withstand before major changes occur. In this case, shellfish aquaculture is the use in question, and shellfish reef restoration and other nearby filter-feeding organisms must also be taken into account. The carrying capacity of each site allows for a certain amount of shellfish in the area before it causes major changes to the planktonic community, affecting the rest of the marine food chain. When designing nature-enhancing aquaculture farms, it is essential that the scale of the farm should be small enough that it does not exceed the carrying capacity. Additionally, because the aim is to contribute to reef recovery efforts, the extent of aquaculture farms should be well below the carrying capacity in order to allow for an increase in wild shellfish population levels. There are existing models such as the Farm Aquaculture Resource Management (FARM) and Sustainable Mariculture (SMILE) models which can help estimate production and changes to environmental conditions such as chlorophyll a concentration and dissolved oxygen (Ferreira, Joao G., 2006). Similar models should be calibrated for the Dutch North Sea area in order to estimate carrying capacity and produce the most accurate predictions for environmental impacts of shellfish aquaculture farms. Based on the calculated carrying capacity, the North Sea Foundation can make recommendations for the maximum extent of offshore aquaculture allowed in a certain area.

5.1.5 Sustainable seed

Another of NSF's criteria for sustainability is that the aquaculture only uses sustainably sourced materials. In relation to sourcing materials, the most important consideration is the source of the shellfish seed that is used. As mentioned in section 4.1.4, the traditional method of trawling for seed is destructive to benthic habitats and should be avoided in order to maximize the net nature enhancement impact. Alternatively, the mussel industry has developed mussel seed capture installations or MZIs to sustainably catch seed from the water column and avoid disturbing the sea floor. Another option for sustainable seed production is hatcheries. Blue mussel seed is not currently sourced from hatcheries, but this is a viable method for increasing seed supply without damaging wild populations. Hatcheries have also been working on producing flat oyster seed, but are not currently capable of reliably producing sufficient quantities for large scale aquaculture. Suggestions for facilitating advancement in hatchery techniques are discussed below in section 5.2.4.

5.1.6 Future research

In order to assure that shellfish aquaculture can meet all of NSF's sustainability criteria, additional research is needed to ensure no negative ecosystem impacts and no negative effects on water quality. One topic that requires further research is the behavior of birds around shellfish farms. Multiple studies have shown that birds tend to perch on mussel buoys and feed on the mussels as well as epibionts attached to longlines (Mascorda Cabre et al., 2021; Roycroft et al., 2007). While the addition of a food source for birds could potentially be a positive ecological effect, there is also increased risk of collisions involved with attracting birds to wind farms (van den Burg et al., 2020). Due to the lack of prior multi-use projects, there is no prior research on this topic. Therefore, in order to ensure that there is no negative ecological impact from installing aquaculture within wind farms, more research should be conducted regarding the potential effects on birds. Another topic that needs more research is the hydrodynamic changes that are induced by aquaculture farms (see section 2.3). Changes to hydrodynamic forces can impact the availability of nutrients through the resuspension and transport of shellfish biodeposits (Mascorda Cabre et al., 2021). Availability of nutrients then influences plankton growth and community composition which can have wide ranging ecological effects (Mascorda Cabre et al., 2021). The impact on hydrodynamics is different for each farm based on site environmental conditions and farm layout, and knowledge of the implications of those changes is limited. Further study is needed to determine what changes are considered "negative" and how that can be formulated into a guideline to ensure that future farms are constructed with no negative impacts. Pilot projects can be useful opportunities for conducting these studies and observing changes over time within a single site.

As additional information on the ecological impacts of offshore shellfish aquaculture becomes available, guidelines for farm construction and operation should remain adaptable and incorporate that new information. There are still a lot of unknowns in regards to the long term effects of adding aquaculture farms within offshore wind farms (see section 2.3). Following the precautionary principle, implementation should be slow in order to ensure no negative effects before scaling up throughout the Dutch North Sea. Therefore, a progression of research, pilot projects, and implementation trials should be decided on between stakeholders in order to determine the pace of implementation and facilitate progress.

5.2 Interventions to facilitate shellfish aquaculture multi-use

5.2.1 Including multi-use earlier in wind farm planning

One of the primary barriers to any multi-use within offshore wind farms is the long and complicated procedure through which wind farm sites are chosen, designed, and ultimately opened for multi-use. Currently, wind farms must be fully constructed and have a published area passport before multi-users are allowed to apply for a permit. From that point there is then a long review process which typically also requires an environmental impact assessment and negotiations with the wind farm operator about how the space will be managed. Designing and building wind farms first before considering multi-use puts wind farm operators in a position of power, as the area is being designed to their needs and specifications. If the goal of the national government is to truly integrate multi-use within wind farms, then **multi-users should be considered during the placement and tendering processes of wind farms** rather than merely as an afterthought. One way to build multi-use into the design phase would be to require demonstrated plans for multi-use during the tender process for wind farms. Currently, tenders look for wind farm operators to be *open* to multi-use. Asking for them to describe how their design and management plans will facilitate multi-use and using that as an assessment criteria when awarding the permit would push wind farm operators to take a more active role in implementing multi-use. This seemingly small adjustment would also set the expectation from the beginning that this space does not belong to the wind farm operators, but rather is designated as a shared space. Alternatively, the government could take a more active role in facilitating negotiations between multi-users and wind farms during the permit application process. The North Sea Foundation can use their connections with various government ministries to advocate for more active support for multi-use within the tendering and permitting processes. At a minimum, NSF should ask that area passports for wind farms be published before construction begins so that multi-users can begin the application process at the beginning of the wind farm construction rather than at the end. Ideally, multi-use would be considered when deciding on the exact location of the wind farm in order to best integrate multi-users from the beginning stages. Additionally, NSF can help to facilitate conversations between prospective multi-users, wind farm operators, and relevant government ministries in order to help determine the best way to include multi-use during the tendering of wind farm sites, and how to evaluate the multi-use plans that would then be included in the subsequent bids.

5.2.3 Pilot projects

Considering the current technical knowledge, legal framework, and costs associated with offshore shellfish aquaculture, more pilot projects are needed to improve technology and profitability before this type of project can safely and efficiently be implemented at a large scale. There are a few pilots running right now looking at oyster restoration, such as those of the Rich North Sea, but these projects do not directly address conditions or technology related to aquaculture (The Rich North Sea, 2021b). The Belgian UNITED project (discussed above in section 4.2. Offshore cultivation technology readiness) is one ongoing pilot project that includes flat oyster cultivation as well as restoration within offshore wind farms (Strothotte et al., 2022). In contrast to flat oyster pilot projects, current offshore blue mussel pilots typically focus on aquaculture rather than nature enhancement. Examples include the UNITED Germany pilot which is using typical longline techniques, and the OOS Semi-submersible Mussel Farm (SMF) which is combining longline techniques with semi-submersible platform design that has previously been used for offshore machinery and accommodation units (OOS

International, 2021; Strothotte et al., 2022). More information will continue to be published about their results, but more research will likely still be needed regarding implementation in the Dutch North Sea.

A major decision that needs to be made before starting a pilot project is who is going to organize and fund the project. This factor presents a roadblock in the Netherlands currently, as there has been a lack of initiative being taken to advance the implementation of offshore shellfish aquaculture, particularly within wind farms. As a result, one intervention that could be taken would be for a non-profit such as The North Sea Foundation to act as the driving force behind such a pilot project. A similar project is currently being undertaken by the North Sea Farmers who are working to formulate successful methods and a profitable business case for offshore seaweed cultivation. Government funding would likely be accessible for such a project as many EU as well as Dutch national policies state support for sustainable aquaculture, food production, and multi-use, especially offshore (see section 3.4 Current policy concerning multi-use). Some of those policies also have associated funds specifically to advance methods for sustainable multi-use, food production, and aquaculture such as the European Maritime Fisheries and Aquaculture Fund (EMFAF) and the North Sea Agreement transition fund.

Table 6. Relevant pilot projects currently underway

Name of Organization	Description	Year Started
UNITED Belgium	Developing techniques for offshore flat oyster aquaculture and restoration	2020
UNITED Germany	Developing techniques for offshore mussel cultivation	2020
Rich North Sea	Flat oyster restoration projects within offshore wind farms	Various
OOS	Semi-submersible mussel farm platform as an alternative method for offshore mussel aquaculture	2022

5.2.4 Socioeconomic/business case factors

Another factor that needs to be addressed before offshore shellfish aquaculture can be realized within wind farms is that there is currently no clear business case or financial benefit to multi-use. Without a business case, there is no interest from shellfish growers or wind farm operators in implementing this type of project (van den Burg et al., 2017). This issue relates back to the same basic problem mentioned above in section 5.2.3 Pilot projects - that there is currently no actor that is taking the lead and moving the project forward. In order to solve this problem, interventions are needed to develop a business case for shellfish aquaculture multi-use within wind farms. One way to do so would be to identify ways that wind farms and shellfish farms could share costs. The most likely area where multi-use could lead to cost reductions would be in operations and maintenance (van den Burg et al., 2017). Currently, when the idea of growing shellfish within wind farms is discussed, businesses that already grow shellfish onshore are consulted. These businesses do the work of maintaining and harvesting the farms themselves using smaller boats and low overhead costs. Moving offshore would represent a sizable change in business model, requiring a large capital investment for a larger boat that is suitable for offshore operations and high costs due to transportation and higher insurance premiums. Within these discussions, however, it is still assumed that shellfish growers would maintain and harvest the offshore farms themselves. If shellfish growers contracted out the maintenance and harvesting then there would be a greater possibility of hiring a multi-purpose maintenance team who could attend to both the wind farm and the shellfish farm (van den Burg et al., 2017). This multi-purpose team would reduce transportation costs including fuel costs, boat personnel salaries, and costs of maintenance staff wages during their time in transit. The North Sea Foundation can use its position as a third party with experience and connections to help facilitate conversations between wind farm operators and potential shellfish aquaculture businesses. It is also possible that the conversation will need to be reframed to include new shellfish companies focused more on facilitation rather than those that are rooted in their traditional, onshore farming methods. As an organization with a lot of experience in the offshore wind sector, the North Sea Foundation would be a valuable facilitator and could contribute new ideas and outlooks to the conversation on how multi-use can be accomplished.

Alternatively, if cutting costs through sharing resources is not an attractive option for these companies, then an incentive structure could be established by the government. One way to provide financial incentives to both wind farm and shellfish farm operators would be to subsidize sustainable food production within offshore wind farms. A number of national and international policies express support for sustainable food production including the EU Farm to Fork, Sustainable blue economy, and Common Fisheries policies as well as the Dutch North Sea Agreement and North Sea Program (see section 3.4 Current policy concerning multi-use). These policies can thus be leveraged to ask the national government to provide a subsidy to shellfish farmers and wind farm operators that is tied to the amount of food produced within the wind farm that meets set sustainability standards. This kind of subsidy would help to make offshore shellfish farming profitable which would encourage new entrants to the market. Increased competition would then likely lead to innovations, and reduce or eliminate dependence on subsidies. Additionally, providing incentives to wind farm operators that are tied to food production will encourage them to help facilitate multi-use rather than fighting it.

Financial support for continued hatcheries research is also essential for implementing large scale multi-use projects. As described in section 4.1.4, there is a significant lack of flat oyster seed, and an unreliable supply of blue mussel seed which would limit implementation of large scale offshore aquaculture. Additionally, due to the limited supply, it is currently prohibitively expensive for many farmers to use hatchery seed (Avdelas et al., 2021). In regard to flat oysters, if hatcheries are able to refine breeding methods so that there is a large and reliable quantity of seed, then the cost of farming them will go down, encouraging more companies to grow them both on and offshore. This increased cultivation would help to produce more sustainable food, and also to increase the population density of flat oysters within the North Sea. With more flat oysters in a given area, they will reproduce and facilitate restoration efforts through larval supplementation (see Spatfall and Connectivity). In regard to mussels, natural seed is more abundant and can be easily obtained with suspended seed capture devices. The amount of seed that is currently harvested from the North Sea, however, cannot support a significant expansion in the mussel industry if farms were to be developed offshore. As the mussel industry grows, use of hatcheries for mussel seed should be encouraged, and one way to do that would be to provide funding to kickstart mussel hatchery programs.

5.2.5 Informational Campaign

Another way to increase the odds of implementing offshore shellfish aquaculture within wind farms is to increase public awareness of the nature enhancement potential and ecosystem services of shellfish. For most people, shellfish are out of sight and out of mind. They are not the most charismatic creatures in the sea, so they don't automatically garner much attention. Due to the range of ecosystem services provided by shellfish, however, increased public awareness can often mean increased public support (Brumbaugh et al., 2006). With increased public support comes volunteers, funding, and increased political pressure to act. Marketing shellfish as a sustainable food choice can also increase the demand for shellfish which would help to motivate shellfish producers into expanding offshore. This can be done through awareness campaigns as well as clearer labeling regarding the environmental impact of certain foods.

Increased awareness would also help aquaculture businesses to differentiate themselves from fisheries, and further, for shellfish aquaculture to differentiate themselves from finfish aquaculture. While fisheries and aquaculture are both seafood industries, they have very different methods and different needs. They are currently combined into one for the purposes of policy discussions, and then the needs of cutter fisheries are met and aquaculture businesses tend to be forgotten about. For example, as mentioned in section 3.3.2, within the North Sea Consultation, fisheries and aquaculture are grouped together into a sector labeled "food and fisheries", but all of the representatives for this topic are from the fisheries sector (North Sea Consultation, 2021). As a result, it is difficult for aquaculture businesses to advocate for themselves through this governing body. Within aquaculture it is also important to differentiate between shellfish aquaculture and finfish aquaculture. Finfish aquaculture generates nutrient and chemical pollution, and requires fish feed that is often unsustainable (Carballeira Braña et al., 2021). As a result, grouping shellfish together with finfish aquaculture contributes to the public perception that shellfish aquaculture is also an unsustainable industry. Government recognition of the ecosystem services of shellfish aquaculture would therefore help increase the visibility of the shellfish industry and frame it in a positive light. Grouping shellfish and finfish aquaculture together also leads to a lack of guidelines for the shellfish industry. For example, the EU strategic guidelines for sustainable aquaculture discuss sustainability in terms of reducing the number of escaped fish, documenting chemicals used, or using sustainable feed which are all relevant to finfish but not shellfish (European Commission & Directorate-General for Maritime Affairs and Fisheries, 2021). No information or regulations are given for how shellfish farms should determine the local carrying capacity and what that means for their stocking density, or how to limit the spread of shellfish diseases. Even though shellfish aquaculture is largely seen as a sustainable industry, there are still guidelines that need to be followed in order for that to remain true. In response to the lack of official sustainability guidelines for shellfish aquaculture, the North Sea Foundation can formulate ideal guidelines based on their criteria for sustainability (see section 1.3.1). It is essential that these types of regulations are in place before scaling up offshore aquaculture in order to ensure that these operations meet the North Sea Foundations goals of sustainability and nature enhancement.

5.3 Suggested next steps

The top priorities for the North Sea Foundation should be working on streamlining the multi-use process and promoting continuing research and pilot projects to determine the viability of offshore nature-enhancing shellfish aquaculture. Regardless of the fate of offshore shellfish aquaculture, NSF wants to ensure that space for nature is established within wind park areas. Therefore, facilitating multi-use in general is essential. The primary policy intervention in this case is to advocate for multi-use to be considered during the design process of wind farms in order to create spaces that are optimized for multi-use, not just theoretically available for it. As a result of this earlier consideration, NSF should also push for area passports to be published at the start of the construction phase, rather than at the end, in order to give multi-users more time to apply for and obtain the required permits.

While advocating for these more proactive wind farm multi-use procedures, NSF should also ensure that research is being done to determine if offshore shellfish aquaculture can be sustainable and economically viable. NSF does not do this type of scientific research themselves, so they should utilize their connections in knowledge institutes to find a suitable research partner who can complete that project. To take a more active role in that research, NSF can act as a partner, helping to secure funding and providing input on the direction of the research. In terms of research topics, the connecting factor between a lot of unanswered questions regarding both ecological and business viability of offshore shellfish aquaculture is carrying capacity. NSF has stated that not exceeding the ecosystem carrying capacity is of utmost importance to them. As a result, accurately determining the carrying capacity before large farms are installed is essential. Determining carrying capacity also includes accounting for the effects of recovering shellfish beds, and the impact of hydrodynamic changes created by aquaculture gear. It is highly possible that the carrying capacity, when accounting for these factors, will be too low for aquaculture companies to make a profit from offshore production while remaining sustainable. If that is the case, then NSF must decide how much time and effort they feel is reasonable to spend on interventions to improve the business case of sustainable offshore shellfish aquaculture. There may be benefits to facilitating this type of food production, but these should be weighed against other projects that NSF could be focusing on instead. If a business case is established for offshore shellfish aquaculture, then NSF should publish their suggestions for best practices and lobby for these practices to be formalized in policy.

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Stichting
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The North Sea Foundation / Stichting De Noordzee is an environmental non-governmental organization advocating the protection and sustainable use of the North Sea marine ecosystem. The goal is a clean, healthy sea and a well-functioning ecosystem. Its activities are focused on clean seas and beaches, clean shipping, sustainable food harvest, eco-friendly energy production, and protected nature.

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Appendix

I. Summary of interviews and email correspondence

Name	Organization	Date	Medium	Topic
Jaap de Rooi	Dutch Oyster Association	20 February, 2022	E-mail	Current views of oyster farmers on offshore cultivation.
Luuk Folkerts	Gemini Wind Park	26 February, 2022	Video interview	Attitudes and outlook of Gemini wind farm regarding multi-use at present and in the future.
Baptiste Foret	SEAPA (European market)	19 April, 2022	E-mail	Best use of SEAPA oyster aquaculture systems for North Sea conditions.
Linda Planthof	North Sea Foundation	11 May, 2022	In-person interview	Internal analysis of North Sea Foundation including organization mission an vision.
Addy Risseeuw	Producer's Organization for Mussel Culture	9 March, 2022	E-mail	Current views of oyster farmers on offshore cultivation
Rimco Slagter	North Sea Farmers	30 March, 2022	Video interview	Multi-use procedures offshore, insights from the seaweed industry which is facing many of the same hurdles when thinking about moving offshore.
Owain Wynn-Jones	Orkney Shellfish Hatchery	12 April, 2022	Video interview	Flat oyster hatchery techniques, current and projected scale of production, disease status

II. Operational wind farm map and energy production

Table i: Operational wind farms and their energy generation capacity as of 2021. Taken from (Ministry of Economic Affairs and Climate Policy, 2021)

Operational wind farms

Wind farm	Capacity wind farm (in megawatts)	In use since
Borssele V (innovation site)	19	2021
Borssele I & II	752	2020
Borssele III & IV	731.5	2020
Gemini	600	2016
Luchterduinen	129	2015
Prinses Amalia	120	2008
Egmond aan Zee (OWEZ)	108	2007
Total	**2.45GW (2459.5 MW)**	

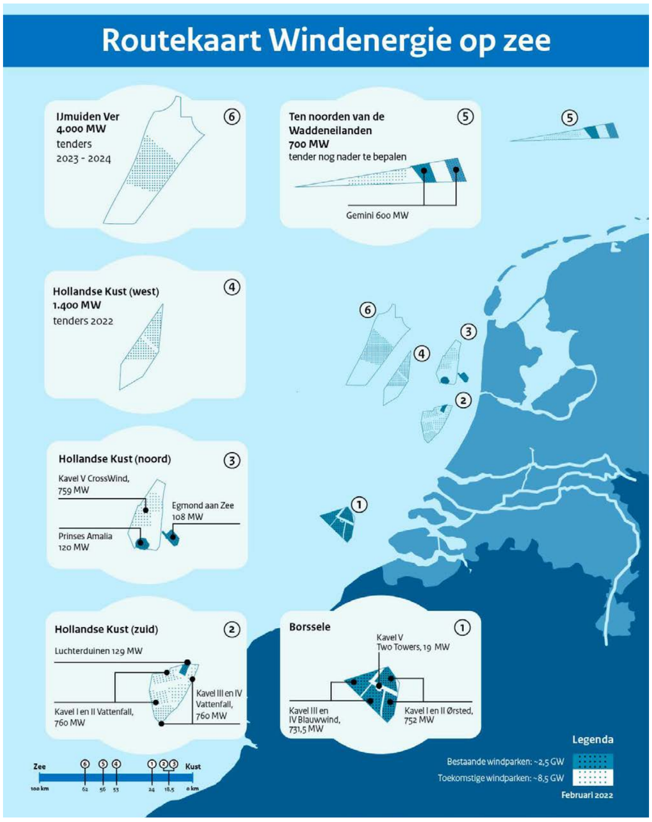

Figure i: Additional map of current wind farm sites with projected dates for future wind farm construction. Note: The projected future tender and construction dates displayed here are no longer relevant. This image is used here only to show the location of the 7 wind farms that are currently operational in the Dutch North Sea as of time of writing (Ministry of General Affairs, 2021).