Engineering nature-inclusive marine infrastructure with an emphasis on flat oyster reef development in offshore wind farms in the Southern North Sea

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Engineering nature-inclusive marine infrastructure
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Remment ter Hofstede

I do it all.

Engineering nature-inclusive marine infrastructure

with an emphasis on flat oyster reef development
in offshore wind farms in the Southern North Sea

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus,
prof. dr. ir. T.H.J.J. van der Hagen,
chair of the Board for Doctorates
to be defended publicly on
6 November 2024 at 15:00 o'clock

by

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Keywords: offshore wind, infrastructure, oyster, reefs, restoration, management, upscaling

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Content

Summary

Rapid changes in the marine environment are taking place worldwide, for which infrastructural development is one of the most extreme anthropogenic drivers. It comes in many forms and covers functionalities for multiple usages, such as coastal defence, transportation, and energy production. Marine infrastructure modifies seascapes by replacing natural habitats and changing environmental conditions critical to habitat persistence, potentially leading to its degradation and biodiversity loss. Although primarily built to meet functional criteria, their designs can incorporate nature-inclusive elements that benefit ecosystem components, i.e. species, habitats or ecosystem processes.

The implementation of nature-inclusive marine infrastructure is increasingly encouraged, but currently fails to achieve impact at scale due to the fragmented nature of individual measures. Without shared objectives, parallel efforts to enhance targeted ecosystem components might not lead to the desired effect, and could even interfere with each other. A jointly established strategy is required to design and implement nature-inclusive marine infrastructure that meets the wanted impact. Such as strategy is based upon overarching objectives for promoting selected ecosystem components at system-scale, i.e. the seascape dimension required to achieve the desired effect. It is furthermore essential to determine and develop design measures that would induce impact and to define the scale needed for these interventions. It is recognized that marine construction works first serve human needs, not nature goals, but nature-inclusive marine infrastructure does provide an opportunity to benefit ecological values at system-scale. Marine construction works can be synergized with the functioning of the ecosystem in which they are build much better than is currently practiced, and one should always strive for nature-inclusive features in their designs.

This dissertation provides insight into the process to identify, select and implement measures for nature-inclusive marine infrastructure to make a desired impact at system-scale, i.e. the seascape dimension required to achieve that impact. First, a stepwise approach is presented to define clear objectives for improving targeted ecosystem components, in which ruling polices, environmental conditions and the potential of using marine infrastructure are aligned. Stakeholders jointly select the most effective design measures for nature-inclusive marine infrastructure to reach shared targets for ecological impact. Next, it is key to define the scale of these interventions needed to achieve significant impact. A method is developed to select appropriate measures to benefit ecosystem components at a range of scales, from micro-scale (materials used) to mega-scale (connectivity between systems), and to assess their potential effects quantitatively. And finally, it is emphasized that nature-inclusive marine infrastructure can only make impact at system-scale if scientific knowledge about ecosystem functioning is paired with industry-based approaches used for infrastructural development. Five basic principles are provided for establishing this alignment, in order to effectively implement nature-inclusive design measures.

The approaches for engineering nature-inclusive marine infrastructure are demonstrated by defining a strategy to develop European flat oyster (*Ostrea edulis*) reefs in offshore wind farms in the Southern North Sea. The huge roll out of offshore wind farms aimed at renewable energy production in the North Sea is currently one of the most prominent marine infrastructural developments globally. Its potential for promoting targeted ecosystem components is recognized, as offshore wind farms provide an undisturbed seabed as well as hard substrate infrastructure, which both provide suitable habitat for a wide range of marine organisms. The results of a dedicated monitoring survey in existing offshore wind farms show that their presence indeed contributes to an increase in marine epibenthic biodiversity. Using the offshore wind farm areas specifically for the development of flat oyster reefs has gained particular interest. This species went near to extinct in the 20th century due to overfishing and diseases, and restoring flat oyster reefs in the North Sea meets international policy agreements. Offshore wind farms can be designed to include elements that benefit the restoration of this flat oyster population, such as using a type of hard substrate as scour protection that is favourable for oyster larvae settlement.

In conclusion, this dissertation provides guidance for defining management strategies for implementing nature-inclusive marine infrastructure to achieve impact at system-scale, with an emphasis on flat oyster reef development in offshore wind farms in the Southern North Sea. Application of the presented methods and outcomes of the studies could lead to the realisation of truly effective nature-inclusive marine infrastructure, seizing the opportunity offered by infrastructural developments to have a positive impact on the marine environment.

Samenvatting

Wereldwijd treden snelle veranderingen op in het mariene milieu, en de ontwikkeling van infrastructuur heeft hierin een belangrijk aandeel. Mariene infrastructuur komt voor in vele varianten en voorziet in diverse functies zoals kustbescherming, transportvoorziening en energieproductie. Mariene infrastructuur beïnvloedt de zeeën doordat natuurlijke leefgebieden worden vervangen of aanzienlijk worden veranderd, met mogelijk cruciale gevolgen voor het mariene milieu en haar biodiversiteit. Hoewel mariene infrastructuur in de eerste plaats wordt aangelegd ten behoeve van de beoogde functionele doelen, kunnen de ontwerpen natuur-inclusieve elementen bevatten welke bewust gekozen onderdelen van het ecosysteem ten goede komen, te weten soorten, leefomgevingen of processen.

De implementatie van natuur-inclusieve mariene infrastructuur wordt in toenemende mate aangemoedigd, maar slaagt er momenteel niet in om op grote schaal impact te hebben omdat de huidige maatregelen gefragmenteerd van aard zijn. Zonder gemeenschappelijke doelstellingen zullen afzonderlijke inspanningen die gericht zijn op verbetering van onderdelen van het ecosysteem hoogstwaarschijnlijk niet tot het gewenste effect leiden, en zelfs conflicterend kunnen uitwerken. Er is een gezamenlijk gedragen aanpak nodig om natuur-inclusieve mariene infrastructuur te ontwerpen en te implementeren, om de gewenste impact te kunnen behalen. Een dergelijke strategie wordt gefundeerd door overkoepelende doelstellingen voor het bevorderen van geselecteerde onderdelen van het ecosysteem op systeem-schaal, dat wil zeggen de ruimtelijke dimensie die nodig is om het gewenste effect te bereiken. Het is bovendien essentieel om ontwerpmaatregelen te gebruiken of te ontwikkelen welke de beoogde impact daadwerkelijk kunnen bewerkstelligen, alsmede om de schaalgrootte te bepalen die hiervoor nodig. Het wordt onderkend dat maritieme constructies in de eerste plaats de behoeften van de mens dienen, en niet de natuurdoelen, maar natuur-inclusieve mariene infrastructuur biedt wel degelijk de mogelijkheid om ecologische waarden te bevorderen. Maritieme constructiewerken kunnen veel meer dan nu het geval is worden gecombineerd met het functies voor het ecosysteem waarin ze worden gebouwd, en men dient te allen tijde te streven naar natuur-inclusieve elementen in hun ontwerp.

Dit proefschrift biedt inzicht in het proces om maatregelen voor natuur-inclusieve mariene infrastructuur te identificeren, selecteren en implementeren, om te komen tot een gewenste impact op systeem-schaal, dat wil zeggen het benodigde gebied om deze impact te bereiken. Ten eerste wordt een stapsgewijze aanpak gepresenteerd om duidelijke doelstellingen te definiëren voor het verbeteren van geselecteerde onderdelen van het ecosysteem, waarbij het heersende beleid, de milieuomstandigheden, en het potentieel van de beoogde infrastructuur met elkaar worden gebundeld. Belanghebbenden selecteren gezamenlijk de meest effectieve ontwerpmaatregelen voor natuur-inclusieve mariene infrastructuur om de gedeelde doelstellingen voor ecologische impact te bereiken. Vervolgens is het van cruciaal belang om te bepalen wat de benodigde omvang van deze interventies is om de doelen te bereiken. Er is een methode

ontwikkeld om passende maatregelen te selecteren die ten goede komen aan het bevorderen van de gekozen onderdelen van het ecosysteem op verschillende schaalniveaus, van micro-schaal (gebruikte materialen) tot mega-schaal (connectiviteit tussen systemen), en om hun potentiële effecten kwantitatief te bepalen. Tenslotte wordt benadrukt dat natuur-inclusieve mariene infrastructuur alleen effectief kan zijn op systeem-schaal wanneer de wetenschappelijke kennis over het functioneren van ecosystemen gepaard gaat met de ervaring van maritieme bouwbedrijven in het uitvoeren van grootschalige werkzaamheden. Er worden vijf basisprincipes gegeven om deze afstemming tot stand te brengen, zodat natuur-inclusieve ontwerpmaatregelen effectief kunnen worden doorgevoerd.

De aanpak voor het ontwikkelen van natuur-inclusieve mariene infrastructuur wordt gedemonstreerd door het bepalen van een strategie voor de ontwikkeling van platte oester (*Ostrea edulis*) riffen in windparken in de zuidelijke Noordzee. De grootschalige aanleg van windparken in de Noordzee om te kunnen voorzien in de behoefte aan duurzame energie is momenteel een van de meest prominente maritieme infrastructurele ontwikkelingen wereldwijd. Het potentieel van windparken op zee om gerichte onderdelen van het ecosysteem te bevorderen wordt erkend, aangezien deze zowel een onberoerde zeebodem als een hard substraat bieden, en beide vormen geschikt habitat voor een grote diversiteit aan mariene organismen. Monitoringonderzoek in bestaande windparken op zee toont dat de aanwezigheid van windparken op zee inderdaad bijdraagt aan een toename in de epibenthische biodiversiteit. Het gebruik van windpark op zee specifiek voor de ontwikkeling van platte oesterriffen heeft bijzondere aandacht. Deze soort is in de 20e eeuw bijna uitgestorven als gevolg van overbevissing en ziekten, en het herstel van platte oesterriffen in de Noordzee komt tegemoet aan internationale beleidsafspraken. In het ontwerp van windparken op zee kunnen elementen worden opgenomen die het herstel van de platte oester populatie bevorderen, bijvoorbeeld het gebruik van een type hard substraat als erosie bescherming welke bevorderlijk is voor de vestiging van oesterlarven.

Concluderend biedt dit proefschrift sturing in het maken van een strategie voor het implementeren van natuur-inclusieve mariene infrastructuur om impact op systeem-schaal te bereiken, met het accent op de ontwikkeling van platte oesterriffen in windparken in de zuidelijke Noordzee. Toepassing van de gepresenteerde methoden en onderzoeksresultaten zou kunnen leiden tot de realisatie van werkelijk effectieve natuur-inclusieve mariene infrastructuur, waarmee de kans wordt benut om met infrastructurele ontwikkelingen het mariene milieu te bevorderen.

1 General introduction

1.1 Nature-inclusive marine infrastructure

The marine environment faces climate threats and suffers from severe human usage at the onset of the Anthropocene, leading to habitat degradation and biodiversity loss globally (e.g. Halpern *et al.*, 2019; He & Silliman, 2019; Smale *et al.*, 2019). Infrastructural development is one of the major anthropogenic pressures on marine ecosystems (Bugnot *et al.*, 2021). It comes in many forms and covers functionalities for multiple usages, including recreation, residency, fisheries, coastal defence, and offshore energy installations (Dafforn *et al.*, 2015b; Dennison, 2008). Marine infrastructure modifies seascapes by replacing natural habitats and changing environmental conditions critical to habitat persistence (Bishop *et al.*, 2017; Bugnot *et al.*, 2021). While these effects are primarily viewed as negative, marine infrastructure can also be designed to incorporate ecological principles that benefit marine life (Dafforn *et al.*, 2015b; Laboyrie *et al.*, 2018). It is referred to in this dissertation as 'nature-inclusive marine infrastructure', defined as marine infrastructure designed to improve the condition of targeted components of the ecosystem during its operational lifetime. These components would be selected species, habitats or ecosystem processes, and improvement relates to comparison with their condition prior to the infrastructural development.

Although marine infrastructure is primarily designed to meet engineering and financial criteria, without considering its value as habitat (Browne and Chapman, 2011; Laboyrie *et al.*, 2018), integration of nature-inclusive measures in its design is increasingly encouraged. The incorporation of elements that enhance ecosystem components and services into marine infrastructural developments has gained strong interest over the last decades (e.g. Sutton-Grier *et al.*, 2015). Initially, focus lied primarily on infrastructure for coastal protection such as seawalls, dikes and groins (e.g. King and Lester, 1995; Capobianco and Stive, 2000; Lamberti and Zanuttigh, 2005; Swann, 2008; Borsje *et al.*, 2010, De Vriend *et al.*, 2015). Traditional engineering structures to mitigate risks to our shorelines have increasingly incorporated nature-inclusive measures across the globe, or are even replaced by fully nature-based solutions (e.g. Temmerman *et al.*, 2013; Smith *et al.*, 2020). More recent developments are to also include measures to enhance ecosystem components in the infrastructure in urban and offshore environments (e.g. Strain *et al.*, 2017; Bugnot *et al.*, 2021).

Problem definition

Although a wide variety of nature-inclusive design measures have been applied to real projects (e.g. O'Shaughnessy *et al.*, 2020 for review), the fragmented character of individual measures has so far not led to the desired effect (Abelson *et al.*, 2020; Duarte *et al.*, 2020). To achieve impact at system-scale, i.e. the seascape dimension required to achieve that desired impact, an overarching approach with shared targets towards effective nature-inclusive marine infrastructure is needed. Another challenge identified to achieve more effective restoration or creation of ecosystem components is the development of scalable methods (Rinkevich, 2008; Abelson *et al.*, 2020; Duarte *et al.*, 2020). The wide sprawl of infrastructural development in coastal marine ecosystems across the globe offers huge potential for enhancement of the ecological values of a system (Bugnot *et al.*, 2021). It is recognized that marine construction works first serves human needs, not nature goals, but optimizing the infrastructure does provide an opportunity to enhance targeted ecosystem components at scale. This should never be used as an excuse to ignore or down-play the negative impact that infrastructural developments may have on a marine ecosystem (Firth *et al.*, 2020). However, marine construction works can be synergized with ecological enhancement much better than is currently practiced, and one should always strive for including nature-friendly features in their designs (Pioch *et al.*, 2018).

This dissertation aims to provide a well-founded process of designing nature-inclusive marine infrastructure, aiming to have a positive impact on subsea ecosystem components at a system-scale. The process starts by defining clear operational objectives, required to achieve a desired effect on targeted marine life aligned with infrastructural developments. Next, a structured approach should be followed to assess quantitatively the potential effect of interventions on the targeted ecosystem components, in order to allow for selection of most effective measures. Insight in the potential effectivity of interventions needs to be acquired, such as knowing the type of construction materials that could provide favourable substrate for colonisation by targeted marine organisms. And finally, basic principles are to be adhered to in order to reach the desired effect at a scale large enough to make significant impact on the targeted ecosystem components.

The methods are demonstrated through application on European flat oyster (*Ostrea edulis* L.) reef development aligned with offshore wind farm infrastructure in the Southern North Sea. Offshore wind energy production has increased rapidly in the North Sea over the past three decades, and there's an urgent demand for effective measures to make use of the potential for ecological enhancement arising from it. The results of this dissertation provide guidance to develop nature-inclusive marine infrastructure, illustrated by initiating flat oyster reefs development coinciding the growing offshore wind energy production in the Southern North Sea.

1.2 Offshore wind energy in the Southern North Sea

The Southern North Sea is defined as the part of the North Sea basin situated north of the entrance of the Channel between Dover (United Kingdom) and Calais (France), and south of the diagonal line between Scarborough (UK) and the tip of Jutland (Denmark) (see Figure 1-1). The area is bordered by the United Kingdom on the west, and Belgium, The Netherlands, Germany and Denmark on the east. The diagonal line roughly follows a 50 m depth contour and is commonly used to make a north-south division of the North Sea basin, in which the southern part has a depth up to approximately 50 m, and the northern part from 50 m down to the continental slope (e.g. Lee, 1980; DEFRA, 2005; Christiansen, 2009). The division is reflected by large-scale ecological patterns in infauna, epifauna and demersal fish communities, resulting from differences in bottom water temperature, bottom water salinity and tidal stress (Reiss *et al.*, 2010). The Southern North Sea has a surface area of approximately 200,000 km^2, and a maximum depth of approximately 40 m. A large sand bank, the Doggersbank lies centrally in the northern part at an average depth of 13 m, and many smaller sand banks and dunes are present in the south.

Historic maps show that the Southern North Sea was once covered with hard substrates such as oyster beds, coarse peat banks and glacial erratics (Olsen, 1883). These substrates provided habitat for many associated marine species, but were destroyed by bottom-trawl fisheries, overexploitation and diseases (Gross and Smyth, 1946; Korringa, 1952). Today, large parts of the seabed are characterized by sandy or silty soft substrate with a relatively poor species community. The remaining natural hard substrate like pebbles and boulders host a different and more biodiverse epibenthic communities than those at the sandy seabed (Bos *et al.*, 2011; Coolen *et al.*, 2015).

The Southern North Sea is known to be one of the most heavily used seas in the world, with extensive anthropogenic pressures including shipping, fishing, recreation, sand extraction, military zones and energy production (Halpern *et al.*, 2008; Kenny *et al.*, 2018). Currently, a lot of attention is given to the rapid increase in offshore wind farms to meet the targets of the European Union for renewable energy production (European Commission, 2023) (see Figure 1-1). The ever growing designation of areas for the development of offshore wind farms since the 1990s, puts severe pressure on the North Sea ecosystem and its usage functions (Guşatu *et al.*, 2021). However, offshore wind farms also provide an environment ideal for the development of marine life, offering substrate through its infrastructure as well as a relatively undisturbed seabed for benthic ecosystems to develop and associated organisms to forage and find shelter (Petersen and Malm, 2006; Coolen *et al.*, 2020; Degraer *et al.*, 2020). The ecological value in terms of biodiversity and biomass in offshore wind farms can be increased by making adjustments to the conventional engineering design, for example by including modified structures that enhance habitat complexity. Such adjustments could mitigate the negative impact of the wind farm construction on ecosystem components, thereby facilitating societal acceptance of the growing offshore wind energy production.

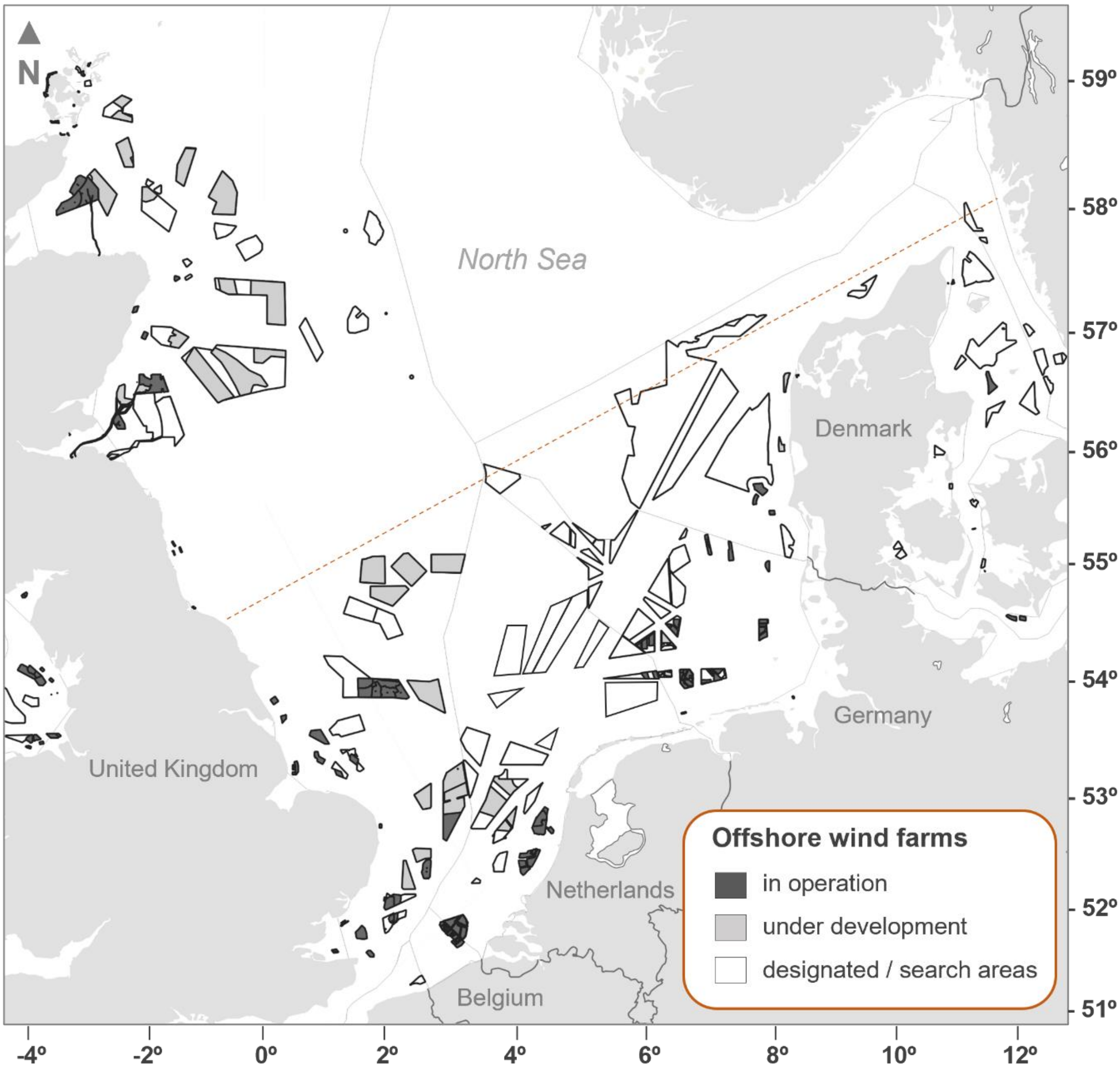

Figure 1-1: Offshore wind farm development in the North Sea. Dashed line indicates split between the Northern and Southern North Sea, roughly following a 50m depth contour. (Compiled from emodnet.ec.europa.eu; Ministry of Infrastructure and Water Management, 2022; d.d. 25/03/2024).

1.3 Oyster reef restoration in the Southern North Sea

One of the ecosystem components in the Southern North Sea gaining momentum for development aligned with offshore wind farms is the restoration of the European flat oyster species (*Ostrea edulis*) (Kamermans *et al.*, 2018; Pogoda *et al.*, 2019). The European flat oyster forms biogenic reefs that contribute to a heterogeneous seabed and a biodiverse ecosystem (Bouma *et al.*, 2009, Smyth and Roberts, 2010; Thrush *et al.*, 2008). The oysters improve water quality through filtration (Dolmer, 2000; Newell, 2004) and their reefs provide a habitat for a diverse associated community (Coen and Luckenbach, 2000; Lown *et al.*, 2021). In a dynamic offshore environment as is the Southern North Sea, oyster reefs can ameliorate physical stresses by creating a hospitable habitat for organisms that would otherwise be unable to tolerate these conditions (Crain and Bertness, 2006). The reefs offer substrate for settlement of algae and sessile epibenthic fauna (e.g. sponges, anemones) and provide shelter and nesting area for fish species and crustaceans (e.g. crabs, lobsters) (Commito *et al.*, 2005; Coen and Luckenbach, 2000; Lown *et al.*, 2021). This reef dwelling marine life often includes species of commercial value, including the oysters themselves, showing the potential of oyster beds to contribute to valuable fisheries resources (Gilby *et al.*, 2018).

The European flat oyster reefs once covered large areas of the North Sea (e.g. Olsen 1883; Bennema *et al.*, 2020), but went near to extinct over the 20th century due to overexploitation, bottom-dwelling fisheries and the outbreak of infection by the parasite *Bonamea ostrea* (Korringa, 1952; Engelsma *et al.*, 2010; Gerken and Schmidt, 2014). The scarce flat oyster populations remaining in some coastal areas of the Southern North Sea, are very isolated from each other, leading to a further deterioration of the remaining stock due to the reduced chance of cross-fertilisation (Gross and Smyth, 1946).

As a consequence of its deterioration, the European flat oyster is internationally recognised as 'threatened and declining' in the NE Atlantic by the OSPAR Commission (OSPAR, 2008). The European Marine Strategy Framework Directive includes the environmental target (D6T5) for the 'return and recovery of biogenic reef structures including flat oyster beds' (European Commission, 2008), meaning that member states of the European Union should undertake action to achieve the return of these oyster reefs. Therefore, there has been growing interest in restoring the flat oyster population, in particular in the North Sea area, and consecutively their valuable contribution to its rich marine ecosystem (e.g. Pogoda *et al.*, 2019; www.derijkenoordzee.nl/en).

Growing attention is given to combine the huge out roll of offshore windfarm constructions in the North Sea with the reinstatement of the European flat oysters (Kamermans *et al.*, 2018b; Sas *et al.*, 2019; Bos *et al.*, 2023). The offshore windfarms are considered promising restoration sites, as these areas are closed for bottom-trawl fisheries and the scour protection at the base of the turbine foundations might act as artificial substrate, potentially offering good conditions for oyster reef development (Smaal *et al.* 2017; Kamermans *et al.*, 2018b; Sas *et al.*, 2019). Despite the effort being put in pilot studies on enhancing oyster development in offshore wind farms (e.g. Didderen *et al.*, 2019, 2020; Sas *et al.*, 2019; Bos *et al.*, 2023), their fragmented character has yet not lead to a significant impact at population scale. An overarching approach is required for the coordination of the studies, and for the application of their outcomes to achieve the desired impact. Such an approach needs clear objectives agreed upon by relevant stakeholders, knowledge about the potential effect of design measures on oyster reef development in offshore wind farms, and understanding of the required scale at which these should be implemented in the Southern North Sea.

Box 1:
Life cycle of the European flat oyster (*Ostrea edulis*) in the Southern North Sea

The life cycle of the European flat oyster (*Ostrea edulis*) is typified by a parental investment through brooding. Spawning is triggered by increasing spring temperatures and generally peaks from late June to early July in the Southern North Sea (Korringa, 1952; 1957). Fertilization of the eggs occurs inside the mantle cavity of the adult females, and the embryo's develop into larvae over 8-10 days (Korringa, 1940). After brooding the larvae swarm into the water column where they have a pelagic stage for 1-2 weeks until settlement (Korringa, 1940). The free-swimming larvae have a dispersal potential being greater than 10 km (Berghahn and Ruth, 2005; Kamermans *et al.*, 2018b), though the larvae behaviour shows high self-recruitment, tailored to reduce dispersal away from parent populations (Rodriguez-Perez *et al.*, 2020). Once the oyster larvae have settled by cementing themselves on hard substrate they are called spat. The spat becomes juvenile growing into adult oysters over the course of 2-3 years, first being males and in subsequent years they can alternate between being females or males, even during a breeding season (Joyce *et al.*, 2013). The males produce sperm clumps which are taken in by the females (Ó Foigil, 1989). With the fertilisation of the eggs within the cavity of the mantle of the female oyster, the life cycle starts again.

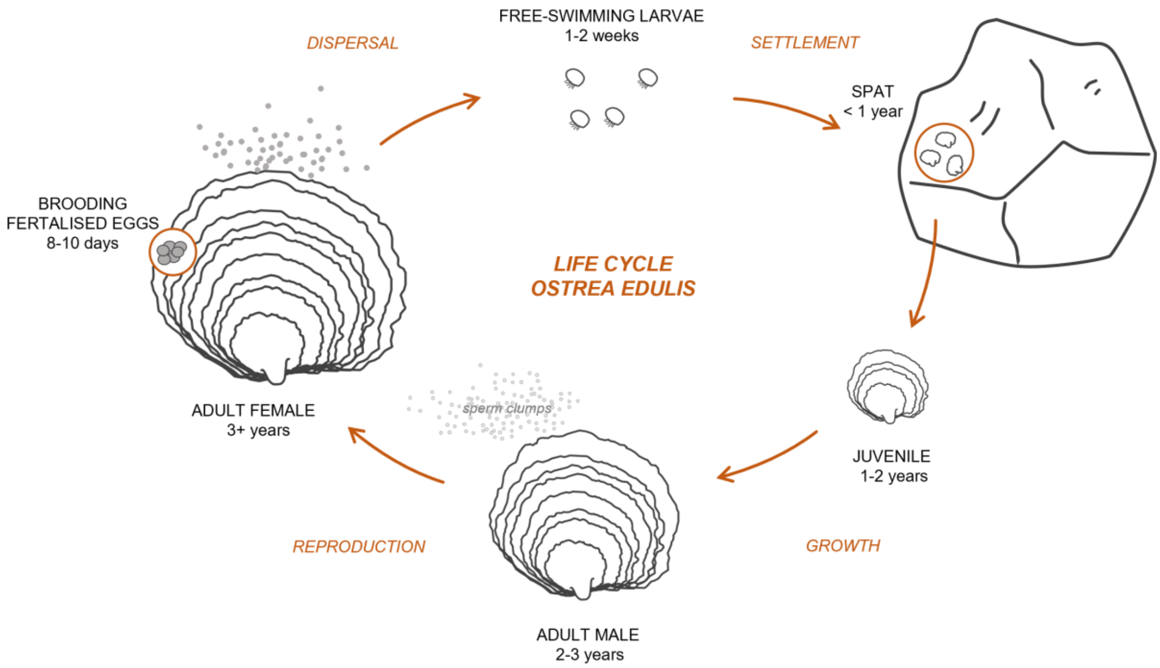

Figure 1-2: Life cycle of the European flat oyster (Ostrea edulis).

1.4 Research questions and outline dissertation

This dissertation provides insight into the process to identify, select and implement measures for nature-inclusive marine infrastructure, with an emphasis on the development of European flat oyster reefs in offshore wind farms in the Southern North Sea (see Figure 1-3).

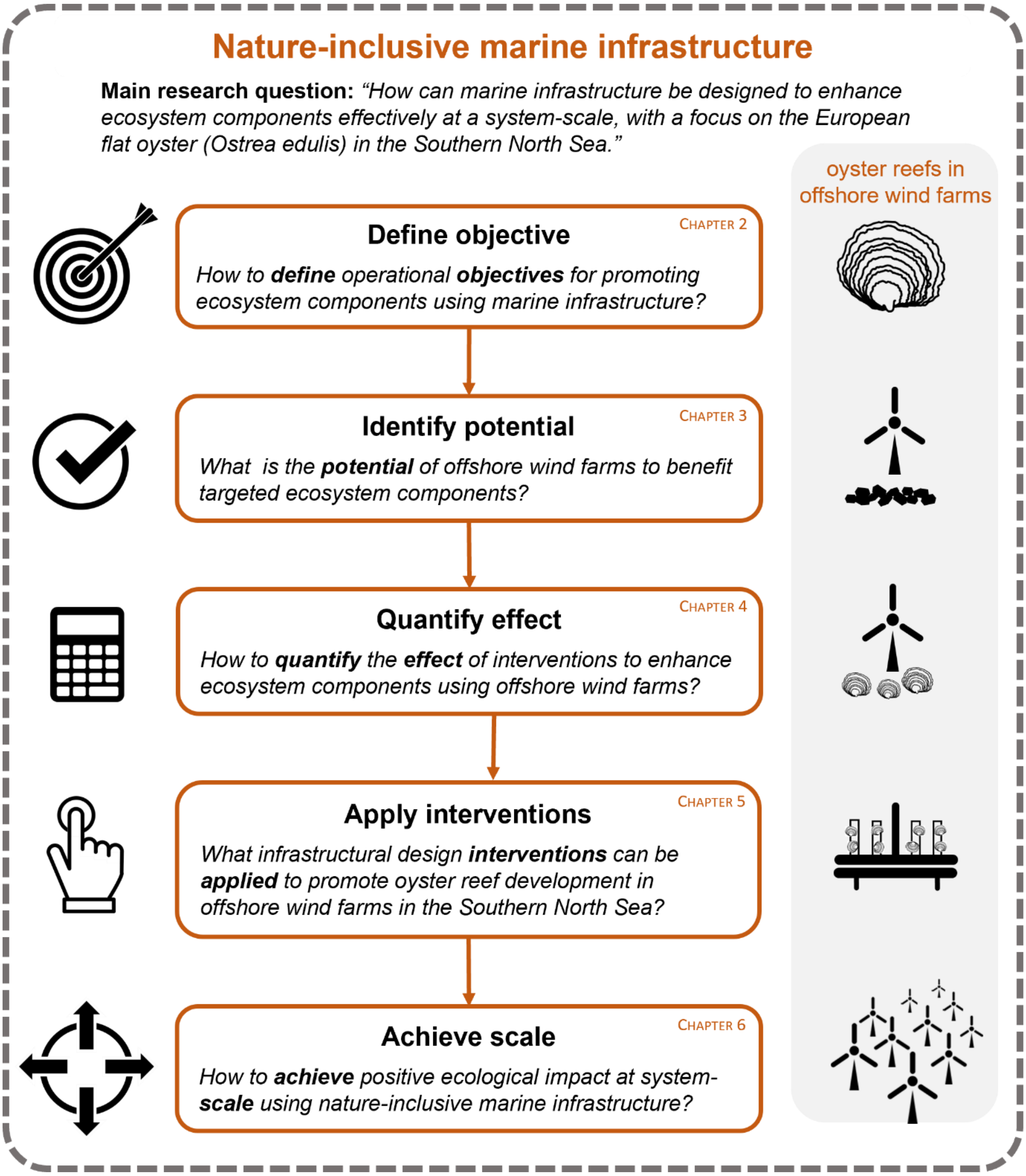

Figure 1-3: Schematic outline of the consecutive steps to achieve nature-inclusive marine infrastructure, illustrated when applied to oyster reef development in the North Sea. These consecutive steps are addressed in Chapters 2 to 6 of this dissertation.

Chapter 1 - ***General introduction***: Marine infrastructure modifies seascapes by replacing natural habitats and changing environmental conditions critical to habitat persistence. Their designs can incorporate elements that benefit ecosystem components, but achieving impact at scale is challenging.

➔ Main Research Question:
"How can marine infrastructure be designed to enhance ecosystem components effectively at a system-scale, with a focus on the European flat oyster (Ostrea edulis) in the Southern North Sea."

Chapter 2 – ***Define objectives***: The process of designing nature-inclusive marine infrastructure, requires defining clear operational objectives, while taking into account the ruling polices, environmental conditions and the potential for using the infrastructure. An approach is developed to support defining such operational objectives, in which stakeholders jointly select the most effective measures to reach shared targets towards effective enhancement of selected ecosystem components. The application of the approach is demonstrated for defining operational objectives to improve the subsea ecosystem of the North Sea using offshore wind farms.

➔ Research Question to Define objectives:
"How to define operational objectives for promoting ecosystem components using marine infrastructure?"

Chapter 3 – ***Identify potential***: The construction of offshore windfarms in the North Sea includes the introduction of hard substrate by means of scour protection around the foundation of wind turbines. It is assumed that this rocky habitat will contribute to the biodiversity of the area in which these are build. A dedicated monitoring survey in Dutch offshore wind farms was carried out to investigate whether the conventional scour protection contributes to marine biodiversity, by comparing the epibenthic community composition present at the scour protection with the one at the surrounding seabed. Knowing the potential effect of the infrastructure on the epibenthic community can support decision-making on including elements to enhance targeted ecosystem components within existing and future offshore wind farms.

➔ Research Question to Identify potential:
"What is the potential of offshore wind farms to benefit targeted ecosystem components?"

Chapter 4 – *Quantify effect*: Interventions can be taken to enhance targeted ecosystem components using marine infrastructure. To allow for their selection it is key to know their potential effect and the required order of magnitude for their application to make a significant impact. A stepwise procedure is developed to quantify the effect of potential interventions at a range of scales, from micro-scale (materials used) to mega-scale (connectivity between systems). Its application is demonstrated for estimating the effects of measures to promote oyster reef development in offshore wind farms in the North Sea.

➔ Research Question to Quantify effect:
"How to quantify the effect of interventions to enhance ecosystem components using offshore wind farms?"

Chapter 5 – *Apply interventions*: The design of marine infrastructure can be optimized to benefit ecosystem components. For oyster reef development, the availability of hard substrate is crucial for initial settlement. Offshore wind farms infrastructure generally offers such substrate by means of quarried rock placed at the base of the wind turbine foundations and on top of cable crossings to prevent scouring of the seabed. As an example of an intervention, it is investigated what type of hard substrate used as scour protection or as part of it, would offer most favourable conditions for oyster larvae settlement.

➔ Research Question to Apply interventions:
"What infrastructural design interventions can be applied to promote oyster reef development in offshore wind farms in the Southern North Sea?"

Chapter 6 – *Achieve scale*: To realise effective scales in enhancement of targeted ecosystem components, scientific knowledge of suitable interventions should be paired with industry-based approaches used for large scale infrastructural development. Five key principles are presented to consciously connect science and industry, increasing the likelihood that developing marine infrastructure and improving selected ecosystem components can be aligned. The principles are illustrated with examples for advancing reef restoration.

➔ Research Question to Achieve scale:
"How to achieve positive ecological impact at system-scale using nature-inclusive marine infrastructure?"

Chapter 7 – ***General Reflection and Conclusions***: This dissertation comprises studies on the process to identify, select and implement design measures for nature-inclusive marine infrastructure in order to enhance targeted components of the subsea ecosystem. The conceptual approaches developed within the studies have been applied on determining potential measures for offshore wind farms to develop flat oyster reefs in the Southern North Sea. The studies come with certain assumptions and uncertainties, upon which is reflected in Chapter 7. Furthermore, general conclusions from the studies are presented, aiming to guide the development of nature-inclusive marine infrastructure, in particular for promoting flat oyster reef development aligned with offshore wind energy production in the Southern North Sea.

2 Define objectives

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Defining operational objectives for nature-inclusive marine infrastructure to achieve system-scale impact

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Chapter 2 – Define objectives

It is increasingly encouraged to integrate nature-inclusive measures in the design of marine infrastructure, but a lack of coordination results in the fragmentation of project-based measures, failing to meet the desired overall effects. To realize impact at system-scale, i.e. the seascape dimension required to achieve the desired effect, overarching targets towards promoting selected ecosystem components are needed. Having clearly defined objectives for these components, that can be species, habitats or ecosystem processes, will provide guidance to project developers to design their infrastructure effectively to achieve the desired impact.

In this Chapter a stepwise approach is presented to define operational objectives for nature-inclusive marine infrastructure aiming to achieve impact at system-scale. Its application is demonstrated by deriving shared objectives for the nature-inclusive design of offshore windfarms in the Dutch part of the North Sea, with the European flat oyster *Ostrea edulis* as target species.

Research Question

How to define operational objectives for promoting ecosystem components using marine infrastructure?

2.1 Introduction

Rapid changes in the marine environment are taking place, driven by human usages and climate change (Halpern *et al.*, 2019; Smale *et al.*, 2019). One of the most extreme human modifications to global seascapes is the extent of marine construction (Bugnot *et al.*, 2021). Marine infrastructure comes in many forms and covers functionalities for multiple usages, including recreation, residency, fisheries, coastal defence, and offshore energy installations (Dafforn *et al.*, 2015b). It is primarily designed to meet engineering and financial criteria, without considering its value as habitat (Browne and Chapman, 2011; Laboyrie *et al.*, 2018). Marine infrastructure modifies seascapes by replacing natural habitats and changing environmental conditions critical to habitat persistence (Bishop *et al.*, 2017; Bugnot *et al.*, 2021). While these effects are primarily viewed as negative, marine infrastructure can also be designed to incorporate ecological principles that benefit marine life (Dafforn *et al.*, 2015b; Laboyrie *et al.*, 2018). This so-called 'nature enhancement' and derivatives thereof are prone to broad interpretation. To avoid ambiguity, we refer primarily to 'nature-inclusive marine infrastructure', which we define as marine infrastructure designed to improve the condition of targeted components of the ecosystem during its operational lifetime. These components would be selected species, habitats or ecosystem processes, and improvement refers to comparison with their condition prior to the infrastructural development. In recent years, a wide variety of nature-inclusive designs were applied to real projects (e.g. O'Shaughnessy *et al.*, 2020 for review). However, the fragmented character of individual measures has so far not led to significant impact at system-scale (Abelson *et al.*, 2020; Duarte *et al.*, 2020), by which we refer to a seascape of the dimension required to achieve a set objective for the targeted ecosystem component. The variety in measures applied in individual projects could partly be due to underlying competitive differences between the developers. Without shared objectives, parallel efforts to include nature-inclusive elements in the design of marine infrastructure might not lead to a desired overall effect, and could even interfere with each other. To achieve a significant system-scale effect, individual initiatives to promote selected ecosystem components should be defragmented into a coordinated system-wide approach, following shared objectives. The process of setting those objectives for different systems involving different usages, would benefit from a generic stepwise approach to do so.

When defining objectives for ecological values as part of infrastructural development in the marine environment, one should aim to limit the negative environmental impact, and try to stimulate positive impact with the usage function. Such potential impact on the environment of marine infrastructural development is generally evaluated through an Environmental Impact Assessment (EIA) (e.g. Carroll *et al.*, 2020). In practice, as most infrastructural designs are optimized for their economic and technical objectives, the EIA process subsequently applies mitigation measures to reduce any significant negative effects identified. But a recent development is that an EIA also addresses the potential of a project to have beneficial effects to the environment, both natural and socio-economic (Laboyrie et al, 2018). Furthermore, priority should be given to the implementation of monitoring programs, in order to be able to assess the long-term effects of newly build infrastructure (Dafforn *et al.*, 2015b). In the end, it is up to authorities in close cooperation with the scientific community and other stakeholders, to determine an approach for implementing the environmental goals and policy objectives for the infrastructural development within the system.

A well-established tool to structurally align policy objectives with technical solutions to meet these objectives is the 'Frame of Reference' approach (Van Koningsveld, 2003). It cyclically defines both a strategic and an operational objective and operationalizes these objectives in a 4-step decision recipe determining (i) a quantitative state concept, (ii) a bench marking procedure, (iii) an intervention procedure and (iv) an evaluation procedure (see Figure 2-1). Originally derived to evaluate and re-define a sustainable coastal policy for the Netherlands (Van Koningsveld and Mulder, 2004), the 'Frame of Reference' approach has since then been applied successfully for a range of civil engineering disciplines. For example, it was used to define coastal management policies for beach areas (Jiménez *et al.*, 2007; Sutherland and Thomas, 2011; Gault *et al.*, 2011), to develop environmental monitoring schemes for offshore renewable energy projects (Garel *et al.*, 2014), and proposed as a tool to assess the sustainability of for example dredging (Laboyrie *et al.*, 2018) and port and waterway projects (Van Koningsveld *et al.*, 2023).

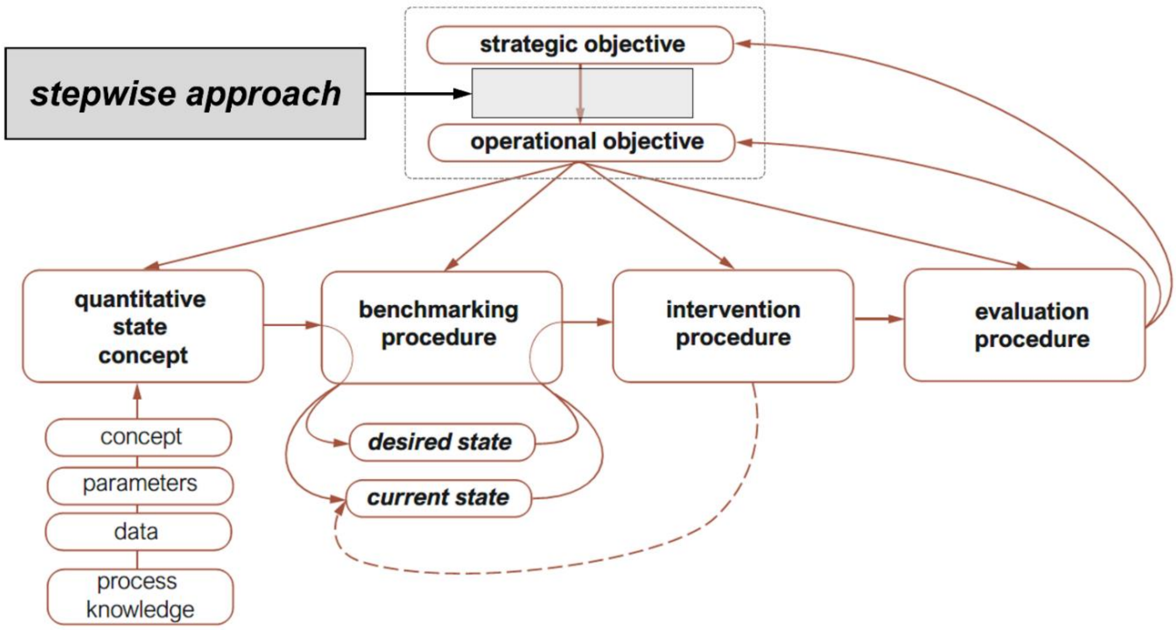

Figure 2-1: The basic Frame of Reference for policy development by Van Koningsveld (2003). The grey rectangle indicates the fit of the stepwise approach for alignment towards operational objectives (Figure after Van Koningsveld et al., 2023).

A key element of establishing a coordinated, system-wide approach for implementing nature-inclusive elements within infrastructural development, is to define the strategic and operational objectives and to break these down into a number of logical elements (De Vries *et al.*, 2020b). Strategic objectives provide the long-term context for a policy, express the vision for a system and its usage, and tend to change slowly (Van Koningsveld *et al.*, 2005). Operational objectives are the concrete implementation of strategic objectives, by expressing how to handle the system and its usage, and include and explicit indication of the spatial and temporal scales involved (Van Koningsveld *et al.*, 2005). Turning strategic objectives into operational ones, as also shown in the 'Frame of Reference' methodology, is a crucial though complicated process. It would benefit from a generic approach that is applicable for different systems involving different usages. Such an approach should include standards for defining the objectives as well as for implementing targets to achieve them, both temporarily and spatially. Although the need to specify clear operational objectives in coastal and marine management is generally recognized (e.g. Van Koningsveld 2003; Cormier *et al.*, 2017; De Vries *et al.*, 2020a), a methodology for facilitating the process of turning strategic objectives into operational ones has not yet been described.

This study is the first in its kind to address an approach to set effective operational objectives for promoting targeted components of the subsea ecosystem, i.e. the environment below the surface of the sea, in areas designated for infrastructural development. It entails a structured methodology, that aligns the ruling socio-economical and environmental conditions of the system with the potential offered by nature-inclusive marine infrastructure to achieve long-term benefits for selected ecosystem components. This stepwise approach is demonstrated by setting operational objectives for the nature-inclusive design of offshore windfarms the Dutch part of the North Sea. We selected offshore wind farms as it is currently one of the most prominent infrastructure developments that severely changes the marine environment (see Chapter 4). This rapid development in renewable energy production has been attributed to the goals set in the Paris Agreement (UNFCCC, 2018), aiming at the reduction of CO2 emissions, and by several of the Sustainable Development Goals of the "2030 UN Agenda for Sustainable Development" (UN, 2015) (Danovaro *et al.*, 2024). We selected the Dutch part of the North Sea as incorporation of nature-inclusive measures in offshore wind farms is highly encouraged by the Dutch government (Ministry of Economic Affairs, 2018). A key driver behind this encouragement is commitment to European policies such as the Green Deal, stating that the development of economic activities should "Do No Significant Harm" to the EU environmental objectives (European Commission, 2019), and the Marine Strategy Framework Directive (MSFD) targeting Good Environmental Status (GES) of the EU marine ecosystems (European Commission, 2008). However, current initiatives for implementation of nature-inclusive design measures in offshore wind farms in the Dutch part of the North Sea are yet uncoordinated and likely not meeting their full potential. Therefore, clear objectives are needed to ensure that the condition of targeted ecosystem components is at least maintained to meet the existing policies, or can even be improved effectively through interventions taken along with the development of offshore wind farms.

2.2 Approach for alignment towards operational objectives

When considering the design of nature-inclusive marine infrastructure, one should first identify the strategic objectives for the ecosystem in which the development is planned, and then define operational objectives to achieve desired environmental targets. Although the inherent dynamic variability of ecosystems makes it difficult to design marine infrastructure such that it contributes to an improved condition of certain targeted components, setting operational objectives is fundamental to enable the implementation of nature-inclusive design measures (De Vries *et al.*, 2020a). This applies for individual infrastructure projects, but even more so for the combined effect of multiple interventions on a system-scale. Addressing large-scale issues will reveal the true impact of measures and support their well-considered selection and implementation to enable their full potential (De Vries *et al.*, 2020b). However, current practices focus too little on their collective impact to reach system-scale effects. On the contrary, current designs of nature-inclusive marine infrastructure still result in an uncoordinated sprawl of individual measures that each may be effective to achieve their individual project objectives, but collectively don't contribute to the system-scale objective to achieve the desired impact for the targeted ecosystem component (De Vries *et al.*, 2020b). To mitigate this shortfall, we present a stepwise approach for alignment of the nature-inclusive designs of marine infrastructure that is to be developed in a system, to support setting operational objectives for making an impact at system-scale (see Figure 2-2).

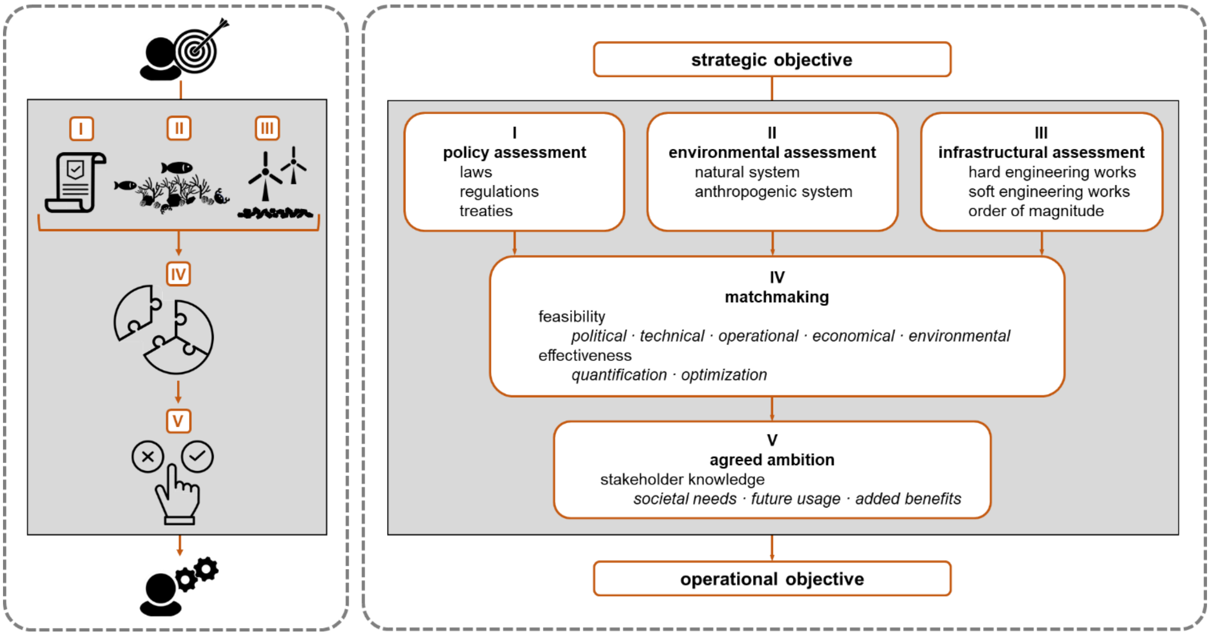

Figure 2-2: Stepwise approach for alignment towards operational objectives for designing nature-inclusive marine infrastructure.

The approach starts with assessing three fundamental elements of the system that are to be aligned: Policy assessment (I), identifying and prioritizing the objectives of existing and future policies and legislation towards nature; Environmental assessment (II), identifying and prioritizing the potential of the environmental conditions for improving ecosystem components; and Infrastructural assessment (III), identifying and prioritizing the potential of nature-inclusive marine infrastructure, including defining design modifications. Next, matchmaking (IV) has to be done between ruling policy, environmental conditions, and infrastructural potential, to determine whether the identified measures don't conflict with each other, preferably even have mutual positive effects, and to achieve a set objective for the targeted ecosystem component, which we defined as system-scale impact. Finally, an achievable agreed ambition (V) between the relevant stakeholders for implementation of potential measures is needed, for which operational objectives can be defined.

2.2.1 Step I - Policy assessment

Policies adhere to (inter)national laws, regulations and treaties, and implementing nature-inclusive elements in infrastructural designs is subject to legislative frameworks and associated permitting processes. Sometimes these processes are complex and uncoordinated, thereby impeding the implementation of nature-inclusive design measures in infrastructural development projects (Shumway et al, 2021). For instance, legislation may require specific requirements of constructions being built using certain materials, inhibiting the use of nature-inclusive elements (Dhakal and Chevalier, 2017). Another example is the observation that local legislation in the Netherlands does not allow sand borrow pits to exceed 2 m in depth, though it has been observed that creating a seabed with deep pits of 20 m during sand extraction would increase benthic biodiversity (de Jong *et al.*, 2015). On the contrary, policy and legislation can also enable incentives for the implementation of nature-inclusive infrastructural development, when policy makers adhere to these, such as the United Nations Decade of Ocean Science for Sustainable Development (2021–2030), the United Nations Decade of Ecosystem Restoration (2021–2030), and the European Green Deal (Abelson *et al.*, 2020). The EU Floods Directive, for example, has inspired at least 26 EU member states to include nature-based solutions in their water retention plans (Gerritsen *et al.* 2021). Another example, but at a local level, exists in Maryland (USA) where living shorelines are promoted by the Living Shoreline Protection act from 2008, stating that by default natural and nature-based infrastructure should be used for shoreline protection, unless a property owner can demonstrate the need to put in a built feature (Sutton-Grier *et al.*, 2018). Depending on the ruling authority, policies vary in extent from local to international seascapes, which should be recognized when defining feasible objectives for nature-inclusive marine infrastructure.

2.2.2 Step II - Environmental assessment

For nature-inclusive marine infrastructure to achieve its full potential at the system-scale, a thorough understanding of the functioning of that system is required. It is important to consider both the historic and present situation (see Chapter 4), but also future site conditions given current projections of global climate change and changes in ecosystem services (Suding, 2011; Howie and Bishop, 2021). The local environment contains both the natural system, which includes abiotic as well as biotic components, and the anthropogenic system. For the description of the conditions of a system is it advisable to adhere to those provided in a standard procedure as commonly used for an Environmental and Social Impact Assessment (Laboyrie *et al.*, 2018), such as to the one mandatory in the European Union, the EU's Environmental Impact Assessment Directive (European Commission, 2014), or to principles practiced more globally and provided by the International Association for Impact Assessment (www.iaia.org/best-practice.php). An impact assessment generally covers basic variables of the physical environment (e.g. geology, meteorology, hydrology, water and air quality, etc.), biological environment (e.g. fish and benthic communities, marine megafauna, birds, etc.), the anthropogenic environment (e.g. fisheries and aquaculture, socio-economic profile, traffic and navigation, cultural and archeological heritage, etc.) (Laboyrie *et al.*, 2018).

Essential for nature-inclusive design of marine infrastructure is to clearly define which components of the ecosystem are to be targeted. One could for example strive for establishing more biodiversity, or for promoting threatened species or habitats. Consensus on the nature-inclusivity target allows for the selection of measures to be incorporated in the design of the foreseen marine infrastructure, and the determination of the system-scale required to achieve the target. Sometimes a specific species is considered to represent a range of co-occurring species, which are assumed to co-develop similarly as that species (Fleishman *et al.*, 2000; Lengkeek *et al.*, 2017). Selecting such a so-called umbrella species as target for nature-inclusive design can be favoured, as focusing on one species eases the design process of measures, while the effect of the measures is assumed to benefit a range of species. Also, when monitoring the effect of the measures, it is often more cost-effective to only sample one species than an entire assembly (Fleishman *et al.*, 2000). However, it is always preferred to monitor the impact of a rigorous intervention such as the construction of marine infrastructure on all abiotic and biotic components of the system, in order to determine whether the desired effect has been achieved and side-effects have occurred.

2.2.3 Step III - Infrastructural assessment

Man-made marine infrastructure such as dredged channels, breakwaters, sea-walls and scour protection can provide important habitat for marine organisms to spawn, to nurse, to forage, or to find shelter (Dafforn *et al.*, 2015b; see Chapter 6). There is a vast potential to include elements that can benefit selected ecosystem components in the design of the infrastructure. The generally long-term lifetime of marine infrastructure allows the associated marine life at and around it to develop, and designs can be optimized to target desired species, habitats or processes (see Chapter 6). Marine infrastructure can be categorized under hard engineering works and soft engineering works. Hard engineering comprises marine infrastructural development using hard structures, including rubble mound structures (e.g. breakwaters), gravity-based structures (e.g. seawalls), pile foundations (e.g. offshore platforms) and floating structures (e.g. offshore wind turbines). Soft engineering involves human control on natural processes primarily through dredging works, including for example beach nourishment, salt marsh creation and capital dredging of channels. Within both categories, conventional engineering solutions can already benefit marine ecosystem components, and optimizations in the design can further increase these benefits.

In order to the determine the potential of using infrastructure development for promoting ecosystem components, one should first identify which design options are available and could function in the system. Second, one should consider design optimizations (see Chapter 6). It is recognized that marine construction works first serve human needs, not nature goals, but optimizing the infrastructure does provide an opportunity to benefit ecological values at system-scale. This should never be used as excuse to ignore or down-play the negative impact that infrastructural developments may have on a marine system (Firth *et al.*, 2020). However, marine construction works can be synergized with the functioning of the ecosystem in which they are build much better than is currently practiced, and one should always strive for nature-inclusive features in their designs (Pioch *et al.*, 2018; see Chapter 6).

2.2.3.1 Hard engineering works

The hard substrate used in marine infrastructure is known to act as artificial reef substrate (e.g. Bishop *et al.*, 2017; Coolen *et al.*, 2020; Degraer *et al.*, 2020), though the associated communities are often observed to be less diverse and abundant than natural assemblages and nonindigenous species due to their low surface complexity and non-natural materials (Glasby et al; 2007; Gittman *et al.*, 2016). Hard engineering works can be adjusted to increase the habitat complexity by bringing in more variety in use of materials and their texture, shape and dimensions, which is expected to result in a higher biodiversity (e.g. Dafforn *et al.*, 2015a; Pioch *et al.*, 2018; Strain *et al.*, 2018). For example, the use of calcareous rock such as limestone or marble will trigger increased settlement by shellfish (Hidu *et al.*, 1975; Soniat *et al.*, 1991). If concrete is used as a construction material, it can be enriched with calcium carbonate, making it potentially a more preferable settlement substrate for shellfish larvae (Cuadrado-Rica *et al.*, 2016; Potet *et al.*). The texture of concrete can also be roughened to mimic natural rock to promote the colonization by pioneering species (Moschella *et al.*, 2005; Potet *et al.*, 2021). The downside of using concrete is its toxicity as the cement mortars often leach trace metals over time (Hillier *et al.*, 1999; Wilding and Sayer, 2002), which can be reduced by using nature-friendly adhesives in the mortar (Perkol-Finkel and Sella, 2014). Irregular extensions of infrastructure in both vertically and horizontally directions will increase surface area and provide leesides for marine organisms to shelter (Firth *et al.*, 2014; Consoli *et al.*, 2018; see Chapter 4). Narrowing down the rock grading in rubble mound structures will results in more crevices, and variation in rock size at different locations will increase habitat diversity, serving a wide range of rock-dwelling species (see Chapter 3). All such measures can be incorporated into the design of nature-inclusive marine infrastructure.

2.2.3.2 Soft engineering works

Soft engineering works may also positively affect marine species (e.g. Todd *et al.*, 2014). For instance, dredged channels were observed to be favoured over other habitat types by dolphins as the structural features aid to trap prey (Allen *et al.*, 2001), and beach nourishments can be used to restore or create nesting habitats for shorebirds and turtles (Jones & Mangun, 2001). The potential optimization of soft engineering works to achieve benefits for the ecosystem lies particularly in the contours created in the seabed. Leaving borrow areas with steep sand ridges and deep pits after sand extraction, leads to a decrease in bed shear stress and settlement of fine sediment and organic matter. This diversity in bedform can result in a 10- to 20-fold higher biomass of benthic and demersal organisms than would be the case with a plane seabed (de Jong *et al.*, 2014; 2015). Applying a mega-nourishment for coastal protection instead of regular nourishment strategies would increase beach volume and the opportunity to vary habitat relief, leading to distinct communities and higher species richness of coastal fauna (van Egmond *et al.*, 2018).

2.2.3.3 Order of magnitude

Actions to promote targeted components of an ecosystem should be executed at a scale large enough to be functionally successful and cost effective (Abelson *et al.*, 2020). Making use of infrastructural development can support this by offering technological advances to reach both efficiency of scale (Abelson *et al.*, 2020) and economy of scale (Price and Toonen, 2017). To estimate the potential effect on ecosystem components, and to determine the required scale of interventions to be taken to become significantly effective, one should quantify the potential effects of the measures prior to their implementation (see Chapter 4). The outcomes may support decision-making when designing nature-inclusive marine infrastructure to contribute to the desired system-scale impact. Predicting the effects of such measures will provide insight into the magnitude of effort required to reach the desired impact (see Chapter 4).

2.2.4 Step IV - Matchmaking

Matchmaking is the process of evaluating the system against its ruling policy (I), its environmental conditions (II), and its foreseen infrastructural development (III), to determine its potential for benefitting selected ecosystem components. These three elements should match in a manner that their combination reveals opportunities for nature-inclusive design at the required system-scale, promoting effectively a targeted component of the ecosystem within the area. An example of a good match, though not at system-scale, is the development of the Sand Motor in front of the Dutch coastline, a large foreshore nourishment of 128 hectares to contribute to long-term coastal protection. The design of the Sand Motor included a lagoon area with the target to become an appealing feeding and resting place for birds, and indeed was observed to have a positive effect on some species of waders, seagulls and cormorants (Huisman *et al.*, 2021). In the case of the Sand Motor, local policy (I) states to protect all wild bird species and to protect and restore their habitats (e.g. European Commission, 2009). Furthermore, the area lies within the distribution range of many of these birds and offering a suitable environment (II) to host them, and the infrastructural design (III) was optimized with the lagoon area to provide optimal feeding and resting grounds. A similar match would not apply in the area if the infrastructural element would be for example a wind farm, which is recognized for causing negative impact on bird populations (e.g. Furness *et al.*, 2013; Garthe *et al.*, 2023). Although this nature-based foreshore nourishment solution is likely able to create an impact at system-scale if also implemented at other locations along the Dutch coastline, the potential effect of multiple applications has yet not been assessed (De Vries *et al.*, 2020b).

Part of matchmaking is checking the feasibility and effectiveness of potential nature-inclusive measures to meet the prospective. A feasibility check comprises for example assessing the political, technical, operational, economical, and environmental elements. The feasibility assessment includes political, technical, operational, economical and environmental aspects. Political feasibility relates to the societal readiness for the implementation of measures, whether these are possible within the local regulations and socially acceptable. Technical feasibility concerns assessing whether the implementation of a foreseen measure is technically possible, for which the Technology Readiness Level (TRL) is a good parameter. The more mature a technology is, the more likely it can be implemented. The operational feasibility includes organizational issues, operability, accessibility of a location, required effort and limitations due to legal aspects. Economical feasibility relates to the costs of a measure to be successful, strongly determined by being active or passive, the latter generally being less expensive, as this requires less labour, technologies and personnel, e.g. the limitation of fishing activities (Fox *et al.*, 2019). Environmental feasibility concerns whether any proposed intervention with the intention to promote selected ecosystem components would fit within the ecological boundaries of the system.

Assessing the effectiveness of measures involves quantifying their potential effect, determining the required scale for implementation, and optimizing designs to achieve the highest results. A quantitative assessment of each intervention would be based upon existing knowledge and should take into account the prevailing conditions in the designated area (see Chapter 4). Knowing the potential effect will allow to make informed decisions on the selection of measures for implementation.

2.2.5 Step V - Agreed ambition

Once the potential has been identified for designing nature-inclusive marine infrastructure to benefit targeted ecosystem components, it is required to reach agreement on achievable ambitions for the system in which actions are foreseen. For this step, knowledge of the system is key, as weighing and ranking ambitions depends on multiple aspects such as, societal demands for the system, whether the identified required scale of a measure fits the system, knowing the future usage of the area, and any additional side-benefits from a measure. During this process of marine spatial planning, the spatial and temporal distribution of human activities in marine areas are analysed and allocated, with the aim to achieve ecological, economic, and social objectives (Ehler and Douvere, 2009). It has been accepted as a practical tool to sustainably manage the marine environment through a participatory approach around the globe, though it is recognized that the process of stakeholder engagement still faces some challenges (e.g. Ehler, 2021; Santos *et al.*, 2021). Profound stakeholder engagement will ensure that all knowledge from different user groups is incorporated when defining interventions that can promote selected ecosystem components. The combination of engineering, ecological and governance perspectives can yield new opportunities to improve the feasibility of nature-inclusive infrastructural development projects in sensitive environments while meeting societal demands and legislative constraints (Laboyrie *et al.*, 2018). To achieve success after implementation, all relevant users of the system should commit to jointly set objectives, long-term as well as financially (Saunders *et al.*, 2020). Tools for stakeholder involvement are available to ensure that their ideas, interests, and concerns are consistently addressed, and include for example open collaboration in policy modelling through building ICT-based scenario’s (Wimmer *et al.* 2012), engaging panels of experts through surveys such as the Delphi method (Linstone and Turoff 1975), or group model building that includes simulating policy choices through role playing (Vennix *et al.* 1996).

During the process of agreeing upon an achievable ambition, the potential impact of measures on the original environment should carefully considered. For example the addition of hard structures in a sandy environment will change the available habitats, affecting the diversity and function of the system (Bulleri and Chapman, 2010; Davis *et al.*, 1982; Martin *et al.*, 2005). The losses of the original habitat need be assessed and in general be minimized if possible (Dafforn *et al.*, 2015b). In situations where hard structures cannot be avoided, or are even desired, there is the potential for eco-engineering to mitigate the impacts of these structures and to maximize potential ecological outcomes (e.g. Chapman and Blockley, 2009).

Once an agreed ambition has been reached, the operational objectives can be defined to achieve the desired ecological impact. These objectives are fundamental for making the design of a nature-inclusive infrastructural development. The 'Frame of Reference' approach can be used to transfer the operational objectives into functional engineering designs, and to assess their performance once applied in practice (Van Koningsveld, 2003; De Vries *et al.*, 2020a; Figure 2-1).

2.3 Application of the approach

To be able to exploit the full potential of infrastructural development to strengthen the ecological values of a system, it is key to set clear operational objectives. Our stepwise approach to determine such operational objectives for a system involves the assessment of the ruling policies in an area, the local natural and anthropogenic system, and the benefits of potential infrastructural developments. Next, an inventory of potential design measures for nature-inclusive marine infrastructure is made and assessed for their feasibility and effectiveness. Finally, an agreed ambition on measures to be taken should be reached between relevant stakeholders, for which then operational objectives can be defined. The functionality of this stepwise approach will be demonstrated in a fictive case for setting operational objectives to promote components of the subsea ecosystem in the Dutch North Sea, aligned with offshore windfarm development.

2.3.1 Case description

2.3.1.1 Offshore windfarm development in the Dutch North Sea

The offshore wind energy industry is rapidly growing in the North Sea. In the southern North Sea alone, 62 windfarms with total surface of 3,388 km2 and capacity of 20,6 GW have been installed during the first two decades of this millennium, and the tenfold in surface area is designated to develop offshore wind energy production (see Chapter 4). These areas are generally closed for bottom-disturbing activities such as bottom-dwelling fisheries or sand extraction during the lifetime of the wind farms. They also offer hard substrate by means of the wind turbine foundations and rock material placed at the base of the turbine foundations and on top of cable crossings to prevent scouring of the seabed (see Chapter 4). For these reasons, offshore wind farms provide an environment ideal for the development of the epibenthic ecosystem, offering opportunities for biogenic reefs to develop and other organisms to forage and find shelter from human disturbances (Petersen and Malm, 2006; Coolen *et al.*, 2020; Degraer *et al.*, 2020).

The Dutch government has the strategic objective to rehabilitate the North Sea ecosystem, and to make offshore wind farms (see Figure 2-2) contribute to it through implementing nature-inclusive design measures (e.g. Ministry of Economic Affairs, 2018). However, in order to reach strategic objectives, one requires a coherent overarching realization scheme for such measures (de Vries *et al.*, 2020b). Enabling large scale ecosystem restoration and/or ecological development in offshore wind farms requires setting up an overarching coordinated framework that sets clear targets. Otherwise, well-meant initiatives are bound to range widely in technical solutions per wind farm, being suboptimal or even ineffective at the larger scale (de Vries *et al.*, 2020b). The systematic approach that we present supports in this process to identify and align applicable policies, the ruling environmental conditions, and the potential of the infrastructure, and determine measures that could promote targeted components of the subsea ecosystem in offshore wind farms in the Dutch part of the North Sea (see Figure 2-3).

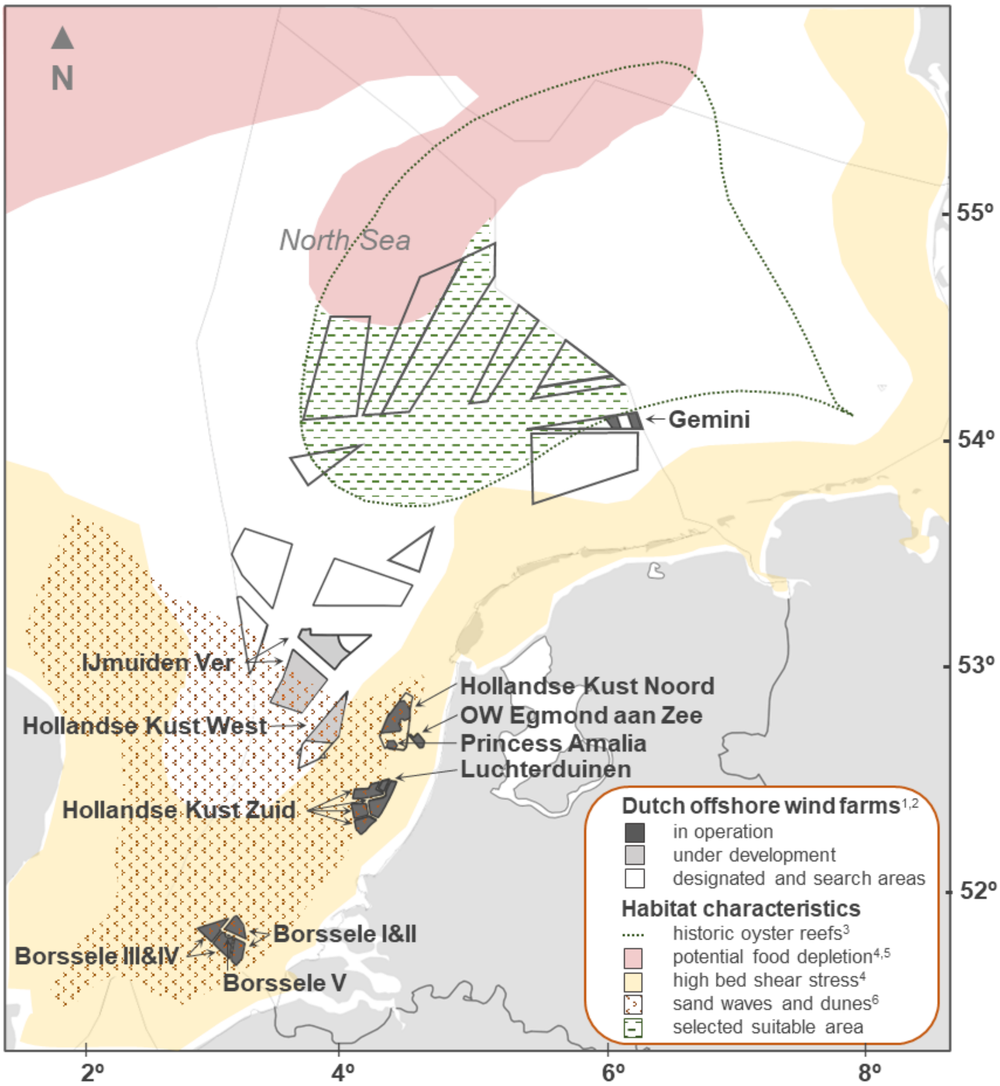

Figure 2-3: Offshore wind farms in the Dutch part of the North Sea. Compiled with QGIS 3.22; data sourced from [1]emodnet.ec.europa.eu; [2]Ministry of Infrastructure and Water Management 2022, [3]Bennema et al., 2020; [4]Kamermans et al., 2018; [5]Van Leeuwen et al., 2015; [6]Van der Veen et al., 2006.

2.3.1.2 Evolving ecological requirements for offshore wind farms

Efforts to protect and improve ecosystem components in the Dutch part of the North Sea using offshore wind farms are evolving. The first Offshore Wind farm Egmond aan Zee is in use since 2007 and its development did not include any nature-inclusive measures, though its impact on the environment was concisely monitored (Lindeboom *et al.*, 2011). The installation of following wind farms Princess Amalia (2008), Luchterduinen (2015) and Gemini (2017) focused mainly on the protection of marine organisms such as mammals and fish from impulsive underwater sound caused by piling of the turbine foundations. A decade after the construction of the first offshore wind farm, their development required an 'obligation to undertake demonstrable efforts' to contribute to the strengthening of a healthy sea and to the preservation and sustainable use of endemic species and habitats in the Netherlands. This commitment was firstly formally included in the site decision of Borssele OWF lots I in 2016 (Staatscourant, 2016), and is considered an effort to utilize the momentum of the large-scale development of offshore wind farms for ecological benefits. Also the extension of the Borssele windfarms (2020) and Hollandse Kust Zuid (2021) and -Noord (2022) required to adhere to this commitment. Currently, preserving and improving the ecology of the North Sea has even become a strong requisite in the design, construction and operation of offshore wind farms, being a determinative component in the most economically advantageous tender (MEAT) criteria for offshore wind farms Hollandse Kust West Lot IV (Staatscourant, 2022) and IJmuiden Ver Lot Alpha (Staatcourant, 2023). Processes like these lead to the commercial incentivization of ecosystem restoration and creation in offshore wind farms (Stechele *et al.*, 2023a).

A way of integrating nature-inclusive designs in offshore wind farms is to promote target species, e.g. being either umbrella species covering 'overall native biodiversity' or policy relevant species (Lengkeek *et al.*, 2017). The umbrella species Atlantic cod (*Gadus morhua*) and policy relevant species European flat oyster (*Ostrea edulis*) were explicitly addressed in the Site Decisions for the recent Dutch wind farms Hollandse Kust Noord (Staatscourant, 2019) and Hollandse Kust West (Staatscourant, 2022). In the Site Decision for the latest offshore wind farm development project IJmuiden Ver, a new policy-relevant species was introduced, namely the biogenic reef building species Ross worm (*Sabellaria spinulosa*) (Staatscourant, 2023). To illustrate the process of the stepwise approach for setting operational objectives for nature-inclusive design of offshore wind farms in the Dutch part of the North Sea, we've selected the European flat oyster as target species (see Table 2-1).

2.3.2 Step I - Policy assessment

The nature policy for the Dutch part of the North Sea is driven by the strategic objective "to restore and conserve the integrity of the ecosystem and sustainably use the ecosystem services and products" (Ministry of Infrastructure and Water Management, 2022). The objective is practiced through commitment to European treaties, primarily by the Marine Strategy Framework Directive providing 11 Descriptors for Good Environmental Status (2008/56/EC; European Commission, 2008), which have the characteristics of operational objectives, and complemented by the Birds- and Habitat Directives (2009/147/EC; European Commission, 2009) (Mulder, 2022). With respect to the development of offshore wind energy, the Dutch nature policy focuses on the nature-inclusive design, installation and operation new wind farms. This approach offers opportunities for strengthening species populations and habitats that occur naturally in the North Sea and for carrying out nature restoration projects within wind farms (Mulder, 2022).

A Dutch policy relevant for the development of the European flat oysters comes from commitment to the European Marine Strategy Framework Directive. Dutch government has set the environmental target (D6T5) for the 'return and recovery of biogenic reef structures including flat oyster beds' in part 1 of the Dutch Strategy for the period 2018-2024 (Ministry of Infrastructure and Water Management, and Ministry of Agriculture, Nature and Food Quality, 2018), and incorporated it as well in the Dutch North Sea Program 2022-2027 (Ministry of Infrastructure and Water Management, 2022).

2.3.3 Step II - Environmental assessment

Wind farm locations relatively suitable for oyster reef development have been appointed based upon habitat suitability, larval retention, food availability, and historical presence (Smaal *et al.*, 2017; Kamermans *et al.*, 2018a,b; Herman and Van Rees, 2022; Stechele *et al.*, 2023b; Van Duren *et al.*, 2022, 2023). The most important characteristics of habitat suitability relate to the presence of a stable seabed, meaning little seabed mobility (sand waves), low bed shear stress, and a composition that provides a consolidated foundation, such as stable sands, stiff muds, shells or rock (Héral and Deslous-Paoli, 1991; Houziaux *et al.*, 2008; Smaal *et al.*, 2017; Hughes *et al.*, 2023). Larval retention is assumed to be highest in areas at or near their production, and therefore its assessment accounted for the source locations and dispersal rates (Herman and Van Rees, 2022). Food availability is related to the stratification of the North Sea during the summer season, reducing the transport of the main food source phytoplankton to the seabed. Areas with high seasonal stratification are therefore assumed less suitable for oyster reef development, opposed to areas that are nearly fully mixed (Kamermans *et al.*, 2018a; van Leeuwen *et al.*, 2015;Stechele *et al.*, 2023b). For estimating the historical presence of oyster reefs, data was used from Olsen (1883), Houziaux *et al.* (2008), and Bennema *et al.* (2020). Note that the potential for oyster reef development offered by the infrastructure in offshore windfarms (see Chapter 4), in particular in terms of hard substrate offered by the rock material used as scour protection, was not taken into account in these studies. Other main factors of importance for the survival of flat oysters are oxygen content in the water and food availability by means of phytoplankton, but these are not limiting in the Dutch part of the North Sea (van Leeuwen *et al.*, 2015; Van Duren *et al.*, 2022). The potential suitable area for oyster reef development in the Dutch part of the North Sea is visualized in Figure 2-3, drafted from their historic distribution (Bennema *et al.*, 2020) and the prime environmental factors that hamper their development, i.e. bed shear stress (Kamermans *et al.*, 2018), sand waves (Van der Veen *et al.*, 2006), and potential food depletion based upon stratification (Van Leeuwen *et al.*, 2015).

2.3.4 Step III - Infrastructural assessment

Once in operation, offshore wind farms provide an undisturbed seabed and hard substrate infrastructure which both make them suitable for oyster reef development (Degraer *et al.*, 2020; Kamermans et al, 2018b; see Chapters 3 and 4). For safety reasons, the wind farm developers have successfully excluded bottom disturbing activities such as bottom-trawl fisheries from the concession zones around their underwater infrastructure such as turbine foundations and cable routes. The exclusion of disturbing activities from these concession zones has resulted in quasi-marine protected areas providing refuge for benthic habitats and species such as oysters (Hammar *et al.*, 2016). The infrastructure of offshore wind farms inherently provides artificial habitat, allowing long-term development of targeted ecosystem components, and its design can even be optimized to target desired species (see Chapter 6). The type of infrastructure used for offshore wind farms is dependent upon the system in which it is build. In particular the support structures for the wind turbines will vary, either fixed-support or floating. The fixed-support types are gravity-based and the turbines are placed on for example monopile foundations or jackets. Their primary constraint is the limited depth in which they can be build, as in waters of over 60 m depth, they become commercially inviable due to a considerable increase in costs (The Carbon Trust, 2015). Floating wind turbines are held in place through mooring cables connected to the seabed. Their costs are generally higher than gravity-based turbines, and also significantly increase with water depth (Kausche *et al.*, 2018). Gravity-based designs of wind turbines can likely include the highest benefits for increasing epibenthic biodiversity, in particularly when placed on sandy substrate. Here they require a scour protection, generally by means of rocky substrate, which forms a suitable habitat for the development of marine flora and fauna (Petersen & Malm, 2006; Degraer et al, 2020; Glarou et al, 2020). Such benefits for epibenthic biodiversity should be taken into account when selection the type of windfarm in the design process. To increase biodiversity or the presence of targeted rock-dwelling species using scour protection, small adaptations in material use, texture, and shape can improve the conditions for settlement, growth and use by a variety of marine organisms even more, while keeping the function of the scour protection intact (see Chapter 4). In case of oyster reef development, the main adaptations in the scour protection design for would include the use of calciferous rock material such as limestone or marble, containing a high amount of calcium which is beneficial to shellfish species (Hidu *et al.*, 1975; Soniat *et al.*, 1991). Furthermore, the scour protection should be designed with rock material of a grading size large enough to provide stable substrate (Van Velzen *et al.*, 2014), as moving rocks cause physical damage or even mortality to the oysters. Also, extending the dimensions of the scour protection would increase the area of hard substrate for settlement by oyster larvae, and variation in shape could create areas with reduced flow velocity to improve the opportunities for settlement (Korringa, 1940; Smaal *et al.*, 2017). Over time, the oyster reef development is even expected to contribute to the stabilization of the scour protection by effectively binding the rocks, in particular those of a smaller grading size (Domisse, 2020).

2.3.5 Step IV - Matchmaking

The combination of the ruling policy, environmental conditions, and presence of offshore wind farms in the Dutch part of the North Sea offers great potential for oyster reef development. This match is based upon an assessment of both the feasibility and effectiveness of the potential measures that can be taken to establish oyster reefs using the infrastructure in offshore wind farms.

2.3.5.1 Feasibility

The feasibility assessment includes political, technical, operational, economical and environmental aspects.

From a political perspective, it is highly feasible to develop oyster reefs in Dutch offshore wind farms, as there’s general support from government, developers, scientists, and the public society. The government has been setting requirements for oyster reef development in the site decisions for new wind farms, e.g. in windfarms Hollandse Kust Noord and -West (Staatscourant, 2019; 2022). Wind farm operators have shown their willingness by taking measures to initiate reef development in wind farms Gemini, Borssele 3&4, Borssele V, and Luchterduinen (e.g. Didderen *et al.*, 2019). The scientific community has stressed the potential to use wind farms for oyster reef restoration practices (e.g. Lengkeek *et al.*, 2017; Kamermans *et al.*, 2018b). From public society, no opposition has been reported, and oyster reef development is generally advocated by non-governmental organizations (e.g. Sas *et al.*, 2019; Vrooman *et al.*, 2019).

From a technical perspective, Dutch offshore wind farms offer great potential for oyster reef development. The seabed in the area refrains from disturbance as no bottom disturbing activities are allowed during the operational lifetime of the wind farms. The infrastructure of the windfarms by means of the scour protection at the base of the turbine foundations and at the cable crossings, offers excellent substrate for settlement of larvae. The infrastructure could even be further optimized by making small adaptations in material use, texture, and shape to further improve settlement conditions (see Chapter 4).

From an operational perspective, multiple pilot studies have shown that interventions can be taken in offshore wind farms to trigger oyster reef development. For example, adjustments to the scour protection were made to facilitate oyster larvae settlement in several Dutch offshore wind farms: In Borssele 3&4, 20 m^3 of clean shell material was placed in the scour protection at the base of 8 wind turbines foundations; in Hollandse Kust Zuid, a sprinkler layer of marble rock was placed at 4 cable crossings; and in Hollandse Kust Noord, berms of marble rock were placed at the scour protection of 42 wind turbines. In addition, to initiate larvae production and kickstart reef development, oyster broodstock was installed in wind farms Borssele 3&4, Borssele V, Luchterduinen, and Gemini (Didderen *et al.*, 2019), and at all locations the broodstock was shown to survive, grow and reproduce after installation.

From an economical perspective, feasibility relates to the costs of a measure to be successful. All activities in the offshore environment are generally considered to be costly due to the required vessel time. However, the fact that many activities have already taken place to develop oyster reefs in offshore wind farms, demonstrates their feasibility, independent of the costs. Cost reductions can be achieved by wisely selecting and implementing interventions. For example on a small scale, the deployment of oyster broodstock fixed on stable structures will provide a dense and lasting source of adult oysters to ensure local larvae production, while deployment via loose distribution would require a far greater amount of oysters to ensure the same sized broodstock over time, due the high risk of losses caused by severe hydrodynamic conditions. On a larger scale, costs of vessel time include the expensive mobilization and demobilization of a vessel for a specific purpose. The longer a vessel can be at sea, the daily costs of the activity becomes relatively lower. Therefore, it is recommended to combine as much as feasible the various activities that are aimed at promoting targeted ecosystem components, or even align them fully with the standard wind farm installation and operation activities. For example, the deployment of calciferous rock aimed at increasing oyster larvae settlement rates should be executed in line with the installation of the functional scour protection, and preferably even be fully integrated in its basic design; post-construction deployment as an add-on should be avoided at all times to save on costs.

From an environmental perspective, offshore wind farms in the Dutch part of the North Sea are generally considered suitable for oyster reef development. The environmental conditions however vary throughout the region, leading to different levels of suitability. Although all current and likely future Dutch offshore wind farms offer substrate for oyster reef development by means of their scour protection at the base of the turbine foundations, the vast seabed area in between the turbines does not. Oysters require a stable seabed with low hydrodynamic forces such as bed shear stress. These conditions are not present in the southern part of the Dutch EEZ (Kamermans 2018b; van Duren *et al.*, 2023; see Figure 2-3). In order to utilize wind farm areas for oyster reef development to its full potential, meaning not only at the scour protections, but also at the seabed in between, it is therefore recommended to focus efforts to establish oyster reefs in the current and future wind farms in the northern part of the Dutch EEZ (Van Duren *et al.*, 2023). However, the tip of the Dutch EEZ around 55º latitude is considered unsuitable due to poor food availability in the summer season as a consequence of stratification (Kamermans *et al.*, 2018a; see Figure 2-3). These considerations would leave an area assumed most suitable for oyster reef development around the 54º latitude (see Figure 2-3).

2.3.5.2 Effectiveness

In order to select measures to establish oyster reefs in offshore wind farms, their potential effect needs to be quantified first. Knowing the impact of the presence of the wind farm itself, and of the additional interventions to increase it, allows to make informed decisions in setting the operational objectives for oyster reef development in an area. The quantification provides insight in the required order of magnitude of the potential effects, needed to determine the type and scale for selecting measures to achieve a desired result. A stepwise procedure designed in particular to guide the selection of appropriate interventions and their required scale for pro-actively facilitating flat oyster reef development in offshore wind farms, is presented in Chapter 4. The procedure makes use of available knowledge, allowing inclusion of most recent insights. An assessment of the wider Southern North Sea bordered by England (UK) on the west, and Belgium, The Netherlands, Germany and Denmark on the east, learned that oyster reef development in offshore wind farms at least requires a human-induced accumulation of broodstock in the wind farms due to the lack of connectivity with the scarce natural reefs (see Chapter 4). Succeeding development of oyster reefs within a wind farm area is suggested to be facilitated by providing suitable substrate for larvae settlement. Provision of clean shell material would be the most beneficial, in potential offering oyster densities 150 times higher than on rock material and 8000 times higher than on a sandy seabed. However, the supply of shell material is not unlimited, and also not without impact on the existing environment when being collected. Therefore, a focus on providing suitable settlement substrate using rock material, such as already applied in the scour protections in wind farms, would be a good alternative. Optimization of these scour protections for oyster reef development can be achieved by using most suitable rock material, and adjustment of the conventional shape. Calciferous rock material such as marble could in increase settlement rates by factor 1.33 (Tonk *et al.*, 2020), and simply extending the scour protection horizontally would increase settlement opportunities linearly, particularly if done for the armour layer which won't disappear on a layer of sand as is the case for the filter layer (see Chapter 3).

2.3.6 Step V - Agreed ambition

Now that the potential for oyster reef development in the Dutch part of the North Sea has been identified, it is needed to reach agreement on achievable ambitions to do so, for which operational objectives can be defined next. The ambition should be agreed upon by relevant stakeholders, of whom their knowledge of the political and environmental system and of the potential for implementation of interventions are key to ensure that the ambition will be achievable. The main four stakeholder groups for this case study would at least include i) relevant Dutch Ministries having legislative authority of the area, ii) research institutes with knowledge about the environmental conditions, iii) marine contractors providing engineering solutions, and iv) wind energy developers being the owners of the offshore wind farms.

The demonstration of the functionality of our stepwise approach is merely applied for a fictive case. Therefore an actual stakeholder involvement process was not performed, but we confined ourselves to assuming a probable perspective for each of the four stakeholders towards oyster reef development in Dutch offshore windfarm: Governmental authorities (i) would be supportive, following their incentive to "return and recover biogenic reef structures including flat oyster beds", and have the powerful tool of setting requirements to enforce oyster reef development in site decisions for new offshore wind farms. The scientific community (ii) would stress the need for windfarms to have suitable environmental conditions, and a connected, preferably continuous, areal large enough to host a self-sustainable population. The wind farm developers (iii) would be willing to invest in taking nature-inclusive measures to meet contractual obligations and to strengthen their corporate image, though a predictable income from energy production should be guaranteed. Marine contractors (iv) would offer the capability to design and implement engineering solutions to support oyster reef development, but require guidance on the required type and extent of interventions.

Considering the stakeholder perspectives, it can be concluded that habitat suitability would be the main driver for agreeing upon development of oyster reefs in specific offshore wind farms, as it is the only aspect that varies across the Dutch part of the North Sea (see Figure 2-3). On the contrary, the Dutch policy (to recover flat oyster beds) and the type of existing and future wind farm infrastructure (a monopile foundation with rocky scour protection at its base), are generally more uniformly distributed.

An area suitable for oyster reef development that offers a stable seabed and year-round food availability, is present in the Dutch part of the North Sea broadly around the 54º latitude (Kamermans *et al.*, 2018b; van Duren *et al.*, 2023; see Figure 2-3). The area is partly overlapping with the historic presence of oyster beds (Olsen, 1883; Houziaux *et al.* 2008; Bennema *et al.*, 2020). The highest potential to establish oyster reefs successfully is generally thought to be in an area with both suitable environmental conditions and historic presence of oyster reefs (Kamermans *et al.*, 2018a,b; Stechele *et al.*, 2023b). Therefore, the area around 54º latitude and between 4º and 6º longitude could be appointed to initiate oyster reef development in the Dutch part of the North Sea (see Figure 2-3). This area also includes search areas for future offshore wind farms (see Figure 2-3), eventually offering the valuable infrastructure for hosting oyster reefs, which could be optimized even further to provide the most suitable conditions.

Currently, observations of flat oyster reefs presence have not been reported for the area, nor is connectivity with existing reefs to be expected (see Chapter 4). Therefore, active introduction of oysters for local larvae production to initiate reef development would be required. A preferred starting population would be one that can become self-sustaining over time. An amount of 20,000 oysters was suggested as the minimum starting population size to exceed a limited critical mass of 100,000 oysters (at high densities of 82 m^{-2}) within 3 years (Smyth et al, 2016; Kamermans *et al.*, 2020). For such a population to be able to develop into a size as used to be present in the late 19th century, a large area, exceeding individual wind farms, is needed (see Chapter 4). This means that all future offshore wind farms in the area should embrace the ambition to host oyster reefs. Further increase of the oyster population can be achieved by optimizing the wind farm areas to provide suitable hard substrate habitat. Optimizations could include increasing the habitat complexity of conventional scour protection by bringing in more variety in use of materials, shapes and dimensions (see Chapter 4), and the installation of longlines hosting vertical mussel reefs that provide a continuous supply of shell material and will thereby provide most suitable settlement substrate for oyster larvae (see Chapters 4 and 6).

The agreed ambition between the prime stakeholders to restore oyster reefs in the Dutch part of the North Sea could be threefold, i.e. 1) to concentrate efforts in the future offshore wind farms located in the area that is considered most suitable for oyster reefs, i.e. around 54º latitude and between 4º and 6º longitude (see Figure 2-3); 2) to initiate oyster reef development by deploying sufficient broodstock for the population to become self-sustainable; and 3) to provide settlement substrate as part of the wind farm infrastructure for the oyster reefs to thrive upon in higher densities than at the existing seabed. The operational objective would accordingly become: Actively introduce oysters to reach an initial critical mass of 100,000 individuals and optimize settlement habitat at all future offshore wind farms in the area with suitable habitat characteristics. This operational objective would provide the starting point for the next step, i.e. defining and actually implementing quantified technical solutions needed to reach the objective, using a tool like the 'Frame of Reference' approach (see Figure 2-1). The application of this approach was demonstrated to further stimulate the integration and cooperation of science, policy and management during the process of defining functional engineering designs and assessing their performance (Van Koningsveld, 2003).

Table 2-1: Overview of the main outcomes when applying the stepwise approach on the case study to derive operational objectives for oyster reef development in offshore wind farms in the Dutch part of the North Sea.

Strategic objective:	**Development of flat oyster reefs in Dutch offshore wind farms**	
Step	***Result***	***Source***
I policy assessment	MSFD target D6T5 'return and recovery of biogenic reef structures including flat oyster beds'	Ministry of Infrastructure and Water Management, and Ministry of Agriculture, Nature and Food Quality, 2018; Ministry of Infrastructure and Water Management, 2022.
II environmental assessment	Area suitability primarily based upon seabed stability (low bed shear stress, no sand waves), food availability (low seasonal stratification), historical presence.	Kamermans *et al.*, 2018a,b; Herman and Van Rees, 2022; Stechele *et al.*, 2023b; Van Duren *et al.*, 2022, 2023.
III infrastructural assessment	Offshore wind farm areas offer suitable habitat by means of undisturbed seabed and hard substrate infrastructure. Optimization potential primarily in scour protection adaptations.	Degraer *et al.*, 2020; Kamermans et al, 2018b; see Chapters 3 and 4.
IV matchmaking	Government set requirements in site decisions. Developers and scientific community showed potential through pilot studies. Cost-effective through incorporation in project design. Suitable environmental conditions present around 54º latitude. Human interventions needed to initiate self-sustaining reefs.	Staatscourant 2019,2022; Didderen *et al.*, 2019; Kamermans *et al.*, 2018a,b, 2020; Van Duren *et al.*, 2023; see Chapters 3 and 4
V agreed ambition	Commitment to required joint effort in focal area to create a self-sustaining oyster population with the potential to develop into a magnitude as historically present.	Probable outcome of stakeholder engagement (this Chapter).
Operational objective:	**Actively introduce oysters to reach an initial critical mass of 100,000 individuals and optimize settlement habitat in all future offshore wind farms in the area with suitable habitat characteristics.**	

2.4 Discussion

Marine infrastructure offers huge potential to improve the ecological functioning of the system in which it is build (Dafforn *et al.*, 2015b; Laboyrie *et al.*, 2018), and it is becoming more and more common to include nature-inclusive elements in marine construction projects (e.g. Borsje *et al.*, 2011; Firth *et al.*, 2014; see Chapter 4). In most cases, these nature-inclusive measures are designed to meet individual project requirements, fragmented, and insufficiently taking into account the opportunity to make a system-scale impact. To do so, a coherent overarching realization scheme of design measures for nature-inclusive marine infrastructure is required, with clear objectives to make the efforts effective at a larger scale beyond individual projects (de Vries *et al.*, 2020b). Strategic objectives are required to address the desired future condition of a system, defining a long-term plan with clear priorities, along with a means to monitor and assess progress (Tunnicliffe *et al.*, 2020). Operational objectives are needed to provide tangible direction to implement strategic objectives, with a clear indication of the spatial and temporal scales involved (Van Koningsveld *et al.*, 2005).

This Chapter presents a stepwise approach for defining clear operational objectives for nature-inclusive marine infrastructure to achieve impact at system-scale, in which ruling polices, environmental conditions and the potential use of marine infrastructure are aligned. It includes careful consideration of the full potential nature-inclusive infrastructure can offer, based upon an assessment of the feasibility of measures and their estimated effects. Our approach can support policy makers in achieving their environmental targets, while at the same time meeting societal demands for infrastructural development. For example member states of the European Union have set policy targets to achieve a Good Environmental Status of their marine ecosystems, being implemented by the Marine Strategy Framework Directive (European Commission, 2008), while at the same time their marine environment is increasingly used for wind energy production in order to meet renewable energy goals (European Commission, 2023). Using our approach could facilitate EU member states in the planning process of their marine waters, by identifying measures that can be implemented in the future marine infrastructure to optimize the potential benefits for ecosystem components targeted by the MSFD. Herewith policy makers might overcome the struggles they face during the marine spatial planning process, e.g. in establishing a shared transboundary vision and in aligning the different interests of stakeholders (e.g. Fraschetti *et al.*, 2018; Santos *et al.* 2021). The final selection of operational objectives for a system is still to be made through strong involvement of these stakeholders. This is to ensure that all required knowledge and expertise from various disciplines are covered, and to achieve commitment to the jointly established objectives. For example, inclusion of the scientific community, allows for the assessment of the objectives to determine their ecological feasibility and their consequences, which is often too little understood by decision makers and developers only (Lackey, 2003). Scientists provide advice on the ecological, social and economic repercussions of the objectives, and can determine courses of actions to be taken (Cormier *et al.*, 2017). However, scientists might also display implicit preferences and advocate a certain ecological state for a system, which should be avoided when providing advice for setting objectives (Lackey, 2003). This illustrates the importance of a balanced stakeholder engagement process, in which the various relevant disciplines are evenly represented.

Reaching agreement upon achievable ambitions between different stakeholder disciplines can be a difficult process. For example, going from overarching strategic objectives towards clear operational objectives was observed to lead to confusion about terminology, baseline and reference states, and defining them quantitatively (Leadley *et al.*, 2022). The process of setting operational objectives for including nature-inclusive elements in the design of marine infrastructure requires strong leadership and political will. A lack of motivation to improve legislation, vested interest in conventional infrastructural development, and insufficient funds and resources will hamper the development and implementation of measures that could benefit marine life (Dhakal and Chevalier, 2017; Johns, 2019). Stakeholder engagement during the stepwise approach to reach operational objectives for nature-inclusive marine infrastructure allows all relevant users of the system to express their interests, essential to reach long-term commitment to the set objectives.

Our stepwise approach to define operational objectives to embed nature-inclusive measures into marine infrastructure has been demonstrated for use to promote oyster reef development in offshore wind farms in the Dutch part of the North Sea. To establish oyster reef restoration in the North Sea, it is recommended to follow a coordinated basin-wide approach to reach connectivity between natural oyster beds, restoration sites, offshore infrastructure, and aquaculture sites (Stechele *et al.*, 2023a). Such can only be achieved if an overarching vision is developed for an area, including the setting of clear operational objectives for implementing measures wisely. Assessing the three major elements within the Dutch North Sea system, i.e. policy, environment and infrastructure, it is concluded that these elements match when striving for oyster reef development in offshore wind farms. The European flat oyster has been characterized as a 'policy relevant species' (Lengkeek *et al.*, 2017) and is already explicitly addressed as a target species in Site Decisions for new offshore wind farms (Staatscourant, 2019; 2022). The environmental conditions are considered most suitable for oyster reefs around the 54º latitude and between 4º and 6º longitude (see Figure 2-3), which is primarily influenced by food availability, the presence of a stable seabed with low hydrodynamic forces, and their historic presence (Kamermans 2018a,b; Bennema *et al.*, 2020; van Duren *et al.*, 2023). The area is furthermore prone to offshore wind farm development in the near future (Ministry of Infrastructure and Water Management, 2022), providing infrastructure that offers suitable substrate for oyster reef development. Considering the interests of the main stakeholders, it is highly likely that an agreement on achievable ambitions can be established, which would result in the operational objective to actively introduce oysters to reach an initial critical mass and optimize settlement habitat in all future offshore wind farms in the area.

Offshore wind farms outside of the identified area with the most suitable habitat characteristics should not be completely discarded from consideration to support oyster reef restoration. In general, at the base of each wind turbine foundation and on top of cable crossings, rock material is placed to prevent scouring of the seabed, providing good conditions for oyster reef formation (see Chapter 4). Although the majority of the seabed within a wind farm in the southern part of the Dutch Nort Sea might not be stable enough for oyster reef development, their scour protections do provide suitable substrate, and could function as steppingstones for the spread of oyster larvae (Adams *et al.*, 2014), thereby contributing to oyster reef restoration throughout the North Sea. The suitability of scour protections within these offshore wind farms can also be further optimized for hosting oyster reefs by the design of their shape and dimension and by the type of rock material used (see Chapter 4). Whichever design optimizations in a scour protection are feasible while still preserving its primary function to prevent seabed erosion, is location-specific and depends on the willingness of the developer to invest, if a cost-increase is applicable.

The final selection of which and where to implement design measures for nature-inclusive marine infrastructure is always to be made through careful consideration of the different interests of relevant stakeholders. If only individual interests are pursued, there's a risk of an uncoordinated fragmentation of well-intended though ineffective measures to promote ecosystem components, which fail the need to strengthen one another, or even may be counteracting. In order for interventions to be truly benefitting marine life, it is required to implement measures at a predetermined scale, large enough to be create impact within the larger system (Abelson *et al.*, 2020; see Chapter 6). When feasible, one should even consider targeting cross-habitat effects, by facilitating positive interactions that occur when processes generated in one habitat benefits other (Vozzo *et al.*, 2023). For effective improvement of targeted components of the ecosystem, an interdisciplinary approach with the involvement of different stakeholders is needed, covering all required aspects with regards to knowledge, expertise, finance, and legislation (Gann *et al.*, 2019; Saunders *et al.*, 2020). Finding mutual ground and reaching agreement on achievable ambitions between all relevant parties is key for setting operational objectives to take measures for nature-inclusive design with and within marine infrastructure at a system-wide scale. This can be achieved through following our stepwise approach in which the potential for nature-inclusive marine infrastructure is determined by matching the ruling policy, its environmental conditions, and its foreseen infrastructural development, followed by jointly determining the most effective operational objectives.

3 Identify potential

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Offshore wind farms contribute to epibenthic biodiversity in the North Sea

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Chapter 3 – Identify potential

The infrastructure of offshore windfarms in the North Sea generally includes hard substrate by means of scour protection around the foundation of wind turbines. It is assumed that scour protection offers a suitable habitat for marine life, thereby positively contributing to the ecosystem. In this Chapter, the results are presented of a quantitative assessment of the effect of the scour protection in offshore wind farms on the epibenthic biodiversity. Data was collected in four wind farms in the Southern North Sea.

Knowing the potential community structure at and around a scour protection supports making designs for nature-inclusive wind farms. Herewith, our study can contribute to efforts to enhance targeted components of the North Sea ecosystem.

Research Question

What is the potential of offshore wind farms to benefit targeted ecosystem components?

3.1 Introduction

Historical maps show that the North Sea was once covered with hard substrates such as oyster beds, coarse peat banks and glacial erratics (Olsen, 1883). These substrates provided habitat for many associated marine species, but were destroyed by bottom-trawl fisheries, overexploitation and diseases (Gross and Smyth, 1946; Korringa, 1952). The most notable change is the loss of oyster beds, which covered approximately 21,000 km^2 in the southern part of the North Sea (Olsen, 1883). Today, large parts of the seabed are characterized by sandy or silty substrate with a relatively poor species community. The remaining natural hard substrate like pebbles and boulders host a different and more biodiverse epibenthic community (Bos *et al.*, 2011; Coolen *et al.*, 2015).

Human constructions in the North Sea provide an opportunity to re-develop the hard substrate habitat and its associated marine life. Research shows that offshore oil and gas platforms, shipwrecks and wind farms act as artificial reefs, hosting a broad range of marine species such as algae, invertebrate species and fish (e.g., Leewis *et al.*, 2000; Coolen *et al.*, 2018). The current rollout of offshore windfarms in the North Sea provides an opportunity to further reinstate epibenthic communities associated with hard substrates. For example, in the Dutch part of the North Sea, the government now requires developers to include elements that benefit ecology in the design of offshore wind farms (e.g. Dutch Ministry of Economic Affairs and Climate, 2022). This implies that new wind farms should make a positive contribution to the marine ecosystem.

Designing offshore wind farms that are practical in installation and technically functional during operation, but also promote positive effects on selected species, proves to be challenging. For example, increasing the complexity in the contours of human-made structures will attract more fish species (Consoli *et al.*, 2018). In most wind farms in the North Sea, layers of rock material are placed at the base of the wind turbines and on top of cable crossings, to prevent the seabed from scouring. More variety in shape and dimension of this so-called scour protection will increase the habitat complexity and is expected to result in a higher biodiversity (Lapointe and Bourget, 1999; Firth *et al.*, 2014).

Due to their geographic distribution, offshore oil and gas platforms have been observed to act as stepping stones and connect species between otherwise isolated populations (Thorpe, 2012; Adams *et al.*, 2014). The increasing amount of offshore wind farms being developed in the North Sea is therefor expected to affect the spread marine life. Currently, the total area of scour protection in wind farms in the Southern North Sea is approximately 1.80 km^2 (see Chapter 4). Rock-associated epibenthic species benefit from this wide distribution of hard substrate, and more variety in its complexity would further increase biodiversity. Yet, the composition and structure of benthic communities at and around the scour protection in offshore wind farms are poorly known.

To understand the consequences of the installation of scour protection for benthic life, data on species communities was collected using a Remote Operated Vehicle (ROV) in four offshore wind farms in the Southern North Sea in September 2020. These scour protections differ in lifetime, geographic location, and rock grading. A quantitative assessment was made to determine the effect of these differences on species abundance and species diversity. This study sets a baseline for the ecological value of scour protection in offshore wind farms and will allow developers to make informed decisions for enhancing nature in their wind farms.

3.2 Materials and Method

3.2.1 Study sites

First, an inventory was made of 16 offshore wind farms in the southern part of the North Sea to select study sites (see Figure 3-1). All turbines in these wind farms are installed on a monopile foundation with pancake-shaped layers of rock material at its base to prevent the seabed from erosion. This scour protection is often composed of a filter layer of small-sized quarried rock, such as granite, topped with an armour layer of large-sized quarried rock . To monitor the effect of differences in lifetime, geographic location, and rock grading of the scour protection on species composition, four windfarms were selected on their range in these characteristics and willingness of the wind farm operators to allow monitoring: Princess Amalia (NL), Belwind (B), Gemini (NL) and Luchterduinen (NL) (see Table 3-1). In each of these four wind farms, the scour protection and its surrounding of three randomly selected wind turbines was monitored.

Table 3-1: Main characteristics of the offshore wind farms in which the species assemblage at and around the scour protection was investigated.

Wind farm		**Belwind**	**Gemini**	**Luchterduinen**	**Princess Amalia**
Country		Belgium	Netherlands	Netherlands	Netherlands
Year of installation		2011	2015	2014	2009
Location	latitude	51°40	54°02	52°24	52°35
	longitude	2°48	5°57	4°09	4°12
Minimum water depth (m)		16.0	29.5	19.5	21.0
Pile diameter (m)		5.0	7.1	5.0	4.0
Armour layer	grading	10/200kg	63/200mm	10/200kg	10/200kg
	$D_{50,avg}$ (mm)	399	135	399	399
	radius* (m)	28.0	21.3	18.2	20.0
	thickness (m)	0.74	1.0	0.8	1.2
Filter layer	grading	-	22/90mm	22/90mm	-
	$D_{50,avg}$ (mm)	-	50	50	-
	radius* (m)	-	30.2	27.4	-
	thickness (m)	-	0.5	0.3	-

**from centre of pile*

Figure 3-1: Map of the Southern North Sea indicating the offshore wind farms explored and the four selected (encircled) for the monitoring.

3.2.2 Video transects

Video footage was collected using an ROV to quantitatively determine benthic organisms at and around the scour protection. The Bluestream Cougar XT ROV was deployed, equipped with 4K subsea camera, adjustable LED lights, and two-line lasers to estimate object sizes and to frame the surface of video transects at a distance of 28 cm. Radial transects were scheduled to be made towards and from the monopile at 0, 45, 90, 135, 180, 225, 270 and 315 degrees (see Figure 3-2). Depending on hydrodynamic conditions, a minimum of four transects of different angles per pile were surveyed, with the aim to cover opposite directions. At each radial transect, a distance of 5 m was kept between the tracks flown towards and from the monopile. The transects covered all substrate types present around a monopile: the armour layer, the transition zone (or filter layer, if present) and the seabed. Experienced ROV pilots were instructed to consistently record video following the transects with a speed of 0.14 m/s and a distance of 0.5 m from the substrate, and to correct for overexposure manually.

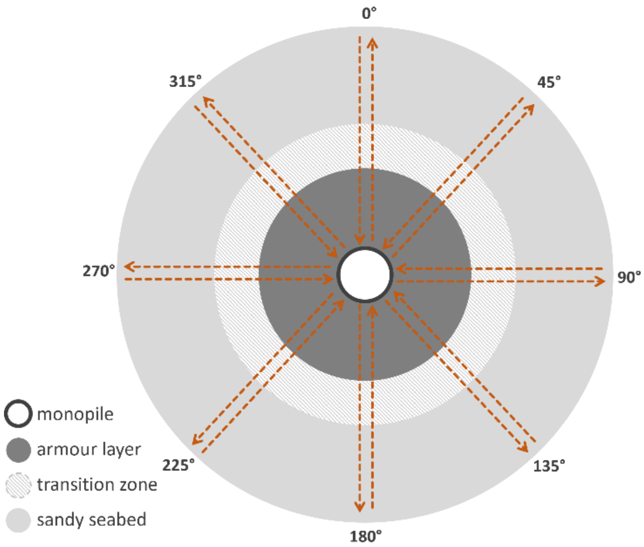


Figure 3-2: Schematic overview of the ROV flight plan for monitoring the scour protection and seabed around a monopile, showing 8 radial transects, each comprising a track from and a track towards the centre of the monopile.

3.2.3 Video analysis

Video transects were analysed using the software package TransectMeasure. Video frames suitable for image analysis were selected on the following criteria: image quality, visibility of laser lines and good display of the seabed in the transect. The laser lines were used as a reference to determine the surface area of each video frame. A minimum of five frames per substrate type were selected for each track, evenly distributed over the transect, and representing the overall species communities observed. For each video frame, individual species were counted and identified to the lowest taxonomic level possible (species, genus, family, class or phylum level). The minimum species size detection limit in frames of good quality was approximately 1 cm. Clustering species such as hydroids and tunicates (see Tables 3-3 and 3-4) were also identified to the highest taxonomy level possible, marking the percentage of the area covered in the video frame.

Distinctive parameters were reported for each video frame: the substrate type was labelled as "armour layer", "transition zone" or "sand"; the laser lines were scored as "present", "partially present" or "absent"; and image quality was scored as "good", "sufficient" or "bad". Note that if a filter layer was installed, the smaller rocks of the filter layer mostly had disappeared under a layer of sand, so it was classified as the transition zone between armour layer to sandy seabed, similar to the wind farms in which no filter layers were installed.

3.2.4 Data analysis

Species observations were reported by their densities. Species density of individual species was calculated as the number of individuals per m^2 in a video frame. Species density of clustering species was calculated in percentage as covered area per video frame. To allow for a combined analysis of densities of individual species and clustering species, data were transformed to the ordinal Marine Nature Conservation Review (MNCR) SACFOR scale using the method of Connor *et al.* (2004). The SACFOR abundance scale assigns the following numerical values to densities: Superabundant=7, Abundant=6, Common=5, Frequent=4, Occasional=3, Rare=2, Present=1.

Before statistical analyses, species with only 1 observation in the dataset were removed to minimize the influence of rare species in multivariate analyses (Poos and Jackson, 2012). Statistical analyses were performed using the software package R version 3.6.3 (R Core Team, 2016) with several functions from the 'vegan package' (Oksanen *et al.*, 2015). Data frames were constructed for hierarchical analysis of species composition per cluster, which was the combination offshore windfarms x monopiles x substrate type. For each cluster, the mean numerical SACFOR species abundance was calculated. Bray-Curtis dissimilarity distance matrices were created and differences between the clusters were tested using PERMOVA. The clusters were presented in dendograms and Non-metric Multi-Dimensional Scaling (NMDS) plots. NMDS plots were created by scaling down the distribution of samples in multidimensional space to 2 dimensions, until a stress value of approximately 0.05 was reached. Finally, stress plots were created to assess whether the original dissimilarities were well preserved in the reduced number of dimensions of the NDMS plot.

Benthic community structure in terms of species abundance and diversity was calculated for the main relevant clusters identified from the hierarchical cluster analysis, i.e. wind farms and substrate types. Mean species abundance (A) was calculated from the numerical SACFOR abundance data, which included data of both individual and clustering species. Diversity is described by species richness (S), species evenness (E) and Shannon diversity index (H). Because the diversity of a community is positively correlated to the number of frames observed, the dataset was first balanced by applying the Monte Carlo resampling strategy. For each cluster wind farm x seabed type, an equal amount of video frames was randomly selected from the entire set, and this process was repeated 100 times. The amount of selected video frames equalled the minimum amount of frames available per cluster, i.e. Belwind N=20, Gemini N=31, Luchterduinen N=19, Princess Amalia N=28. The average of these 100 random selections provided a balanced dataset per wind farm on which further analyses were performed. When a species was not observed, abundance was assumed to be zero. Species richness (S) was calculated by counting the number of species within a certain cluster. The Shannon diversity index (H) was calculated as $H = -\Sigma(Pi*\ln[Pi])$, where Pi is the proportion of species i relative to the total number of species. Species evenness (E) was calculated by dividing the Shannon diversity index H by the natural logarithm of species richness ln(S) ($E = H / \ln(S)$). In all cases the results presenting variability refer to the standard deviation of the mean.

To investigate differences between the community structure at the three types of seabed within the wind farms, analysis of variance (ANOVA) was used. This was combined with Tukey-test for means with a significance level of $p \leq 0.05$.

3.3 Results

In total, over 10 hours of ROV video footage was collected, from which 1497 video frames were selected for analysis, based upon image quality that allowed for identification up to species level (see Table 3-2). The frames covered average 0.061±0.017 m^2 per frame, without significant variation between the wind farms and seabed types ($p=0.55$). The number of frames analysed varied between windfarms, monopiles and seabed type due to variation in video quality and number of radial transects flown per monopile. Wind farm Belwind had the lowest number of analysed video frames, mainly due to low light conditions, which often made the footage unsuitable for analysis as species smaller than 5cm could not be identified. In each wind farm, the number of analysed video frames for the transition zone were much lower than for the armour layer and sandy seabed, because the area covered by the transects was lowest in the transition zones. No species were observed in 210 of the 1497 video frames, all frames recorded above the sandy seabed, and most of them in wind farm Belwind (60%).

Table 3-2: The number of video frames analysed and area covered per seabed type in each wind farm.

wind farm	video frames	seabed type			total
		armour layer	transition zone	sand	
Belwind	number (#)	116	20	160	296
	area (m^2)	*7.23*	*1.23*	*9.81*	*18.27*
Gemini	number (#)	212	31	195	438
	area (m^2)	*13.29*	*1.92*	*11.71*	*26.92*
Luchterduinen	number (#)	125	19	176	320
	area (m^2)	*7.23*	*1.08*	*9.59*	*17.9*
Princess Amalia	number (#)	188	28	227	443
	area (m^2)	*13.73*	*1.84*	*12.15*	*27.72*
All wind farms	number (#)	641	98	758	1497
	area (m^2)	*41.47*	*6.08*	*43.27*	*90.82*

3.3.1 Species inventory

In total, 47 species from 7 different phyla were identified from the video footage, of which 15 species could only be identified at genus level. Table 3-3 shows for each species the total number of observations and the mean SACFOR abundance and number of observations per wind farm. Table 3-4 shows for shows for each species the total number of observations and the mean SACFOR abundance and number of observations per seabed type. Many species (21) were observed at all seabed types in all wind farms, the most common being anemones (*Metridium senile* and *Sagartia* spec.), the edible crab (*Cancer pagurus*), swimming crabs (*Liocarcinus* spec., *Necora puber*), the common starfish (*Asterias rubens*), gobies (*Gobius* spec.), and cod-like fish (*Trisopterus* spec., *Gadus morhua*). Some species were mainly or uniquely observed at the scour protection, such as the dead men's finger (*Alcyonium digitatum*), the common lobster (*Homarus gammarus*), tunicates (*Diplosoma*), goldsinny wrasse (*Ctenolabrus rupestris*), and the rock gunnel (*Pholis gunnellus*). Other species were mainly or uniquely recorded at the sandy seabed, such as the mason sand worm (*Lanice conchilega*), the sand sea star (*Astropecten irregularis*), dragonets (*Callionymus*), and the common sole (*Solea solea*). Ten species were only observed once and discarded from further analyses, to minimize noise in the data caused by rare species.

3.3.2 Species groups per wind farm

The hierarchical clustering of all offshore windfarms and the three survey locations (monopiles) within each wind farm showed a clustering at ~50% dissimilarity in species composition of the offshore windfarms Luchterduinen and Princess Amalia located near the West coast of The Netherlands compared to Gemini and Belwind located respectively north of the Wadden Sea and near the coast of Belgium (Figure 3-3; left). Wind farms Luchterduinen and Princess Amalia have a fairly similar species composition (~30% dissimilarity), as is to be expected because they are closely located. A NMDS plot confirms this clustering (Figure 3-3; right), and illustrates that some species were more associated to certain wind farms than to others. For example, the sand sea star *Astropecten irregularis* (air) was only observed in the most northernly located wind farm Gemini and the sea beard *Nemertesia* (nem) only in Belwind, while common species such as the plumose anemone *Metridium senile* (mse), edible crab *Cancer pagurus* (cpa), and common starfish *Asterias rubens* (aru), were observed in all windfarms.

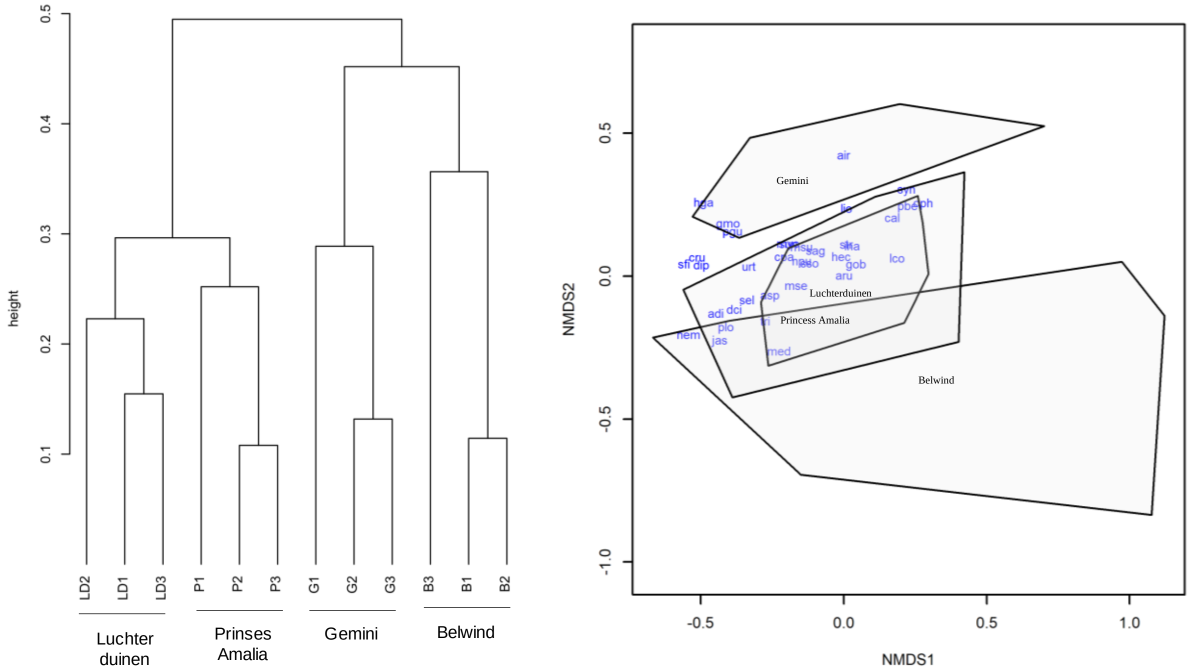


Figure 3-3: Hierarchical cluster dendogram (left) and NMDS plot (right) of the benthic community structure of the three surveyed locations within each of the wind farms. Dendrogram based on Bray Curtis dissimilarity distances calculated from mean numerical SACFOR species abundances. NMDS plot (stress = 0.05) shows species (3-letter codes) in relation to each seabed type (polygons).

Table 3-3: Mean abundance per species by offshore windfarm, using the numerical SACFOR scale. Superabundant=7, Abundant=6, Common=5, Frequent=4, Occasional=3, Rare=2, Present=1.

Phylum	Species *(code)*	Observations	Offshore windfarm							
			Belwind		Gemini		Luchterduinen		Princess Amalia	
		(# frames)	N	*mean(±sd)*	N	*mean(±sd)*	N	*mean(±sd)*	N	*mean(±sd)*
Porifera	*Cliona celata*#* (cce)*	1			1	*1*				
	Suberites ficus# (sfi)	2	1	*3*	1	*3*				
Cnidaria	*Actinothoe sphyrodeta (asp)*	92	16	*5.7(±0.5)*			1	*5*	75	*5.8(±0.6)*
	Alcyonium digitatum# (adi)	16	1	*4*	4	*1.8(±0.5)*			11	*1.5(±0.5)*
	Diadumene cincta (dci)	6	1	*5*					5	*5.6(±0.5)*
	Halecium# (hal)*	1			1	*3*				
	Hydractinia echinate# (hec)	16					8	*1.1(±0.4)*	8	*1.3(±0.7)*
	Metridium senile# (mse)	556	118	*6.7(±0.5)*	105	*6.5(±0.5)*	126	*6.9(±0.3)*	207	*6.9(±0.3)*
	Nemertesia# (nem)	11	11	*3.9(±1.3)*						
	Sagartia (sag)	77	5	*6(±0)*	34	*6.1(±0.4)*	16	*6.5(±0.5)*	22	*6.2(±0.4)*
	Sagartia elegans# (sel)	210	30	*6.7(±0.4)*	99	*6.3(±0.5)*	28	*6.7(±0.5)*	53	*6.7(±0.5)*
	Sagartia troglodytes (str)	91			13	*6.1(±0.3)*	58	*6.6(±0.5)*	20	*6.2(±0.4)*
	Sagartiogeton undatus (sun)	14			5	*6.2(±0.4)*	1	*6*	8	*6(±0)*
	Urticina (urt)	15	5	*6(±0)*	6	*6(±0)*	2	*6(±0)*	2	*6(±0)*
Annelida	*Lanice conchilega (lco)*	435	14	*5.2(±0.4)*	124	*5.5(±0.5)*	90	*5.7(±0.8)*	207	*6.2(±0.7)*
Arthropoda	*Cancer pagurus (cpa)*	176	20	*6.9(±0.3)*	93	*7(±0)*	17	*6.9(±0.2)*	46	*6.9(±0.2)*
	Caprella (cap)*	1					1	*5*		
	Homarus gammarus (hga)	3			3	*7(±0)*				
	Hyas (hya)*	1	1	*6*						
	Inachus (ina)	8					2	*5(±0)*	6	*5.2(±0.4)*
	Jassa# (jas)	13							13	*4.2(±1.1)*
	Liocarcinus (lio)	94	1	*6*	35	*6(±0)*	42	*6(±0)*	16	*6(±0)*
	Necora puber (npu)	233	40	*6(±0)*	78	*6(±0)*	40	*6(±0.2)*	75	*5.9(±0.3)*
	Pagurus bernhardus (pbe)	41	2	*6(±0)*	4	*6(±0)*	20	*6(±0)*	15	*6(±0)*
	Pisidia longicornis (plo)	2					1	*5*	1	*5*
Mollusca	*Alloteuthis* (all)*	1	1	*7*						
	Mytilus edulis# (med)	27	15	*5.6(±0.5)*			10	*5.8(±0.8)*	2	*6(±0)*
	Sepia officinalis (sof)*	1	1	*7*						
Echinodermata	*Asterias rubens (aru)*	336	32	*7(±0)*	99	*7(±0)*	117	*7(±0.1)*	88	*6.9(±0.2)*
	Astropecten irregularis (air)	22			22	*6(±0)*				
	Ophiura (oph)	24	1	*6*	3	*6(±0)*	7	*6(±0)*	13	*6(±0)*
Chordata	*Callionymus (cal)*	23			6	*6(±0)*	5	*6(±0)*	12	*6(±0)*
	Chelidonichthys lucerna (clu)*	1			1	*7*				
	Ctenolabrus rupestris (cru)	17	1	*6*	16	*6(±0)*				
	Diplosoma# (dip)	21	6	*2(±1.1)*	15	*2(±0.5)*				
	Entelurus aequoreus (eae)*	1							1	*7*
	Gadus morhua (gmo)	16	1	*7*	14	*7(±0)*			1	*6*
	Gobius (gob)	114	9	*6(±0)*	19	*6.1(±0.2)*	56	*6(±0.1)*	30	*6(±0)*
	Mullus surmuletus (msu)	12	3	*7(±0)*	7	*7(±0)*			2	*6.5(±0.7)*
	Myoxocephalus (myo)	3			2	*7(±0)*	1	*7*		
	Parablennius gattorugine (pga)*	1							1	*6*
	Pholis gunnellus (pgu)	7			5	*7(±0)*	2	*7(±0)*		
	Platichthys flesus (pfl)*	1							1	*7*
	Solea solea (sso)	6	2	*7(±0)*	4	*7(±0)*				
	Syngnathus (syn)	3							3	*7(±0)*
	Taurulus bubalis (tbu)*	1					1	*6*		
	Trisopterus (tri)	50	22	*7(±0)*	4	*7(±0)*	4	*6.8(±0.5)*	20	*7(±0.2)*

**species excluded from data analyses; #clustering species*

3.3.3 Species groups per seabed type

The hierarchical clustering of the seabed types and the surveyed locations in the wind farms showed a clustering at ~80% dissimilarity of the species composition mostly associated with the armour layer compared to the sandy seabed (Figure 3-4; left). The transition zone can be described as a habitat containing both rocks and sand, and the benthic community associated with this seabed type clusters therefore mainly with either the armour layer or the sandy seabed. The NDMS plot (Figure 3-4; right) illustrates the distinction of the benthic species between the armour layer and sandy seabed, as well as its overlapping properties in the transition zone. Species with a preference for a certain seabed type can be clearly distinguished, such as *Jassa* (jas) and dead men's thumb *Alcyionidium digitatum* (adi) have for the armour layer, and brittle star *Ophiura* (oph) and common hermit crab *Pagurus bernardus* (pbe) for the sandy seabed.

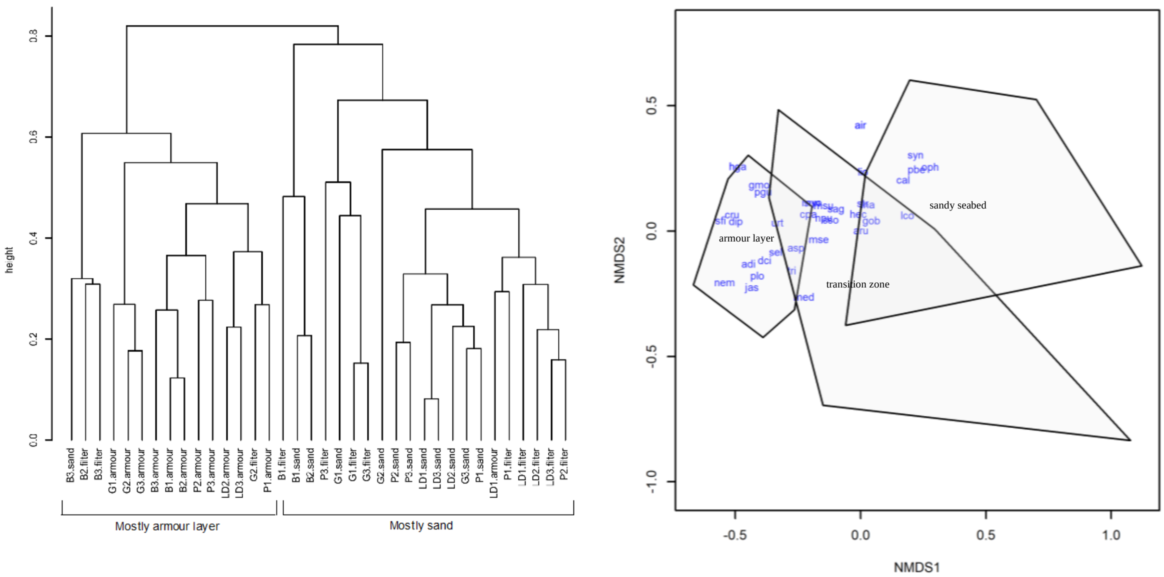


Figure 3-4: Hierarchical cluster dendogram (left) and NMDS plot (right) of the benthic community structure of the different seabed types at the surveyed locations within the wind farms. Dendrogram based on Bray Curtis dissimilarity distances calculated from mean numerical SACFOR species abundances. NMDS plot (stress = 0.05) shows species (3-letter codes) in relation to each seabed type (polygons).

Table 3-4: Mean abundance per species by seabed type, using the numerical SACFOR scale. Superabundant=7, Abundant=6, Common=5, Frequent=4, Occasional=3, Rare=2, Present=1.

Phylum	Species *(code)*	Observations (# frames)	Seabed type: armour layer N	armour layer mean(±sd)	transition zone N	transition zone mean(±sd)	sand N	sand mean(±sd)
Porifera	*Cliona celata**# (cce)*	1			1	*1*		
	Suberites ficus# (sfi)	2	2	*3(±0)*				
Cnidaria	*Actinothoe sphyrodeta (asp)*	92	79	*5.9(±0.6)*	6	*5.5(±0.5)*	7	*5.1(±0.4)*
	Alcyonium digitatum# (adi)	16	15	*1.7(±0.8)*	1	*1*		
	Diadumene cincta (dci)	6	5	*5.6(±0.5)*			1	*5*
	*Halecium**# (hal)*	1	1	*3*				
	Hydractinia echinate# (hec)	16	1	*3*			15	*1.1(±0.3)*
	Metridium senile# (mse)	556	497	*6.8(±0.4)*	47	*6.5(±0.5)*	12	*6.2(±0.4)*
	Nemertesia# (nem)	11	11	*3.9(±1.3)*				
	Sagartia (sag)	77	33	*6.2(±0.5)*	23	*6.2(±0.4)*	21	*6.2(±0.4)*
	Sagartia elegans# (sel)	210	198	*6.5(±0.5)*	10	*6.1(±0.3)*	2	*6(±0)*
	Sagartia troglodytes (str)	91	17	*6.3(±0.5)*	26	*6.4(±0.5)*	48	*6.5(±0.5)*
	Sagartiogeton undatus (sun)	14	6	*6(±0)*	3	*6.3(±0.6)*	5	*6(±0)*
	Urticina (urt)	15	12	*6(±0)*	1	*6*	2	*6(±0)*
Annelida	*Lanice conchilega (lco)*	435	3	*6(±0)*	21	*6(±0.7)*	411	*5.9(±0.8)*
Arthropoda	*Cancer pagurus (cpa)*	176	151	*7(±0.2)*	16	*7(±0)*	9	*7(±0)*
	*Caprella** (cap)*	1	1	*5*				
	Homarus gammarus (hga)	3	3	*7(±0)*				
	*Hyas** (hya)*	1	1	*6*				
	Inachus (ina)	8	2	*5(±0)*	1	*5*	5	*5.2(±0.4)*
	Jassa# (jas)	13	13	*4.2(±1.1)*				
	Liocarcinus (lio)	94	10	*6(±0)*	4	*6(±0)*	80	*6(±0)*
	Necora puber (npu)	233	190	*6(±0.2)*	25	*6(±0)*	18	*6(±0)*
	Pagurus bernhardus (pbe)	41	2	*6(±0)*			39	*6(±0)*
	Pisidia longicornis (plo)	2	2	*5(±0)*				
Mollusca	*Alloteuthis** (all)*	1					1	*7*
	Mytilus edulis# (med)	27	20	*5.8(±0.6)*	2	*5.5(±0.7)*	5	*5.4(±0.5)*
	*Sepia officinalis** (sof)*	1					1	*7*
Echinodermata	*Asterias rubens (aru)*	336	130	*6.9(±0.2)*	42	*7(±0)*	164	*7(±0)*
	Astropecten irregularis (air)	22	2	*6(±0)*	2	*6(±0)*	18	*6(±0)*
	Ophiura (oph)	24			1	*6*	23	*6(±0)*
Chordata	*Callionymus (cal)*	23	1	*6*	1	*6*	21	*6(±0)*
	*Chelidonichthys lucerna** (clu)*	1					1	*7*
	Ctenolabrus rupestris (cru)	17	17	*6(±0)*				
	Diplosoma# (dip)	21	21	*2(±0.7)*				
	*Entelurus aequoreus** (eae)*	1					1	*7*
	Gadus morhua (gmo)	16	11	*6.9(±0.3)*	4	*7(±0)*	1	*7*
	Gobius (gob)	114	8	*6(±0)*	8	*6.1(±0.4)*	98	*6(±0.1)*
	Mullus surmuletus (msu)	12	3	*6.7(±0.6)*	1	*7*	8	*7(±0)*
	Myoxocephalus (myo)	3	2	*7(±0)*	1	*7*		
	*Parablennius gattorugine** (pga)*	1			1	*6*		
	Pholis gunnellus (pgu)	7	7	*7(±0)*				
	*Platichthys flesus** (pfl)*	1					1	*7*
	Solea solea (sso)	6	1	*7*	1	*7*	4	*7(±0)*
	Syngnathus (syn)	3					3	*7(±0)*
	*Taurulus bubalis** (tbu)*	1	1	*6*				
	Trisopterus (tri)	50	40	*7(±0.2)*	7	*7(±0)*	3	*7(±0)*

**species excluded from data analyses; #clustering species*

3.3.4 Benthic community structure

Comparisons among the communities are made between wind farms and seabed type using the attributes species richness (S), species evenness (E), Shannon diversity index (H) and SACFOR abundance (A). Using the balanced dataset of each wind farm, the means for each attribute per wind farm and seabed type were calculated. The mean species richness, the mean species evenness, and the mean Shannon diversity index of the balanced dataset generally differed between wind farms and per seabed type within a wind farm, while the mean SACFOR abundance more often did not vary between communities.

Species richness is the number of species in a community. It was significantly highest for the communities at the armour layer in both Belwind ($p<0.001$) and Gemini ($p<0.001$), and lowest at the armour layer in Luchterduinen ($p<0.001$) and Princess Amalia ($p<0.001$). Species richness did not differ between the communities at the transition zone and sandy seabed in Luchterduinen ($p=0.31$), and between the armour layer and sandy seabed in Princess Amalia ($p=0.67$) (see Figure 3-5.I).

Species evenness describes the distribution of abundance across the species in a community. A higher evenness implies that the species are present in more similar proportions, meaning that the community has a higher species diversity. Species evenness was remarkably high at the sandy seabed in Belwind ($p<0.001$) (see Figure 3-5.II), which is explained by a relatively high amount of samples of videoframes ($N=23$) in which only a small amount of species (2-4) was observed that all were represented by only 1 individual per framework. Similar to the diversity indicator species richness, species evenness was lowest at the sandy seabed in Gemini ($p<0.001$), lowest at the armour layer in Luchterduinen ($p<0.001$) and Princess Amalia ($p<0.001$), and did not significantly differ between the communities at the armour layer and sandy seabed in Princess Amalia ($p=0.052$).

The Shannon diversity index combines species richness and evenness by taking into account both the number of species and their relative abundance. A higher Shannon index corresponds to a higher species diversity. Comparing communities between the armour layer and the sandy seabed shows a significantly higher Shannon diversity index at the armour layer in wind farms Belwind ($p<0.001$) Gemini ($p<0.001$) and Princess Amalia ($p<0.001$), but a lower species diversity at the armour layer in Luchterduinen ($p<0.001$) (see Figure 3-5.III). The area defined as a transition zone has significantly the highest Shannon diversity index wind in farms Gemini ($p<0.001$; filter layer) and Princess Amalia ($p<0.001$; no filter layer).

The mean abundance using SACFOR scale (A) ranged from 5.9 ± 0.7 at the sandy seabed in Belwind to 6.7 ± 0.5 at the armour layer in Luchterduinen (see Figure 3-5.IV), which translates to 'abundant benthic marine life'. Mean SACFOR abundances differed between wind farms at the armour layer ($p<0.001$), but not at the transition zone ($p=0.14$), and mostly not at the sandy seabed (only between Princess Amalia and Gemini ($p=0.01$) and Princess Amalia and Luchterduinen (p=0.01)). Mean SACFOR abundance was lowest at the sandy seabed in each windfarm (Belwind p<0.001; Gemini p<0.001; Luchterduinen p<0.001; Princess Amalia p=0.16, n.s.).

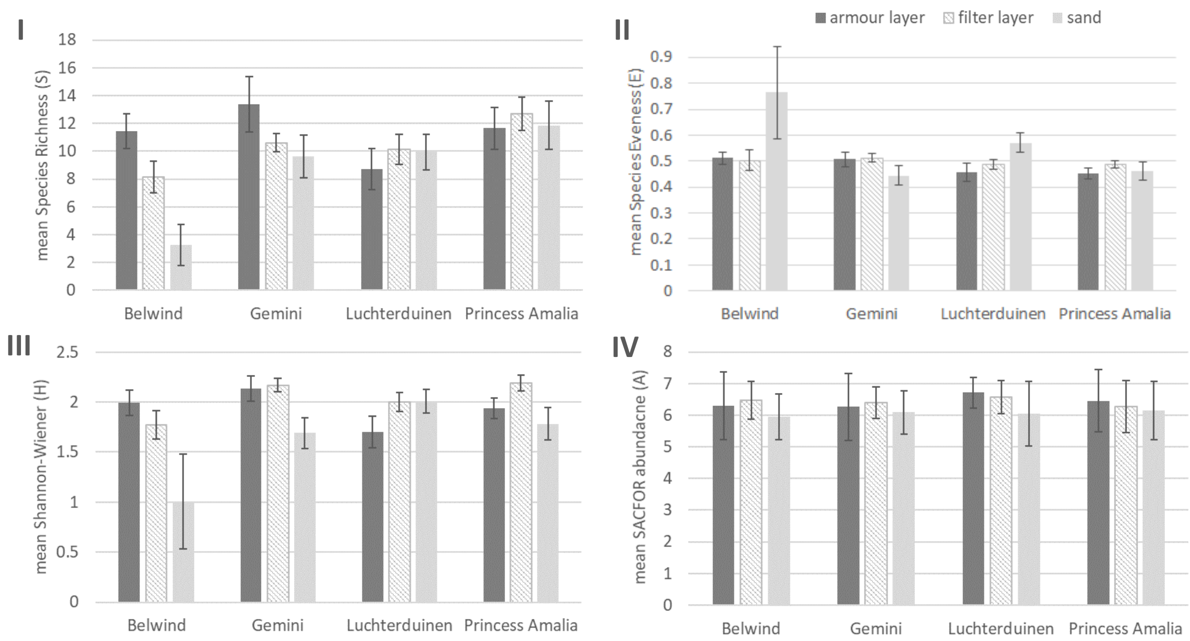


Figure 3-5: Community attributes for different seabed types in the four offshore windfarms. I) mean Species Richness (S), II) mean Species Evenness (E), III) mean Shannon-Wiener diversity (H), and IV) mean abundance using SACFOR scale (A).

3.4 Discussion

3.4.1 ROV video monitoring

This study provides insight in the structure of epibenthic communities living at and around scour protections in four offshore wind farms in the Southern North Sea. A rich benthic species community was observed using ROV footage, consisting of 47 species from 7 different phyla. This is slightly higher compared to other ROV studies of hard substrate associated communities on offshore oil and gas platforms in the Southern North Sea. For example Van der Stap *et al.* (2016) reported 30 taxa from 7 phyla, and Schutter *et al.* (2019) observed 38 species from 8 phyla. These lower numbers of species abundance compared to our study can likely be explained as these studies used ROV footage collected for inspections of the technical integrity of the installations, while our monitoring with ROV was designed specifically for biological research. ROV surveys generally underestimate the abundance and diversity of a benthic community. Video footage collected along transects only shows benthic organisms present on the surface, not those that are hidden in cavities, underneath fouling layers, or in the seabed. Furthermore, limitation in light, unstable footage due to movement of the camera, and a required distance between the camera and the substrate, make it difficult to identify small-sized organisms. More detailed monitoring techniques such as visual observations by scientific divers and taking samples for analyses under laboratory conditions, generally result in higher diversity estimates of the community. Coolen *et al.* (2020) assessed data from studies of the epibenthic community at the scour protection in wind farm Princess Amalia by Vanagt *et al.* (2013) and Vanagt & Faasse (2014). Small rocks were collected at random locations around four turbine foundations, and on these rocks 95 species were identified. This is threefold the amount as observed during our ROV survey. In particular the more precise analysis of samples in a laboratory contributes to a higher biodiversity estimate, as it allows species identification at a microscopic level.

3.4.2 Comparing wind farms

The variation in species presence at (artificial) reefs depends on various drivers, such as age, materials used, and complexity of the structures. Epifouling communities on offshore installations evolve over time with dominance changing among species (Whomersley & Picken, 2003), and species richness may increase with installation age (Van der Stap *et al.*, 2016). Texture and structure of marine constructions determine settlement and growth conditions for algae and macrobenthos (Borsje *et al.*, 2010; Green *et al.*, 2012). Structural complexity of (artificial) reefs, e.g. by means of crevices and pits, increases the abundance and diversity of benthic species living at and in the structures (Lapointe and Bourget, 1999; Firth *et al.*, 2014). When comparing these drivers that determine a community structure, no major differences are observed between the four studied wind farms. Wind farm Gemini does have a smaller rock grading of the armour layer than the other three wind farms, and both Belwind and Princess Amalia do not have a filter layer and are a few years older than the other two wind farms. However, in general the scour protections in the four wind farms studied do not differ much in age (about 5 years maximum), face relatively similar offshore conditions in terms of depths and hydrodynamics, and are structurally comparable, i.e. pancake shapes made of quarried rock with a transition zone between an armour layer and the surrounding seabed. Therefore, it is not unexpected that no remarkable differences in community structure were observed between the wind farms using hierarchical clustering, showing a similarity of ~50% between the wind farms. More variation in the scour protections, for example in shape, dimensions and rock grading would probably have resulted in a more distinct benthic communities, as habitat complexity generally leads to more diversity in marine life. The similarity in benthic community structure is also shown as most of the species are observed in multiple wind farms, and generally no major differences in species abundance were observed between the wind farms. Wind farms Luchterduinen and Princess Amalia are most similar in community structure (~70%), likely because these two wind farms are geographically closely located (21 km centre-centre), and have a similar rock grading at the armour layer (10-200kg).

3.4.3 Effect of seabed type on benthic communities

Our observations indicate that seabed type is a much stronger explanator of the benthic community structure than wind farm. Clusters of 'mostly armour layer' and 'mostly sandy seabed' were distinguished at ~80% dissimilarity, meaning them being only for approximately 20% similar in benthic structure. Species abundance and species diversity of epibenthic communities are generally higher at rocky habitats than in sandy systems, as a rocky habitat can be very stable to support a variety of marine organisms, while a sandy system is unstable at its surface as the fine mineral particles are easily moved by currents and waves. In line with this, our observations show that the benthic communities have lowest species abundances at the sandy seabed in each of the four windfarms. Also, species diversity (richness, evenness, Shannon index) is generally highest for the community at the armour layer in both Belwind and Gemini, although little differences were observed in Princess Amalia and species diversity was unexpectedly higher at the sandy seabed than at the armour layer in Luchterduinen. Fact remains that the deployment of rock material as scour protection at the base of wind turbines results in the creation of isolated rocky habitats in a sandy environment. This allows the accumulation of both rocky and sandy species communities in a wind farm, leading to an increase of total biodiversity in the area, meaning that a wind farm area would host a more diverse benthic community than the surrounding areas. One could further stimulate the abundance and diversity of the benthic community structure around wind turbines by providing more complexity in the scour protection by means of shape and materials used, proving habitat and shelter to both rocky and sandy species. In addition, these small islands of scour protection in offshore wind farms provide stepping stones for rock-dwelling species (Adams, 2014), which may enhance the movement of these species throughout the North Sea. Therefore, the installation of wind turbine infrastructure and adjustments thereof, is expected to have an effect on benthic communities at the scale of the wind farm itself, as well as at the wider area.

3.5 Conclusion

Offshore wind farms are considered to have a positive effect on epibenthic communities during their operational lifetime, and beyond if the scour protection is left in place. The absence of bottom-disturbing activities, such as sand mining and bottom-trawl fisheries, and also the installation of wind farms structures, provide refuge and complex habitat to many benthic species (Coates *et al.*, 2014; Langhamer, 2012; Petersen and Malm, 2006). An increase in benthic life will provide additional food sources for the higher trophic levels, including fish, mammals and birds (Reubens *et al.*, 2014; Russel *et al.*, 2014). This study demonstrates that marine life can benefit from scour protection in offshore wind farms, as these provide rocky habitat that is currently not present in the area. Species abundance was found to be higher on the scour protection than on the surrounding seabed. Also species associated with a rocky habitat such as lobster and several fish species, now get an opportunity to thrive in the naturally sandy system of the Southern North Sea. This study shows that the addition of scour protection results in a higher abundance and diversity of benthic species in offshore wind farms. Integrating tailor-made components into the design of scour protection that further benefit epibenthic biodiversity could assist new wind farms to contribute to biodiversity in the North Sea.

4 Quantify effect

AQUATIC LIVING RESOURCES 36:4
(2023)

THE POTENTIAL IMPACT OF HUMAN INTERVENTIONS AT DIFFERENT SCALES IN OFFSHORE WIND FARMS TO PROMOTE FLAT OYSTER (OSTREA EDULIS) REEF DEVELOPMENT IN THE SOUTHERN NORTH SEA

TER HOFSTEDE R, WILLIAMS G, VAN KONINGSVELD M

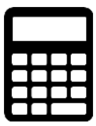
CHAPTER 4 – QUANTIFY EFFECT

Achieving system-scale impact for oyster reef development in offshore wind farms (Chapter 2) is currently hindered by the lack of quantitative knowledge on the effects of technical interventions that could stimulate the reef development. Consequently, it is unclear what scale of intervention would actually be required to achieve a desired state.

In this Chapter a stepwise procedure is presented, designed to guide the selection of appropriate measures and their required scale for pro-actively facilitating flat oyster reef development in offshore wind farms. It is applied at the scale of the Southern North Sea. The outcomes provide direction in identifying research needs to fill knowledge gaps, as well as in decision-making during the design process for inducing oyster reef development. Herewith, application of the stepwise procedure supports authorities in enforcing the successful reinstatement of flat oyster reefs in the Southern North Sea.

RESEARCH QUESTION

How to quantify the effect of interventions to enhance ecosystem components using offshore wind farms?



4.1 Introduction

Incorporation of ecology and ecosystem services into marine infrastructural developments in general has gained interest over the last decades. Initial focus lied primarily on coastal infrastructure (e.g. King and Lester, 1995; Capobianco and Stive, 2000; Lamberti and Zanuttigh, 2005; Swann, 2008; Borsje *et al.*, 2010; Waterman, 2010; De Vriend *et al.*, 2015; Laboyrie *et al.*, 2018), but recently attention also goes out to offshore construction works, in particular wind farms (Dafforn *et al.*, 2015a; Lengkeek *et al.*, 2017; Van Duren *et al.*, 2016; Degraer *et al.*, 2020). For example in the Dutch part of the North Sea, the government now requires developers to include elements that benefit ecology in the design of offshore wind farms (e.g. Dutch Ministry of Economic Affairs and Climate, 2022). This implies that demonstrable efforts should be undertaken to design and build an offshore wind farm in an eco-friendly manner that actively helps to foster conservation goals for species and habitats.

The infrastructure in offshore wind farms, such as the piles of the turbines and the rock material placed at their base to prevent scouring of the seabed, provides hard-bottom habitat and three-dimensional structures used by marine life to settle, forage and shelter, generating a reef-effect (Peterson and Malm, 2006; Lindeboom *et al.*, 2011; Coolen *et al.*, 2020; Degraer *et al.*, 2020). This spontaneously arising ecological value in terms of biodiversity and biomass of offshore wind farms, can be enhanced by making deliberate adjustments to the conventional engineering design. One can include modified structures that enhance habitat complexity and promote the colonisation by selected target species. One can use materials that facilitate settlement of new species, such as shells or calciferous rock that contain a high amount of calcium, which is beneficial to shellfish species (Hidu *et al.*, 1975; Soniat *et al.* 1991). Or one can create more shapes and cavities to provide areas and places in which animals can shelter, by making the constructions more organic in shape, or by installing artificial reef structures. The more variation in habitat one offers, the more variety one gets in marine life living in, at and around the marine infrastructure (Lapointe and Bourget, 1999; Firth *et al.*, 2014). Furthermore, one can actively introduce certain target species to kickstart the colonisation of the infrastructure by preferred species. Such pro-active interventions to enforce nature could promote the ecological value of offshore wind farms facilitating their required permitting process and community acceptance. Or, more ambitious even, the huge momentum of offshore wind development can be used to achieve large scale restoration ambitions that would otherwise be unaffordable.

The aforementioned can be observed in practice in the growing attention to combine the construction of offshore wind farms in the North Sea with the reinstatement of hard substrate epibenthic communities, in particular of the European flat oysters (*Ostrea edulis*) (Kamermans *et al.*, 2018b; Sas *et al.*, 2019). This species can form immense reefs; tower-like, biogenic structures with a height of 7 m, a length of 30-50 m, and a width of 10 m have been observed along the Bulgarian coast (Todorova *et al.*, 2009). In a dynamic offshore environment as is the North sea, oyster reefs can ameliorate physical stresses by creating a hospitable habitat for organisms that would otherwise be unable to tolerate these conditions (Crain and Bertness, 2006). Oysters influence water quality by filtering the water (Dolmer, 2000; Newell, 2004), and their reefs provide a habitat for a diverse associated community (Coen and Luckenbach, 2000; Lown *et al.*, 2021), from offering substrate for settlement of algae and sessile benthic fauna (e.g. sponges, anemones) to providing shelter and nesting area for fish species and crustaceans (e.g. crabs, lobsters). This reef dwelling marine life often includes species of commercial value, including the oysters themselves, showing the potential of oyster beds to contribute to valuable fisheries resources. Flat oyster reefs once covered large areas of the North Sea (Olsen, 1883), but went near to extinct due to overexploitation, bottom-dwelling fisheries and the outbreak of a disease (Gross and Smyth, 1946; Korringa, 1952). Overfishing in the past increased the isolation of the oyster populations in the Southern North Sea, leading to a further deterioration of the remaining stock due to the reduced chance of fertilisation between the colonies (Gross and Smyth, 1946). The recent increasing amount of hard substrate offered by rock installations in offshore wind farms in the Southern North Sea offers potential for connecting existing or new oyster reefs. Due to the geographic distribution of offshore wind farms, they can serve as stepping stones to connect species between otherwise isolated populations, as also observed for oil and gas platforms (Thorpe, 2012; Adams *et al.*, 2014), thereby facilitating the colonization of new hard substrates in the future.

Oyster reef restoration in the North Sea is supported under the EU Marine Strategy Framework Directive, and a target in e.g. Dutch policy (Min. IenW & Min. LNV, 2018). Offshore wind farms are identified to potentially host these reefs, and accordingly, growing effort is being put in pilot studies stimulating oyster development in offshore wind farms (e.g. Didderen *et al.*, 2019; Sas *et al.*, 2019; Tonk *et al.*, 2020). However, overarching management objectives are still lacking for the actual implementation of the research outcomes. This may be due to the lack of insight into the level at which to incorporate technical modifications of offshore wind farms, what the effect of these measures could be, and how much intervention is needed to be of significance. The successful development and implementation of a policy for oyster reef development in offshore wind farms requires a systematic approach to reach predefined objectives.

A method that was successfully applied in previous studies to assess the operational status of new policies is the 'Frame of Reference' approach (Van Koningsveld, 2003). It was originally derived to evaluate and re-define a sustainable coastal policy for the Netherlands (Van Koningsveld and Mulder, 2004) and has since then been used for a range civil engineering disciplines. For example, it was used to define coastal management policies for beach areas (Jiménez *et al.*, 2007; Sutherland and Thomas, 2011; Gault *et al.*, 2011), to develop environmental monitoring schemes for offshore renewable energy projects (Garel *et al.*; 2014), and proposed as a tool to assess the sustainability of dredging projects (Laboyrie *et al.*, 2018). The approach cyclically defines both a strategic and an operational objective and operationalizes these objectives in a 4-step decision recipe determining (i) a quantitative state concept, (ii) a bench marking procedure, (iii) an intervention procedure and (iv) an evaluation procedure (see Figure 4-1).

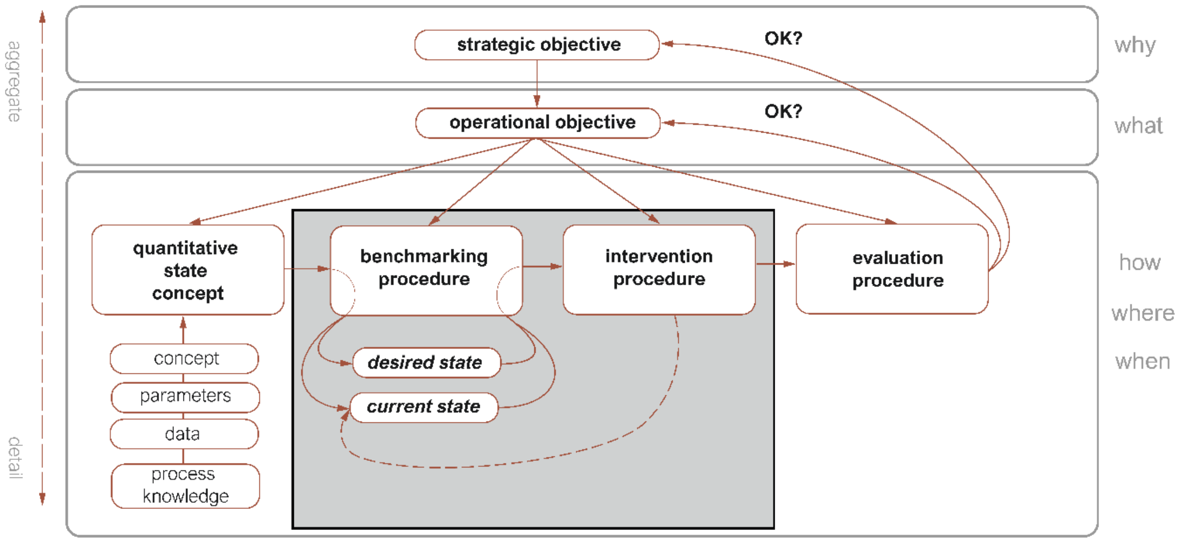


Figure 4-1: A 'basic' frame of reference for policy development (source: Van Koningsveld et al., 2023). The grey area indicates the step addressed in this study.

For this study we use the Frame of Reference approach to analyze the operational maturity of nature inclusive policies related to oyster reef development in offshore wind farms. We focus on the second and third steps of the decision recipe, i.e. defining the gap between a current and a desired state and the intervention options available to close this gap (see grey area in Figure 4-1). The aim of this study is to provide a detailed procedure to select intervention measures for the design or adjustment of offshore wind farms, to induce oyster reef development at a desired scale. The selection of measures is supported by a quantitative estimation of their expected effect.

4.2 Methodology

4.2.1 Stepwise procedure

To provide direction in the selection of interventions for promoting flat oyster reef development by engineering offshore wind farms, a stepwise approach is required, addressing the physical and social environment and providing quantitative information on a range of interventions that can be taken to influence the current state towards the desired state (see Figure 4-2). Such a stepwise procedure supports the selection of appropriate measures for pro-actively facilitating oyster reef development, taking into account dynamic interactions and the effects at varying spatial scales. To change the design of a conventional offshore wind farm void of oysters (current state) into a wind farm hosting oyster reefs (desired state), the procedure comprises three steps. First, the historical and current situation are assessed of the socio-environmental system in which the wind farm is foreseen or situated, addressing the prevailing physical conditions and actors of influence (users, regulation). Second, it provides information on potential oyster-promoting interventions at different scales that can be incorporated in the design or after construction. And third, the procedure aids to quantify the effects that can be achieved with such modifications, to allow for a proper selection of the preferred intervention(s).

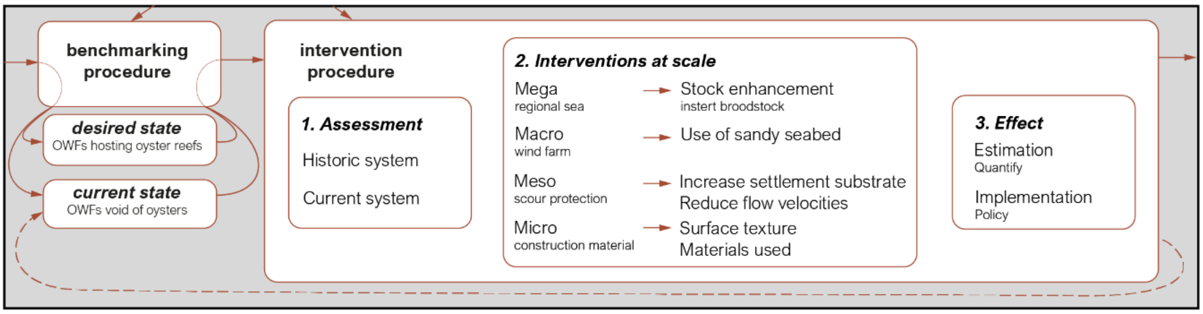


Figure 4-2: Stepwise procedure to assess the potential effect of interventions at different scales on oyster reef development in an offshore wind farm, bringing a wind farm void of oysters towards one hosting oyster reefs.

Step 1. Asses the system

First step is to assess the local system in which the wind farm is located or to be constructed. The historical and current situation of the area provides information whether it is suitable for the desired objective, in this case hosting oyster reefs. If the species is known to have been present in the past, or has been (incidentally) observed in or nearby the area, this would indicate a site's suitability for development of oyster beds. When assessing the area, not only presence, but also anthropogenic and environmental factors should be taken into account, as these both positively and negatively affect oysters. Promotional factors comprise food abundance, suitable substrate, and current for supply of oxygen and nutrients (e.g. Millican and Helm, 1994; Pogoda *et al.*, 2011). Inhibiting factors include bottom-disturbing human activities (e.g. fishing), predators, water depth, competition for food and habitat, a minimum population size to obtain a healthy population, strong currents, sand waves, and diseases (e.g. Gerken and Schmidt, 2014; Korringa, 1940; Smyth *et al.*, 2018). The absence of oyster beds is not an indication that an area is unsuitable for oyster reefs per se, as it can be influenced by a recent, often human-induced, decrease in the promotional, or increase in inhibiting factors. Therefore it is necessary to first investigate the historical situation of the area to verify its potential for oyster reef development.

Once the potential of an area for oyster reef development has been confirmed based upon the historical situation, the current situation should be assessed whether an area is already or can be made suitable for oyster reef development. The assessment should include an investigation of the physical environment such as the presence or potential for a stable substrate, but also the social institutions should be addressed to identify prevailing regulations and societal desires. If the area is positively assessed for oyster reef development but not yet suitable, the assessment should indicate which promotional factors should be stimulated and which inhibiting factors minimized.

Step 2. Interventions at scale

An offshore wind farm in an area with environmental conditions suitable for oysters offers is in its existence the fundament for oyster reef development: Bottom-disturbing activities are excluded and substrate is provided by means of scour protection made of quarried rock installed at the base of the turbines or covering cables. Various measures at different scales can be taken to further promote oyster reef development, or should be taken to kickstart the development of an oyster reef. For example, providing more complexity in the scour protection than is functionally required, by means of shape, with irregular extensions in both vertical and horizontal directions, will increase surface area and provide more area for shelter. Also, the use of calciferous rock, such as limestone or marble, will trigger increased settlement by shellfish (Hidu *et al.*, 1975; Soniat *et al.*, 1991), opposed to the conventionally used non-calciferous rock such as granite and eclogite.
Four scales of potential interventions are defined: a region hosting wind farms (mega), a wind farm itself (macro), individual structures, i.e. scour protection (meso), and the construction material (micro) (see Figure 4-3).

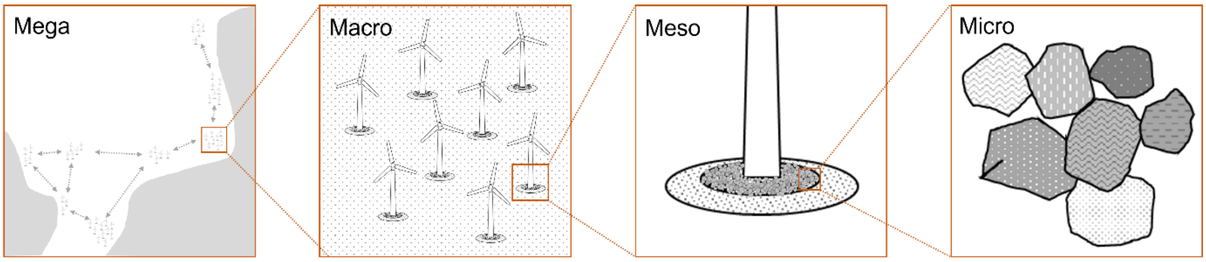


Figure 4-3: Scale division of interventions that can be taken to stimulate oyster reef development in offshore wind farms. From left to right: Mega-scale: connectivity within a regional sea; Macro-scale: undisturbed seabed between turbines in a wind farm; Meso-scale: scour protection at the base of wind turbines (armour layer on top of filter layer); Micro-scale: characteristics of construction material.

i) mega-scale –connectivity of different offshore wind farms in a seascape

The flat oyster is an immobile species who's populations only spread during the larvae stage prior to settlement. Larval dispersal depends on a number of factors including food availability, water temperature, current transport and suitable settlement sites (Kennedy and Roberts, 2006; Rodriguez-Perez *et al.*, 2021). The larvae of the flat oyster have a pelagic stage with a dispersal potential being greater than 10 km (Berghahn and Ruth, 2005; Kamermans *et al.*, 2018b), though the larvae behaviour shows high self-recruitment, tailored to reduce dispersal away from parent populations (Rodriguez-Perez *et al.*, 2020). Therefore, spread of larvae within a wind farm is likely once broodstock is present. However, oysters are not able to colonize newly built wind farms when the distance from existing populations is too large, and human intervention by means of introducing oysters in the wind farm might be required.

Oysters can be introduced in wind farms during different life stages, being adult or spat. The advantages of using adults for stock enhancement is that these are robust, and can contribute to the reef development already during the next spawning season. Using spat is beneficial as these are easier to obtain in large quantities and will have less impact on existing oyster populations. Both life stages require the use of a method that allows the oysters to survive, grow and reproduce to be able to become a thriving broodstock for reef initiation over time.

ii) macro-scale –surface area of the designated wind farm

Offshore wind farms are often constructed in a sandy environment with varying abiotic conditions, ranging from fine mud to coarse sand, and from a stable seabed to highly moving sand waves. The development of oyster reefs requires stable settlement substrate. Adding hard substrates by means of artificial reef structures using natural or artificial materials, can create settlement opportunities for oyster larvae to initiate reef development. The infrastructure in wind farms, by means of the turbines and the scour protection at their base and at cable crossings, offers such settlement substrate, but the area between the infrastructure, which is the majority of a wind farm, remains a sandy seabed. A huge variety of artificial reef structures can be installed in this area to provide settlement opportunities for oysters. However, often these structures cannot cope with strong hydrodynamic currents and high sedimentation rates, and are generally prone to erosion around their base (e.g. Walles *et al.*, 2016; Didderen *et al.*, 2019).

A more sustainable approach would be to strive for establishing a biogenic oyster reef without interference of hard structures, which would transition the dynamic sandy seabed towards a self-sustaining hard and stable environment. The agglomeration of shells from living and dead oysters forms a complex matrix for settling juveniles, and associated fauna, therefore being crucial for reef persistence over time. It should be high enough to compensate for the losses due to sedimentation and shell degradation (Mann and Powell, 2007). Triggering the establishment of biogenic oyster reefs has occurred successfully by initiating high vertical relief reefs (>25 cm) made of a conglomeration of shell from living and dead oysters (Schulte *et al.*, 2009; Scyphers *et al.*, 2009), serving as the base for the extant population, spat settlement, and reef persistence (Schulte *et al.*, 2009).

iii) meso-scale –shape and dimension of scour protection

Marine construction works often offer important refuges for marine life by means of crevices, pits and rock pools (e.g. Firth *et al.*, 2014; Consoli *et al.*, 2018). In offshore wind farms, this meso-scale habitat can be found in the scour protections at the base of wind turbines and at cable crossings. A scour protection prevents the seabed around wind farm infrastructure from erosion, and is generally composed of a filter layer of small-sized quarried rock, such as granite, topped with an armour layer of large-sized quarried rock. Promoting marine life at the scour protections, can be achieved through adjusting the dimensions and shapes to generate suitable habitat.

The European flat oyster benefits mostly from hard substrate surface to settle upon, and it should be stable as moving rocks cause physical damage or even mortality. Increasing the grading size of the rock material used for scour protection would increase its stability and provide a more stable substrate (Van Velzen *et al.*, 2014). Furthermore, changing the horizontal and vertical dimension and shape of the scour protection would increase the area of hard substrate for settlement by oyster larvae, and could create areas with reduced flow velocity, which improve the opportunities for settlement (Korringa, 1940; Smaal *et al.*, 2017).

iv) micro-scale –type and texture of construction material

The geological origin and surface roughness of building materials on a micro-scale (<1 cm) have a significant effect on the structure and functioning of colonising species assemblages (Coombes *et al.*, 2011; Green *et al.*, 2012). Small adaptations of both texture and structure of concrete constructions were observed to lead to better settlement and growth conditions for algae and macrobenthos in intertidal zones of the marine environment (Borsje *et al.*, 2010). Similar effects are to be expected when adjusting the type and texture of installations in offshore wind farms. The larvae of *O. edulis* are able to attach themselves on a wide range of substrates, but appear to have a strong preference for shells or coralline algae (e.g. Gerken and Schmidt, 2014; Smyth *et al.*, 2018; Allison *et al.*, 2020), likely due to surface roughness and presence of calcium carbonate (e.g. Cuadrado-Rica *et al.*, 2016). Tonk *et al.* (2020) tested various types of substrates for recruitment densities of *O. edulis* larvae, and observed that granite, marble and concrete were most successful for settlement per surface area. Potet *et al.* (2021) observed a positive effect on *O. edulis* larvae settlement of concrete that contains a high proportion of shell material and a surface texture that has a pattern with a coarse roughcast look resembling natural stone. Such micro-scale adaptations to materials used for infrastructure can be considered the basis for effective oyster reef development in offshore wind farms.

Step 3: Quantify effects

To determine whether measures that can be taken in the design and/or adjustment of offshore wind farms will have the desired effect on oyster reef development, the expected effects of the measures should be estimated. A quantitative assessment should be performed for each intervention based upon existing knowledge, taking into account the prevailing conditions in the designated area as much as feasible. This will allow the wind farm developer to make informed decisions on the selection of interventions to be implemented, when making a trade-off between desired impact and costs.

4.2.2 Application of the stepwise procedure to the Southern North Sea

The stepwise procedure was applied to an existing situation, to assess its application for selecting quantified measures to modify offshore wind farms for facilitating oyster reef development. The area selected for this assessment is the Southern North Sea, in which offshore wind farm development is growing rapidly. An inventory was made of all offshore wind farms present in the area up to the date 31 December 2020. The assessed wind farm data included general information on their capacity (MW), geographic location, area covered, number of turbines, foundation type, and pile diameter, and specific data on the scour protection, i.e. type, dimensions and rock size of the armour and filter layers. Data was obtained by approaching the wind farm owners, and if data was not provided upon request, information was obtained from the wind farm websites or from the web-based sources www.4coffshore.com and www.emodnet.ec.europe.eu.

The physical conditions that dominate oyster reef development in the Southern North Sea are bed shear stress and suspended particle matter (Kamermans *et al.*, 2018b) The geographic locations of all wind farms were projected in maps showing shear stress (Kamermans *et al.*, 2018b) and suspended particle matter (Gayer, 2020) using Google Earth Pro. From these maps, it was determined whether the prevailing conditions in a wind farm location fall within the boundaries suitable for oyster reefs, using thresholds provided by Kamermans *et al.* (2018b), i.e. average sea bed shear stress <0.6Pa and maximum concentration of suspended particle matter <60mg/L.

4.3 Results

4.3.1 Asses the system

The area assessed is the Southern North Sea, defined as the part of the North Sea south of the diagonal line between Scarborough (UK) and the tip of Jutland (Denmark), and north of the entrance of the Channel between Dover (UK) and Calais (F) (see Figure 4-4). This line roughly follows a 50 m depth contour and is commonly used to make a north-south division of the North Sea, in which the southern part has a depth up to approximately 50 m, and the northern part from 50 m down to the continental slope (e.g. Lee, 1980; DEFRA, 2005; Christiansen, 2009). The division is reflected by large-scale ecological patterns in infaunal, epifaunal and demersal fish communities, resulting from differences in bottom water temperature, bottom water salinity and tidal stress (Reiss *et al.*, 2010). The area is bordered by England (UK) on the west, and Belgium, The Netherlands, Germany and Denmark on the east. It has a surface area of approximately 200,000 km^2, and a maximum depth of approximately 40 m. A large sand bank, the Doggersbank lies centrally in the northern part at an average depth of 13 m, and many smaller sand banks and dunes are present in the south.

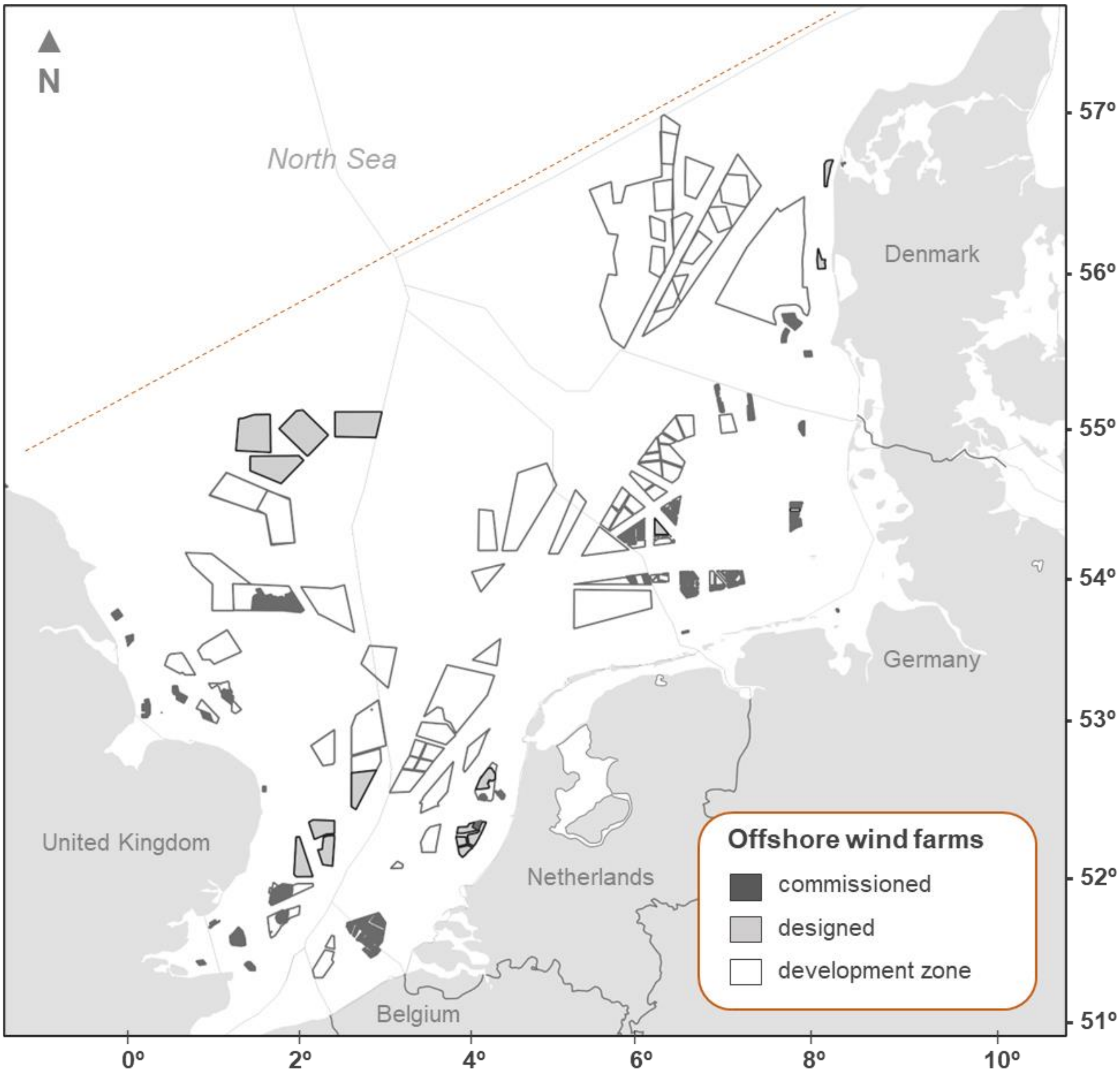


Figure 4-4: Offshore wind farms in the Southern North Sea (d.d. 31/12/2020).

European flat oysters (Ostrea edulis)

The European flat oyster beds covered large areas in the Southern North Sea (Olsen, 1883; Houziaux, 2008) with a conservatively estimated density of 1 oyster per 8 m^2 in an area of 21,202 km^2 (Berghahn and Ruth, 2005), which could imply a population of $2.65*10^9$ oysters. After their decline due to primarily overexploitation and diseases in the 19th century, the remaining oyster populations were too small to reproduce successfully (Gross and Smyth, 1946) and currently the flat oyster has almost completely disappeared from the North Sea (De Vooys *et al.*, 2004; Gerken and Schmidt, 2014). Also suitable habitat was declining, as the flat oyster prefers to settle on existing oyster or other shellfish reefs, which were also removed by the fishing activities (Korringa, 1952). The flat oyster has survived in estuaries surrounding the Southern North Sea (Smaal *et* *al.*, 2015) and recent records of pilots outplacements in open sea show survival, growth and fecundity (Didderen *et al.*, 2019, 2020; Merk *et al.*, 2020), indicating that the existing conditions in the Southern North Sea may favour a large scale return of the flat oysters.

The historic data show that the Southern North Sea offers suitable environmental conditions to host huge areas of flat oyster reefs. However, widespread bottom-disturbing activities, primarily fisheries and sand extraction, prevent stabilization of the sandy seabed, reef-formation of any type of shellfish species, and thereby inhibit oyster reef regeneration. In addition, considering the flat oyster larvae behaviour to reduce dispersal away from natal populations (Rodriguez-Perez *et al.*, 2020), reef growth is only possible from nearby existing oyster beds, which are yet only present in small amounts in coastal areas. A recovery of flat oyster reefs throughout the Southern North Sea is therefore not expected to occur naturally and requires human intervention. European institutions put focus on oyster reef restoration in the North Sea, as the OSPAR Convention lists *O. edulis* as a threatened species and habitat, worthy of protection and conservation, and the EU Habitats Directive and the Marine Strategy Framework Directive put particular emphasis on the protection and conservation of biogenic reefs such as oyster reefs. It is generally acknowledged by experts from science, nature conservation, commercial production, bio-consulting and policy advisers, that native oyster restoration in Europe should be promoted (Pogoda *et al.*, 2019).

Offshore wind farms

Up until the end of 2020, 62 wind farms with total surface of 3,388 km^2 have been installed the Southern North Sea (see Table 4-1), covering approximately 1.7% of the entire area, and many more wind farms are foreseen to be constructed. Information on the wind farms was provided by wind farm developers upon request for 27 out of the 62 wind farms. For the remaining wind farms, general information was obtained from web-based sources and specific data on the scour protection was estimated using the average of the 27 wind farms. The 62 wind farms in total produce 20.6 GW renewable energy per year from 3,959 turbines (see Table 4-1), of which the most are installed on monopiles (89.0%), some on 4-legged jackets (2.7%) and tri-piles (6.1%), and few are gravity-based (2.0%). The foundations of the first three types are hammered or drilled into the seabed and in the are generally surrounded by a rock bed to prevent erosion. This so-called scour protection generally consists of a filter layer of granite rock (commonly used size ranges between 22/90 mm and 45/180 mm) with an average diameter of 33.4(±8.5) m and thickness of 0.5(±0.1) m (N=15). The filter layer is generally topped with an armour layer of larger granite rock (common size ranges between 5-40kg and 60-300 kg) with an average diameter of 26.0(±6.5) m and thickness of 0.9(±0.3) m (N=27). The rock sizes and dimensions used in the scour protection depend on local water depth, geomorphological and hydrodynamical conditions, and diameter of the wind turbine foundation.

Table 4-1: Overview of offshore wind farms per country in the Southern North Sea (d.d. 31/12/2020).

	total capacity (MW)	**total area** (km^2)	**total turbines** (#)	**total monopiles** (%)	**total armour rock** (km^2)	**total sandy seabed** (km^2)
Denmark	776	170	220	100	0.08	170
Germany	6,567	749	1,268	78	0.67	748
Netherlands	2,461	391	462	100	0.18	391
Belgium	2,262	185	399	86	0.22	184
United Kingdom	8,532	1,893	1,610	94	0.65	1,892
Total	20,598	3,388	3,959	89	1.80	3,385

All countries bordering the Southern North Sea, i.e. Belgium, The Netherlands, Germany, Denmark and the United Kingdom, are increasing their offshore wind capacity, and the construction of offshore wind farms offers great potential for nature development activities. New installed wind farms provide suitable seabed conditions by means of hard substrate for settlement and large undisturbed areas free from bottom trawling fisheries. Although bottom-disturbing fisheries are currently allowed in operational offshore wind farms in the UK, in practice most fishermen don't resume their activities in the wind farms due to the risks involved (Gray *et al.*, 2016). Therefore, in our assessment all offshore wind farms in the Southern North sea are considered to offer undisturbed areas. Thus far, the wind farms have only been designed taking into account technical and financial aspects, but currently a transition is taking place to incorporate the active enhancement of the ecosystem, for example through requirements as those set in The Netherlands that when developing wind energy at sea 'measures have been and will be taken to make and keep the ecosystem healthy and make its use more sustainable' (Dutch Ministry of Economic Affairs and Ministry of Infrastructure and Environment, 2015).

4.3.2 Interventions at scale

Mega-scale - connectivity

To initiate oyster reef development in offshore wind farms remotely located from natural oyster reefs, likely a broodstock should be provided to generate larvae locally, as the dispersion potential larvae is greater than 10 km, but their behaviour is aimed at self-recruitment (Berghahn and Ruth, 2014; Kamermans *et al.*, 2018b; Rodriguez-Perez *et al.*, 2020). The average size of an offshore wind farm in the Southern North Sea is 54.6 (±80.4) km^2, with 1 turbine per 2.3 (±2.1) km^2, meaning that it is safe to assume that each wind farm should at least have its own broodstock to initiate oyster reef development. As the proportion of females in an oyster population is observed to be higher for larger individuals

(Kamphausen *et al.*, 2010), the broodstock should consist of a population with different size classes, to ensure the inclusion of both sexes.

The recruitment of oyster stock is determined by density, as the fertilization success and thereby broodsize increases with density (Gercken and Schmidt, 2014); oysters with a nearest neighbour ≤1.5 m were found to brood significantly more larvae than individuals with nearest neighbours ≥1.5 m (Guy *et al.*, 2018). Using broodstock structures as opposed to loosely distributed mature oysters will assure the high density of the broodstock. Kennedy and Roberts (2006) attributed an estimated total larval production per season of $1.08*10^{11}$ to a commercial stock size of 125,000 individuals, with sizes ranging between 50 and 109 mm shell diameter, i.e. 867,000 larvae per individual, indifferent of the ratio male/female. This means that a broodstock of 1,000 individuals, for example as used in offshore wind farm Borssele V with an average size of 78.9(±5.1) mm shell diameter (Schutter *et al.*, 2021), could produce $8.7x10^8$ larvae each spawning season.

The mortality rate of *O. edulis* during the planktonic phase and the first juvenile period of life is estimated to be very high: from 1 million larvae only 250 reach spat stage, of which 95% die before winter (Korringa, 1946). A broodstock of 1,000 individuals could therefore lead to a recruitment of 10,837 juveniles (ignoring uncertainties) at the start of the winter. It is suggested that about 15% of these juveniles will reach the age of 1 year (Guerra, 2002), and 70% of them is estimated to survive until maturity (Bodoy *et al.*, 1991), meaning that of the initial 1000 individuals, yearly 1,137 individuals are estimated to be produced that eventually contribute to new broodstock. Assuming no mortalities of mature oysters caused by external factors, an initial broodstock of 1,000 adults would then result in approximately 35,000 mature oysters after 10 years.

Macro-scale – sandy environment

In the Southern North Sea, the area of undisturbed sandy seabed in wind farms (total wind farm area minus the estimated amount of scour protection) is calculated to be 3,385 km^2 (Situation A in Figure 4-5). Comparison with the historical distribution of *O. edulis*, made Kamermans *et al.* (2018b) assume that areas where bed shear stress is less than 0.6 N are suitable for the development of flat oyster beds. Following this, only 21 out of the 62 offshore wind farms can be considered suitable for oyster reef development, ruling out all wind farms in Belgium waters, most of those in Dutch and UK waters (except Gemini and Horn Sea 1 and 2) and some in German waters. The total amount of sandy seabed available in these 21 wind farms with suitable conditions for oyster reef development is estimated to be 1,614 km^2 (Situation C in Figure 4-5). Densities of *O. edulis* in the North Sea system at a sandy seabed were conservatively estimated to be 0.125 individuals m^{-2} (Berghahn and Ruth, 2005). Once broodstock has been installed, this could result in a population of $2.02*10^8$ oysters at the 1,614 km^2 of suitable sandy seabed in the Southern North Sea (Situation C in Figure 4-5).

Settlement and densities of oysters at the sandy seabed in offshore wind farms can be increased by providing substrate by means of shell material, as is the case at natural oyster reefs (Allison *et al.*, 2020). Initiating high vertical relief reefs (>25 cm) made of a conglomeration of shell from living and dead oysters could result in densities of 1,026 oysters m^{-2} (Schulte *et al.*, 2009; Scyphers *et al.*, 2009). Applying this method to 1% of the sandy seabed in the 21 offshore wind farms suitable for oyster reefs, could result in an addition of $1.65*10^{10}$ oysters to the Southern North Sea (Situation D in Figure 4-5). However, it would require $4.13*10^{6}$ m^{3} of shell material, equivalent to a volume of 1,652 Olympic swimming pools (a 2,500 m^{3}). For comparison, covering a surface area with shell reef to a size equal to the available armour rock material (see below, 0.74 km^{2}), would result in an addition of $7.28*10^{8}$ oysters (Situation E in Figure 4-5), and require $1.82*10^{5}$ m^{3} of shell material, equivalent to the volume of 73 Olympic swimming pools.

Meso-scale - scour protection

While the subsea rock installations in existing offshore wind farms have been functionally designed for scour protection only, they provide hard substrate on which epibenthic rock dwelling species can thrive. During a dedicated scour protection monitoring survey undertaken in 4 Dutch wind farms in 2020, it was observed that filter layers largely disappear under a layer of sand (see Chapter 3). Therefore, only the armour layer is considered suitable for providing rocky habitat for oyster reef development. In the Southern North Sea, the area of armour rock around a single monopile in a wind farm is on average 530.2(±255.5) m^{2} (N=27). The total amount of armour layer available in the Southern North Sea is estimated to be 1.80 km^{2} (Situation B in Figure 4-5). Considering only the 21 offshore wind farms with suitable conditions for oyster reef development based upon shear stress, the total amount of armour layer available is estimated to be 0.74 km^{2} (Situation C in Figure 4-5). Oyster densities at an existing bed in the Voordelta (Netherlands) were observed to be 6.8±0.6 oysters m^{-2}, and these were most often found to grow in areas with hard substrate, i.e. rock and stones (Christianen *et al.*, 2018). We assume this number as densities that can be expected at the available scour protection. Once broodstock has been installed, this could result in a population of $5.03*10^{6}$ oysters at the available armour rock material (0.74 km^{2}) in the Southern North Sea (Situation C in Figure 4-5).

The diameter of the armour layer is on average 4.3±1.1 times the diameter of the pile (N=27). Increasing the horizontal extent of the armour layer of the scour protection with 1 pile diameter, a value taken arbitrary, would result in more armour surface area to support oyster reef development. The new total amount of armour layer available in the Southern North Sea is estimated to be 2.91 km^{2}, of which 1.27 km^{2} in de areas with suitable conditions (Situation F in Figure 4-5). Using the density of 6.8±0.6 oysters m^{-2} (Christianen *et al.*, 2018), this could result in a population of $8.64*10^{6}$ oysters at the scour protection in offshore wind farms in the Southern North Sea.

Micro-scale – materials used

Interventions at micro-scale to promote oyster reef development in offshore wind farms are primarily intended to improve settlement rates of the larvae. Adjustments can be made in substrate surface texture and substrate type. Potet *et al.* (2021) observed that a surface structure mostly resembling natural stone led to highest larvae settlement of *O. edulis*, from which can be concluded that quarried rock as conventionally used as scour protection suffices. Tonk *et al.* (2020) found that calciferous-rich marble rock had a factor 1.33 higher settlement rates of *C. gigas* larvae than conventionally used granite rock. Assuming that a similar effect would occur for *O. edulis*, and that density of oysters would linearly increase with the settlement rate, adding a marble layer on top of all existing scour protection, could thus potentially result in a total population of $5.03*10^6$ x 1.33 = $6.69*10^6$ oysters on the scour protection in offshore wind farms the Southern North Sea (Situation G in Figure 4-5).

situation	intervention	Available surface (km^2): Scour Protection	Available surface (km^2): Soft Sediment	Available surface (km^2): Shell Reef	Potential # oysters: Scour Protection (6.8 oysters m^{-2}) (Christianen *et al.* 2018)	Potential # oysters: Soft Sediment (0.125 oysters m^{-2}) (Berghahn & Ruth 2005)	Potential # oysters: Shell Reef (1,026 oysters m^{-2}) (Schulte *et al.* 2009)	Total
A	none	2.80	3,385	0	-	-	-	-
B	only armour layer to ensure stability (disregard filter layer) (ter Hofstede *et al.* 2022)	1.80	3,385	0	-	-	-	-
C	only wind farms with suitable environmental conditions (Kamermans *et al.* 2018)	0.74	1,614	0	$5.03*10^6$	$2.02*10^8$	0	$2.07*10^8$
D	25 cm layer shell material at 1% of soft sediment (Schulte *et al.* 2009)	0.74	1,598	16,1	$5.03*10^6$	$2.00*10^8$	$1.65*10^{10}$	$1.67*10^{10}$
E	25 cm layer shell material at soft sediment, area size as armour layer (Schulte *et al.* 2009)	0.74	1,613	0.7	$5.03*10^6$	$2.02*10^8$	$7.59*10^8$	$9.66*10^8$
F	horizontal extension armour layer by 1 D_{pile}	1.27	1,613	0	$8.64*10^6$	$2.02*10^8$	0	$2.10*10^8$
G	marble armour layer (settlement x 1.33) (Tonk *et al.* 2020)	0.74	1,614	0	$6.69*10^6$	$2.02*10^8$	0	$2.08*10^8$

Figure 4-5: Potential interventions in existing offshore wind farms, and the estimated order of magnitude effect on available substrate and the potential amount of oysters.

4.3.3 Future scenario

Our assessment of the system revealed that another 15 offshore wind farms are designed to be built in the Southern North Sea the coming years (see Figure 4-4), covering 3,657 km^2 with a total of 1,009 turbines delivering 13,025 MW of energy. Another 26,141 km^2 has been designated as development zone for offshore wind energy in the future. Assuming that the 15 designed wind farms are representative for the wind farms in the development zones, based on increase in surface area one may expect an addition of 7,213 turbines delivering 93,116 MW from wind energy.

Assuming that all these wind turbines will be built on a monopile foundation with scour protection at its base of a similar dimension and design as currently are used (armour 530.2(±255.5) m^2/pile; filter 388.4(±337.1) m^2/pile), a total of 4.83 km^2 armour rock, 3.54 km^2 filter and 33,013 km^2 sandy seabed will become available for oyster reef development in these future wind farms. When taking into account the assumed suitability of these wind farms for oyster reef development based upon bed shear stress, a total area of 23,321 km^2 is considered suitable for oyster reefs (70,6% of all wind farm development area). This could result in a population of $3.14*10^9$ oysters within in the Southern North Sea without interventions (Situation C). Interventions could lead population sizes of $2.59*10^{11}$ (situation D), $7.40*10^9$ (Situation E), $3.16*10^9$ (Situation F), $3.15*10^9$ (Situation G) oysters.

Table 4-2: Overview of future offshore wind farms per country in the Southern North Sea, designed and development zones. It is assumed that all turbines are built on a monopile and scour protection is applied.

Future wind farms	**total capacity** (MW)	**total area** (km^2)	**total turbines** (#)	**total armour rock** (km^2)	**total sandy seabed** (km^2)
Designed	13,025	3,657	1,009	0.53	3,656
Development zone	93,116	26,141	7,213	3.82	26,134
Total	106,140	29,797	8,223	4.36	29,790

4.3.4 The selection of interventions

Multiple interventions at different scales by means of introducing broodstock and suitable substrate have been presented, which all have the potential to contribute to oyster reef development in offshore wind farms in the Southern North Sea. Each of these interventions will have a different effect on the oyster population. It is important to know the required effort, the effect, and the interaction of such interventions, in order to support decision-makers in defining their policy objectives.

Active oyster reef development in offshore wind farms starts with the confirmation that the environmental conditions are suitable for oysters. Once confirmed, human intervention to regenerate oyster reefs is likely required, due to the lack of connectivity between the scarce natural oyster reefs and the newly build offshore wind farms. Therefore, any oyster bed development programme in offshore wind farms would probably require a human-induced accumulation of oysters, for example broodstock. How much broodstock is needed depends on the desired population size. The average offshore wind farm in the Southern North Sea contains 0.030(±0.022) km^2 of armour rock and 54.6(±80.4) km^2 of sandy seabed, meaning it potentially can host an oyster population of $7.02*10^6$ oysters, assuming the same densities used in the earlier calculations (Christianen *et al.*, 2018; Berghahn and Ruth, 2005). Fully filling up such a wind farm in 15 years' time with oysters, would require an initial broodstock of roughly 39,000 oysters, based upon the assumptions that larvae reach maturity in 3 years, the broodstock increases over that period as calculated before (factor 1.137), and no mortalities of adults occur caused by external factors.

Increasing the numbers of oysters within an wind farm area can furthermore be facilitated by providing suitable substrate. Our calculations using the densities for the three habitat types shellfish reefs (Schulte *et al.*, 2009), rock (Christianen *et al.*, 2018), and sandy seabed (Berghahn and Ruth, 2005) show that most effect can be achieved by creating permanent reefs of shell material, as assumed densities at these reefs are thought to be 150 times higher than on rock material, and 8,000 times higher than on a sandy seabed.

If the objective of the oyster reef development would be to return the flat oyster reef population to its estimated size of $2.65*10^9$ oysters in the 19th century (Berghahn and Ruth, 2005) using the amount of wind farms currently available, only the creation of shell reefs would be an effective intervention (see Figure 4-5). The total amount of habitat surface offered by the scour protection in the areas with assumed suitable conditions, is not large enough to host that size of a population, also not yet when interventions have been applied. However, creating shell reefs would require a large amount of shell material, which is difficult to purchase in practice, l*et al*one the practical constraints for installation of permanent shell reefs in offshore waters. In the future scenario when all the offshore wind farms have been installed, sufficient area with suitable conditions (bed shear stress <0.6Pa) will be available to host an oyster population as present in the 19^{th} century. The only intervention then needed would be the introduction of broodstock to overcome connectivity issues and start oyster reef development.

4.4 Discussion

4.4.1 Nature enhancement of marine infrastructure

When introducing marine infrastructure into an ecosystem, the impact on the original environment should be taken into account, even if the purpose is restoration. The addition of hard structures on the seascape can cause significant losses of sandy seabed habitats, affecting the diversity and function of marine systems in general (Bulleri and Chapman, 2010; Dafforn *et al.*, 2015a). The creation of new hard substrate habitats, albeit often essential for infrastructural purposes and considered valuable for nature enhancement, have shown loss of soft-sediment communities and their services (Davis *et al.*, 1982; Martin *et al.*, 2005). The losses of the original habitat need be assessed and minimised if possible (Dafforn *et al.*, 2015b). In situations where hard structures cannot be avoided, such as when used to prevent scouring around the foundation of a wind turbine in offshore wind farms, there is the potential for eco-engineering to mitigate the impacts of these structures and to maximise potential ecological outcomes. The scour protection can for example be engineered to enhance biodiversity through the addition of complexity and microhabitats. Small adaptations in material use, texture, and shape can improve the conditions for settlement, growth and use by a variety of marine life, while keeping the function of the scour protection intact. Also, nature enhancement can be beneficial for the marine infrastructure itself. For example, oyster presence at the scour protection of wind turbines will affect the connection of rocks and thereby its stability. The extent of this effect depends on the coverage ratio of oysters and the rock size. Smaller rock gradings such as those in the filter layer will experience a greater stability increase compared to larger rock gradings under the same coverage ratios because they require fewer oysters for effective binding (Domisse, 2020).

The spatial scale to which artificial hard structures can affect the marine environment has been found to range from 10s of metres to 1000s of kilometres (Dafforn *et al.*, 2015a). Efforts to enrich nature by adjusting infrastructure have been tested throughout the marine environment, most of these are at meso- and micro-scale. For example at meso-scale, the addition of artificial rock pools in a seawall that retain water during low tide, led to an increase in biodiversity at the seawall (Chapman and Blockley, 2009). Also at micro-scale, more often consideration is given to the use of materials, not only for the integrity of a structure, but also to promote the development of marine life (e.g. Firth *et al.*, 2014, Tonk *et al.*, 2020). At a macro- and mega-scale, the spatial arrangement of how near or far artificial structures are positioned from each other determines their impact on the environment, as it has the potential to affect the connectivity of marine organisms. The construction of offshore wind farms results in the creation of isolated rocky habitats used as scour protection at the base of each wind turbine. The isolation of these modified habitats is likely to cease as the hydrodynamics will lead to the exchange of small marine life such as larvae and seeds between the rocky habitats, and larger species will migrate within the wind farm. At a larger scale, climate change drives species range shifts (e.g. ter Hofstede *et al.*, 2010), and the expansion of marine infrastructure such as offshore wind farms may enhance these movements by providing stepping stones for rock-dwelling species by means of these small scour protections (Adams, 2014). Studies on the impact of the construction of offshore wind farms should be undertaken to not only assess possible long-term effects of the infrastructure at a local scale, but also to take into account regional scales, resulting from the potential connectivity of wind farms and consequently the introduction of invasive species.

4.4.2 Estimating the effect of interventions to support oyster reef development

The effects of interventions to initiate and facilitate oyster reef development as presented are rough estimates. Substantial assumptions have been made throughout the assessment to provide a quantitative prediction of the effect of taking interventions for developing oyster reefs in offshore wind farms, and refinement is needed. The actual outcomes of the interventions presented would remain unknown until being put in practice and will vary at each location where implemented. Nevertheless, the calculations do provide a first estimate to obtain insight into the magnitude of effort required to reach a desired effect with the interventions.

The assumptions were taken across all scales when quantifying the effects of interventions to stimulate oyster reef development in offshore wind farms. For example, at a macro-scale the assessment included only offshore wind farms that are considered suitable for the development of flat oyster beds based upon the prevailing environmental conditions. However, oyster presence can still be observed in the wind farms that are not included in this assessment, such as in the 2006-erected Dutch offshore wind farm Egmond aan Zee. Here, despite the assumed unfavourable conditions, European flat oysters were documented being settled at the top of the monopile in the intertidal zone in 2011, though noteworthy no oysters were found in the scour protection area (Bouma and Lengkeek, 2012). At meso-scale, an example of an assumption made relates to flow velocities and related settlement opportunities of oyster larvae at the scour protections. Increased turbulence generation may amplify the bed shear stress to 5-11 times higher near the foundation of a monopile than at the remainder of the scour protection (Sumer and Fredsøe, 2002). However, this variation was not taken not account as it is impossible to predict what the exact bed shear stress will be where, and when these become unsuitable for settlement. Furthermore, substantial assumptions were made on oyster densities during the quantification. Fixed oyster densities were used for the three habitat types, i.e. rocky scour protection, sandy seabed, and shell reefs, but of course in practice, many hydrological, morphological and biological factors will determine the actual densities, which are all location specific and will vary throughout time. For example, the timing of the installation of substrate such as rock material is crucial for the settlement success of oyster spat. Settlement rates are highest if the substrate is placed during the peak of larval abundance, and if placed too early, it will be fouled with other organisms that prevent oyster spat from settling, or overgrow spat that does manage to settle (MacKenzie 1970; van den Brink *et al.*, 2020). However, the construction of offshore wind farms takes place year-round, mostly outside of the short spawning period of oysters, meaning that much of the available substrate for oyster spat is likely to have been colonised by competing organisms.

Also, the interventions available for enhancing oyster reefs in offshore wind farms are not limited to the ones presented here, and more options can be considered. For example, instead of introducing oyster broodstock to initiate reef development in a wind farm, one can also consider the introduction of oyster spat. Although it will take a couple of years before the spat has matured and can start producing larvae to distribute throughout the wind farm, spat is easier to obtain in large quantities with less impact on existing oyster populations. Another example, at a meso-scale, adding vertical variability is a method to create low-current areas, which can benefit the settlement of oyster larvae. This can be done by creating piles of rock or installing artificial reef structures. The benefit of creating a piles of rocks is that it can be done by using the same type of rock as is used for the scour protection, which is easier to acquire. If rock of similar size is used, the same equipment for installation of the scour protection can be used.

If larger rocks or artificial reef structures are used, one might need to install a filter layer to stabilize the seabed first if installed independently, or account for secondary scour if these structures are installed on-top of the scour protection itself, and other equipment for installation might be required, which complicates the installation procedure.

4.5 Conclusion

Innovative eco-designs for marine constructions are developed to be beneficial for marine life and associated societal interests, and should become an integral part of large-scale infrastructural development. It remains to be determined how the various elements of marine infrastructure can be used or attuned to positively influence the marine ecosystem, not in the last place because it is not clearly defined and even arguable what changes may be considered positive. Currently, clear objectives are lacking for stimulating nature values in offshore wind farms, which inhibits a coordinated implementation of knowledge gained from small scale pilots into larger scale policies. This also requires thinking beyond individual pilots, and consideration of the effect of each intervention across different scales.

In this Chapter a stepwise procedure is to quantitatively estimate the potential effects of interventions at various scales, from micro-scale (materials used) to mega-scale (connectivity between wind farms). It has been applied using the knowledge available for initiating oyster reefs in the current and future wind farms in the Southern North Sea. The stepwise procedure provides insight in what are the most promising measures, and where uncertainty or lack of knowledge is cause for concern. This may guide future research, as well as contribute to determining a coordinated selection of interventions to adjust conventional designs of wind farms to promote flat oyster reef development, with the aim to establish significant effects in a regional seascape.

The inclusion of hard substrate and the absence of seabed disturbing fisheries are the main components of wind farms in the Southern North Sea to be suitable for flat oyster reef development. The presence of hard substrate provides settlement opportunities for the flat oyster spat, which can be increased with selected interventions. The absence of bottom disturbing fisheries within a wind park provides the opportunity for oysters to build their reef without having the habitat being destroyed. Due to the lack of connectivity between natural oyster reefs and the wind farms, active introduction of oysters in the wind farms is required to kickstart the development of eventually self-sustainable oyster reefs.

5 Apply interventions

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Settlement success of European flat oyster (Ostrea edulis) on different types of hard substrate to support reef development in offshore wind farms

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Chapter 5 – Apply interventions

The availability of hard substrate is crucial for initial settlement of flat oyster larvae and successive reef development. Such substrate is offered in offshore wind farms, often by means of quarried rock placed at the base of the wind turbine foundations and on top of cable crossings to prevent scouring of the seabed. As an example of an intervention, oyster reef initiation can be increased by using the most favoured substrate for larvae settlement as scour protection.

In this Chapter, the results are presented of a study on the settlement preference of flat oyster larvae on 9 different types of substrate, under controlled and natural conditions. Total settlement, spat densities and spat survival were assessed as indicators for settlement preference. Knowing these favourable substrates and conditions for oyster larvae settlement allows for the selection of pro-active measures that contribute to flat oyster reef restoration in the North Sea. Applying materials that are suitable for colonisation by specific species is one of the interventions one can apply in the design of marine infrastructure to promote targeted ecosystem components.

Research Question

What infrastructural design interventions can be applied to promote oyster reef development in offshore wind farms in the Southern North Sea?

5.1 Introduction

European flat oysters (*Ostrea edulis*) form biogenic reefs that contribute to a heterogeneous seabed and a biodiverse ecosystem (Bouma *et al.*, 2009, Smyth and Roberts, 2010; Thrush *et al.*, 2008). These oyster reefs improve water quality through filtration (Dolmer, 2000; Newell, 2004) and provide a habitat for a diverse associated community by offering settlement substrate, food and shelter (Coen and Luckenbach, 2000; Lown *et al.*, 2021). Oyster reefs can counterbalance physical and biological stresses in a dynamic marine environment, creating a hospitable habitat for organisms that would otherwise be unable to tolerate severe conditions (Crain and Bertness, 2006).

Flat oyster reefs were abundant in the North Sea until late 19th century (Olsen, 1883), but became nearly extinct due to human disturbances such as overfishing, introduction of diseases and habitat destruction (e.g. Gross and Smyth, 1946; Korringa, 1952). In recent years, there has been growing interest in restoring these native oyster reefs for their valuable contribution to a rich marine ecosystem (e.g. Pogoda *et al.*, 2019; Preston *et al.* 2020). An opportunity to restore these once abundant ecosystem engineers arises from the rapidly growing offshore wind energy industry. In the Southern North Sea alone, 62 windfarms have been installed during the first two decades of this millennium covering a total area of 3,388 km^2, with a projected tenfold increase due to further development of offshore wind energy production (see Chapter 4). These wind farm areas are largely closed for bottom-disturbing activities such as bottom-trawl fisheries or sand extraction, providing an undisturbed seabed needed for oyster reef development. A small part of the seabed in a windfarm area (~0.0005%) offers hard substrate, usually the quarried rock granite, placed at the base of the wind turbine foundations and on top of cable crossings to prevent scouring of the seabed (see Chapter 4). This scour protection is generally composed of a flat filter base layer consisting of small-sized rock, topped with an armour layer of larger rocks at the wind turbine foundations, or topped with a sprinkler layer of gravel at cable crossings (see Chapter 4). The deployment of scour protection modifies the seascape, by changing a sandy seabed to rocky substrates, creating a heterogeneous seabed (Krone *et al.*, 2013). Furthermore, the three-dimensional hard-substrate provides a habitat on which marine life can settle, forage and find shelter, leading to a local increase in species abundance and species diversity (Coolen *et al.*, 2020; Degraer *et al.*, 2020; Chapter 3). Scour protection in wind farms offers the potential for flat oyster reef restoration providing hard substrate that is crucial for the settlement of oyster larvae (Wieczorek and Todd, 1998). The type of hard substrate used for scour protection affects oyster settlement rates and thereby the success of potential reef development (Tamburri *et al.*, 2009; Smyth *et al.*, 2018; Chuku *et al.* 2020).

Despite the availability of hard substrate in offshore wind farms in the North Sea, spontaneous establishment of oyster reefs has not yet been reported. European flat oyster larvae have a pelagic stage of several weeks and their behaviour is aimed at self-recruitment (Rodriguez-Perez *et al.*, 2020). The remaining absence of oyster settlement in offshore windfarms could be therefore be due to a lack of connectivity between existing oyster beds and the newly developed wind farms (Kamermans *et al.*, 2018b; Rodriguez-Perez *et al.*, 2020). Hence, the development of oyster reefs in offshore wind farms likely requires the active introduction of oysters to initiate settlement (see Chapter 4), allocated at sites where high self-recruitment is expected (Stechele *et al.*, 2023a). In the Dutch part of the North Sea, adult oyster broodstock has been introduced in offshore wind farms, aiming to locally produce larvae that can settle and develop into thriving reefs on the available substrates (e.g. Didderen *et al.*, 2019; Schutter *et al.*, 2021). Alternatively, deploying substrate pre-settled with oyster spat could also be an option to initiate reef development (Preston *et al.*, 2020). Both oyster deployment methods of either broodstock or spat-on-substrate have their advantages. For instance, the benefit of using broodstock is that they can reproduce in the first spawning season after deployment for fast reef initiation. Using spat has the advantage that it can be produced in hatcheries or ponds without affecting natural populations for collection of source material and limited competition with other fouling organisms. To select the preferred strategy for actively initiating oyster reef development in offshore wind farms, it is required to consider the differences between spat yield in a natural environment (after deployment of broodstock) and in a controlled environment (using pre-settled substrate).

In this study we evaluate the settlement success of flat oyster larvae on different types of substrate, allowing us to determine their suitability for use in offshore wind farms to facilitate the initiation of oyster reef development. Our experiments were conducted in a spatting pond and in a natural bay to determine differences in spat yield on the substrate types under both controlled and natural conditions. Knowing the favourable substrates and conditions for oyster larvae settlement contributes to allowing governments and wind farm developers to select appropriate measures that support oyster reef restoration. Optimizing the infrastructure of offshore wind farms for flat oyster reef restoration purposes will greatly improve the involvement of wind energy production to increasing the nature values of the North Sea.

5.2 Material & methods

5.2.1 Substrate material

An experiment was conducted to assess settlement success of flat oyster larvae on nine different types of hard substrate (Figure 5-1; Table 5-1). These substrate types were selected based on their application as scour protection in offshore windfarms (granite, sandstone and flint), as substrates that are used in shellfish reef restoration (conventional concrete, concrete with natural adhesives (ECOncrete; http://econcretetech.com), galvanized steel, and circular biodegradable reef blocks (Biodegradable EcoSystem Engineering elements – BESE; htttp://bese-products.com) and as substrates that are commonly used for spat collection in oyster farms (mussel shell and clay roof tiles).

Figure 5-1: A) basket used to hold the substrates, in this example filled with silex. B) overview of the different substrates used in the field experiments. From top left to bottom right: mussel shells, granite, sandstone, silex, concrete, ECOncrete, roof tile, BESE, steel.

Table 5-1: Overview of the number and weight of the substrates used in the experiment.

Substrate	Spatting pond			Natural bay		
	# baskets	Mean weight/basket (g) (SD)	Mean surface/basket (cm²) (SD)	# baskets	Mean weight/basket (g) (SD)	Mean surface/basket (cm²) (SD)
mussel	5	753.4 (47.7)	6795.6 (430.0)	2	1010.0 (41.0)	9110.2 (366.9)
granite	5	4313.2 (208.8)	3306.6 (160.1)	4	4347.0 (138.5)	3332.5 (106.1)
sandstone	5	3461.2 (120.0)	5396.2 (187.1)	5	3596.0 (262.1)	5606.3 (408.7)
silex	5	3951.4 (251.6)	2461.0 (156.7)	5	4465.2 (156.8)	2781.0 (97.6)
concrete	5	4498.2 (311.7)	2990.6 (207.2)	4	4653.8 (244.3)	3094.1 (162.5)
ECOncrete	5	3108.4 (491.3)	2170.8 (343.1)	4	3293.5 (343.8)	2300.1 (240.1)
rooftile	5	3309.8 (150.0)	3196.6 (144.9)	3	3491.3 (62.4)	3371.9 (60.3)
BESE	5	152.6 (3.6)	1742.5 (40.9)	5	292.6 (44.6)	3341.1 (509.4)
steel	5	1512.6 (31.5)	1768.6 (36.8)	3	1582.3 (93.4)	1850.2 (109.2)

5.2.2 Spat collection locations

The experiment took place at two different locations in Ireland (Figure 5-2). To assess settlement success under controlled conditions, an oyster spatting pond was selected, located in New Quay, County Clare, (53°09'25.9"N 9°04'00.2"W) (Figure 5-2). The spatting pond is a square pond of 25 by 25m with a depth of 2m. Brood stock was placed in the ponds and once the oysters started spawning, water refreshment was kept to a minimum to prevent the oyster larvae from washing out. To observe settlement under natural conditions, a site with a resident wild population of oysters in the natural environment was selected, located on the west coast of Tralee Bay, County Kerry (52°16'18.8"N 9°51'43.3"W) (Figure 5-2). Tralee Bay is known for its natural reproduction capability of flat oysters and sustains one of the few self-seeding wild flat oyster fisheries found in Europe. The substrates were deployed in the water column using longlines of approximately 60m length, in a relatively shallow part of the bay (6-8m) near a resident population of flat oysters.

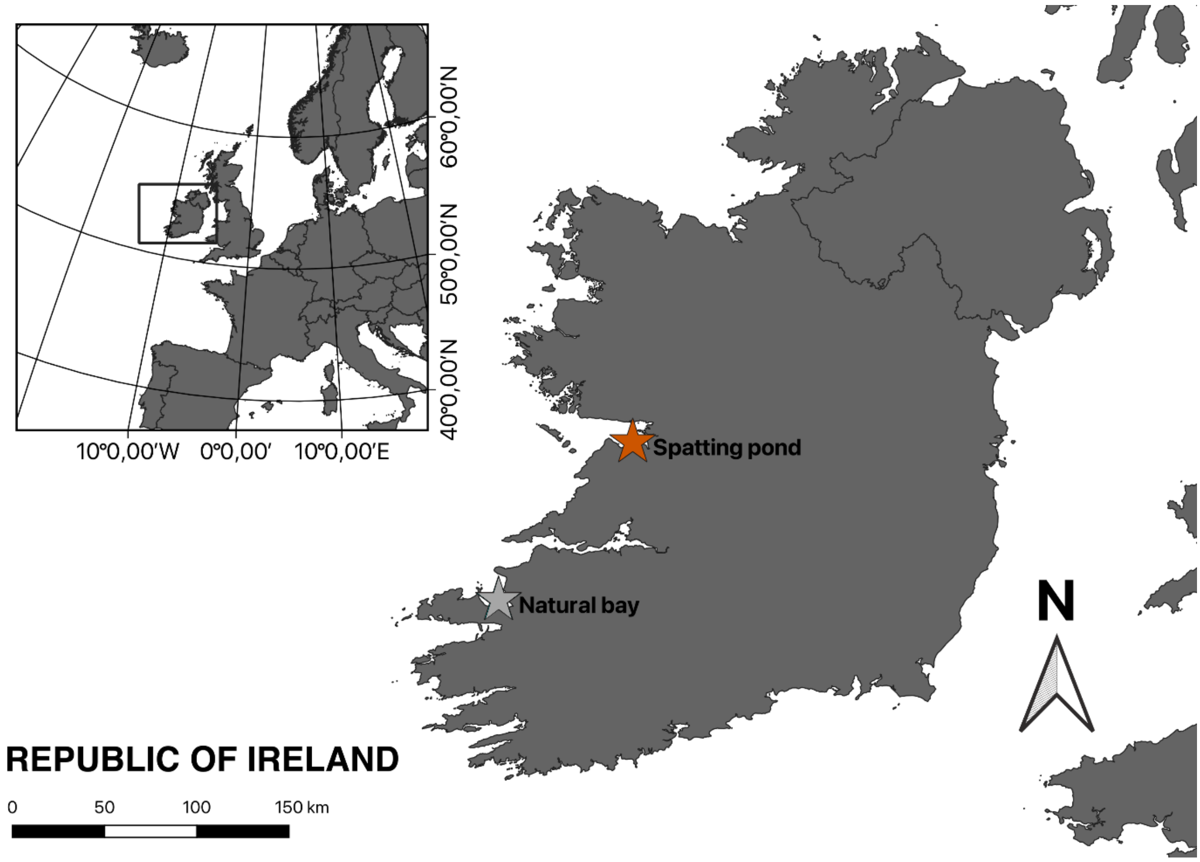

Figure 5-2: Map indicating the two locations where the field experiments were conducted, the spatting pond in New Quay (orange star) and the natural bay in Tralee (grey star).

5.2.3 Deployment of substrate baskets

The substrates were contained in polyethylene baskets (diameter 15cm, height 40cm) with a 2x2cm mesh size. Weight and volume of the content in each basket was determined prior to deployment. At both locations, the substrate baskets (n=5 per substrate type) were suspended 20-30cm below the water surface, approximately 30cm apart. The sequence of the substrate baskets was randomly assigned. To limit biofouling that could potentially interfere with settlement of oyster larvae, the substrate baskets were deployed shortly before the expected peak in larvae settlement. The settlement peak of flat oyster larvae generally occurs about two weeks after a peak in larvae numbers is observed (Maathuis *et al.*, 2020; van den Brink *et al.*, 2020). Peaks in larvae numbers were determined through daily monitoring of free-swimming larvae numbers from water samples in the spatting pond from June 9th until August 23rd 2019, providing an indication of expected peaks in larvae settlement. Peaks in settlement were determined by counting spat on standard settlement plates, in the spatting pond on a daily basis over the same period, and in the natural bay on three days (July 15th, August 18th, September 2nd). Several peaks in larvae settlement were observed in the spatting pond, starting from June 19th with the highest peak in settlement on July 2nd. Oyster larvae settlement in the natural bay was confirmed on all three monitoring occasions. The substrate baskets were deployed in the spatting pond on June 25th and all were retrieved on September 23rd. The substrate baskets were deployed in the natural bay on July 1st and retrieved on September 25th. Some of the baskets in the natural bay were lost due to severe weather conditions, resulting in less than 5 replicates for some substrate types (Table 6-1).

5.2.4 Counting spat

After retrieval of the substrate baskets, the substrates in each basket were weighed, biofouling was removed, and if necessary, the substrate was cleaned using filtered seawater. Then, the total number of oyster spat on the substrate was counted. In order to assess the initial settlement preference, the total number of spat included both living and dead spat, which was recorded separately. If the total number of spat was estimated to be over 250 individuals per basket before counting, a subsample was taken by spreading out the substrate evenly and splitting it into equal parts. The numbers of spat were then counted in the subsample, while ensuring that subsamples always contained a minimum of 100 spat. The substrate in the subsample was weighed and the total number of spat in the basket was estimated by multiplying the number of spat counted in the subsample by the fraction of the total weight in the subsample.

5.2.5 Determining the surface area

In order to compare the spat densities on the different substrate types, the three-dimensional surface area of the different substrates was estimated using a combination of double wax dipping and 3D scanning. Double wax dipping involves dipping a substrate in melted paraffin wax twice, and the increase in weight between the first and second dip is taken as an indication for the surface area (Stimson and Kinzie,1991; Holmes, 2008). In order to determine the available settlement surface, a representative subsample of a random size mix of pieces of each substrate type was used for double wax dipping. Five different sized pieces of every substrate type that were used for wax dipping were also scanned with a 3D scanner (Artec Eva Handheld scanner). The surface area of these pieces of substrate was calculated using 3D models created with Artec Studio (V14). A calibration curve was then calculated based on the 3D models to determine the available surface area from the weight difference between the first and second wax dip:

*3D surface area=3.41 +27.48*weight difference*

Where, 3.41 mm^2 is the minimum possible surface where there is no substrate but just a drop of wax, and the weight difference is the difference between the first and second wax layer. Based on the subsample that was dipped in wax, the surface area in cm^2 per kg was calculated using the above formula. This was then multiplied by the weight of the substrates in each basket to estimate the available surface in cm^2 for settlement in each basket.

5.2.6 Data analysis

To determine which substrate collected the highest numbers of spat, the total numbers of spat were compared between the two locations and between different substrate types. Spat density was taken as an indicator for settlement preference, calculated by dividing total spat by the available settlement surface in cm^2. Spat survival was calculated as the fraction of living spat out of the total spat counted after retrieval, and also compared between locations and substrate types. Because the variance of the settlement differed greatly between the substrate types and locations, statistical analyses were performed using non-parametric Kruskal-Wallis tests. If the Kruskal-Wallis test indicated significant differences between substrates, Conover-Iman post-hoc tests were performed to determine which substrates differed significantly in terms of spat survival, total spat or spat density. In all cases, the results presenting variability refer to the standard deviation of the mean.

Data analysis was done in R (version 4.3.1, R Core Team, 2021) with the Tidyverse package (Wickham, Vaughan & Girlich, 2023). Kruskal-Wallis tests were performed using the Stats package (R Core Team). Conover-Iman post-hoc tests were performed using the conover.test package (Dinno, 2017). The maps were created in QGIS (version 3.30) and all other plots were made using ggplot2 (Wickham, 2016). For ease of understanding the plots, compact letter displays generated with the rcompanion package were added to plots (Mangiafico, 2023).

5.3 Results

After retrieving the baskets with substrates, there was no biofouling observed on the substrates deployed in the spatting pond, while those deployed in the natural bay contained soft-bodied fouling organisms such as *Ectopleura larynx* (ringed tubularia), different species of anemones, sponges and bryozoa, as well as *Spirobranchus triqueter* (brushworm), saddle oysters (*Anomiidae*), scallops

(*Pectinidae*) and other molluscs. Sizes of oyster spat collected on the substrates differed from several mm to 1.5cm due to the occurrence of multiple settlement peaks during the experiment.

The settlement success rate in terms of average total spat (both living and dead) per basket was significantly higher on the substrates placed in the spatting pond (469.1±517.5) than in the natural bay (98.7±74.4) (Kruskal-Wallis, H=13.31, df=1, p <.01). There were significant differences between the total numbers of spat on the different types of substrates in both locations (Kruskal-Wallis: spatting pond H=36.49, df=8, p <.01; natural bay H=26.26, df=8, p <.01). On average the most spat was found on granite, both in the spatting pond (1120.8±796.7) and in the natural bay environment (206.8±32.1) (Figure 5-3). The substrate BESE had the lowest settlement in the spatting pond (2.8±2.4), and collected no spat in the natural bay environment. The average spat survival (fraction living spat of total spat) significantly differed between the spatting pond (0.79±0.16) and natural bay environment (0.77±0.39) (Kruskal-Wallis: H=14.70, df=1, p <.01; Figure 5-3). Spat survival per substrate type was generally higher in the natural bay. The highest average spat survival was on mussel shells, both in the spatting pond (0.90±0.05) and in the natural bay (0.99±0.01). The lowest average spat survival was observed on steel, both in the spatting pond (0.68±0.18) and in the natural bay (0.33±0.58).

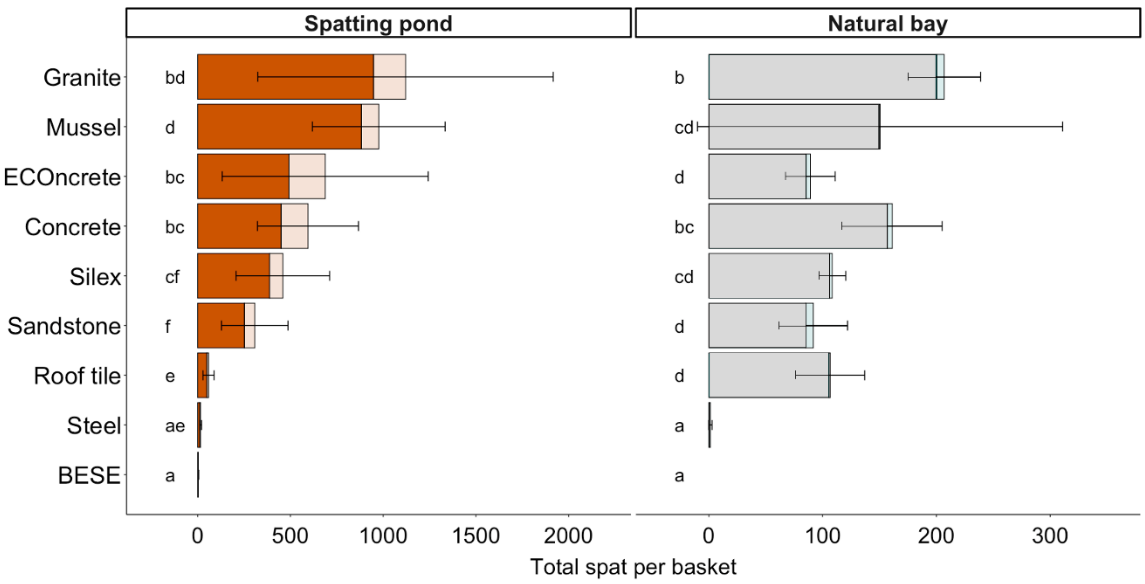

Figure 5-3: Total spat per basket (mean and SD) per substrate for the two locations. To illustrate survival total spat is divided into living (dark colour) and dead spat (light colour). Significant difference was observed between the locations per substrate type. Letters indicate the effect of substrate type on total spat per basket; if substrate types have letters in common, they do not significantly differ from each other. Note the difference in magnitude of the x-axes for the Spatting pond (in orange) and the Natural bay (in grey).

Based on the total number of spat per surface area (cm^2), settlement preference differed for specific types of substrate at both locations (Kruskal-Wallis: spatting pond H=37.79, df=8, p <.01; natural bay H=30.61, df=8, p <.01; Figure 5-4). Oyster larvae preferably settled on granite, both in the spatting pond and in the natural bay, on average 0.35±0.26 and 0.06±0.01 spat per cm^2 respectively. In the spatting pond, a group of five substrate types (granite (0.35±0.26), mussel shells (0.15±0.06), ECOncrete (0.31±0.22), concrete (0.20±0.10), silex (0.19±0.12)) had significantly higher settlement rates than the other substrate types (sandstone (0.06±0.03), roof tile (0.02±0.01), steel (0.01±<.01), BESE (<.01±<.01)) (Figure 5-4). In the natural bay, settlement preference between substrates was more pronounced, as only two substrate types, i.e. granite (0.06±0.01) and concrete (0.05±0.01), showed significantly higher settlement preference than all other substrates (Figure 5-4). Steel and BESE had very low settlement rates compared to the other substrates, both in the spatting pond and the natural bay.

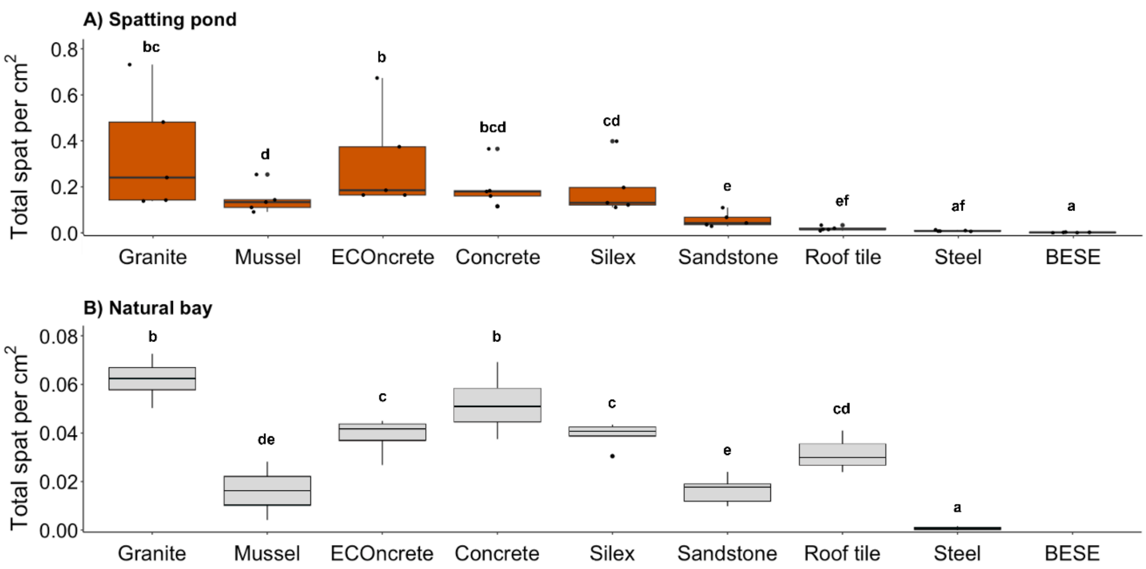

Figure 5-4: Total spat per cm² indicating settlement preference per substrate type for the A) Spatting pond (in orange) and B) Natural bay (in grey). Boxplots depict the median, quantile, outliers and distribution of the spat per cm² in the baskets. Letters indicate the effect of substrate type on spat density; if substrate types have letters in common, they do not significantly differ from each other. Note the difference in magnitude of the y-axes between the Spatting pond and the Natural bay graphs.

5.4 Discussion

5.4.1 Settlement preference

Overall, a variable settlement of spat across multiple substrates was observed, with some distinct outcomes. Settlement rates in the spatting pond were higher than in the bay area hosting natural oyster reefs, which was to be expected as the oyster larvae are restricted to the confined space of the pond and their main settlement opportunity was on the provided substrate types. Also, the average spat survival until retrieval of the substrates differed significantly between the spatting pond and natural environment, being higher in the natural bay. Our finding that the survival in an uncontrolled natural environment was higher than in a confined spatting pond could be considered remarkable, since in the natural bay the spat is exposed to external stressors such as predators and fouling organisms competing for space. However, the higher settlement densities in the spatting pond could also lead to higher mortality of the spat, as also observed by Zorita *et al.* (2021) when comparing survival of *O. edulis* spat between different stocking densities, for example due to competition for food and space. Furthermore, our experimental setup of placing the substrates in baskets and hanging them on a long-line off-bottom has likely severely reduced predation pressure, in particular from benthic organisms like crabs and starfish.

Settlement of *O. edulis* was generally the highest on granite, in total spat per basket as well as in numbers per surface area (cm^2), both in the spatting pond and in the natural bay. Granite rock material is commonly used as scour protection in offshore wind farms (see Chapter 4), which implies that wind farms generally offer favourable settlement substrate for oyster larvae. Settlement densities (per cm^2) of *O. edulis* were also observed particularly high on concrete in the natural bay. Concrete has been observed previously as an even more preferable settlement substrate than natural materials like rock and shell for oyster larvae of the species *Crassostrea virginica* (Graham *et al.*, 2017). Total settlement per basket was also high for mussel shells, which is not unexpected as shell material generally attracts high numbers of oyster larvae for settlement (Levine *et al.*, 2017; Smyth *et al.*, 2018; van den Brink *et al.*, 2020). On the contrary, the spat densities (per cm^2) on mussel shells were low. In our study mussel shells had the highest surface area/weight ratio compared to the other substrate types used. Therefore, even if spat densities were low, the total spat in a basket filled with shells was high because of the large total surface area offered for settlement. This implies that offering substrate with a large surface area such as shells, could be an efficient way for spat collection compared to more compact substrates (Kuykendall *et al.*, 2015).

Oyster larvae settlement was observed to be the lowest on the steel and BESE substrates, though both materials have shown to be successfully colonized by bivalve larvae in previous studies (e.g. Pouvreau *et al.*, 2021; Nauta *et al.*, 2023; Temmink *et al.*, 2022). Experiments by Pouvreau *et al.* (2021) indicate high colonization rates by *O. edulis* on untreated steel. This is in contrast to our results and might be explained by the fact that the steel used in our experiment was smooth and galvanized, therefore likely less suitable for larvae settlement. Also BESE appears unsuitable as settlement substrate for *O. edulis* larvae, at least in its grid shape as used in our experiments. However, BESE has shown to be a suitable habitat modifier in other shellfish reef restoration projects (e.g. Nauta *et al.*, 2023; Temmink *et al.*, 2022).

5.4.2 Implementation in offshore wind farms

The deployment of favourable settlement substrate could be an adequate intervention to support oyster reef development in offshore wind farms. The selection of substrate material highly depends on its application, whether it is merely used for nature enhancement including oyster development, such as artificial reef structures, or whether it should have a function as part of the infrastructure of the wind farm, such as scour protection. Artificial reef structures are commonly installed to provide the hard substrate required for oyster reef restoration (Baine, 2001; La Peyre *et al.*, 2014). Concrete is often used as the main construction material for artificial reefs (Baine, 2001), which according to the outcome of our experiments appears to be a suitable substrate for oyster larvae settlement. A material like concrete easily allows formation into shapes that are optimal for oyster larvae settlement, for example by the inclusion of specific surface roughness and richness in calcium carbonate (Cuadrado-Rica *et al.*, 2016; Potet *et al.*, 2021), making it a potentially preferable settlement substrate. However, the downside of concrete is it being toxic as the cement mortars often leach trace metals over time (Hillier *et al.*, 1999; Wilding and Sayer, 2002). ECOncrete partly compensates for this, as it contains nature-friendly adhesives (Perkol-Finkel and Sella, 2014), thereby notably reducing its toxicity compared to conventional concrete. Still, the manufacturing process of artificial reef structures made of concrete or ECOncrete causes substantial emissions of carbon dioxide (Blankendaal *et al.*, 2014; Fennell *et al.*, 2021). Furthermore, these structures would need to be produced in large amounts to achieve impact at scale (Bohnsack and Sutherland, 1985).

Instead of installing artificial reef structures in offshore wind farms to provide substrate for oyster reef development, our study implies that it would be more advantageous to achieve the desired impact by using and enhancing the infrastructure of the wind farm itself. Marine infrastructures inherently provide artificial habitat at large scale: its long-term presence allows nature development, and designs can be optimized to target certain species (see Chapter 4). The scour protection in offshore wind farms can be made of the natural rock material granite, observed in our study as the most favourable substrate for oyster larvae settlement. It can even be designed to further increase opportunities for oyster larvae settlement. Oyster larvae benefit from reduced flow velocities at the seabed (Korringa, 1940), and these conditions can be created within the scour protection through more irregular extensions in both vertical and horizontal directions. Incorporating such microhabitats with reduced flow velocities in the design of a scour protection, would enhance settlement opportunities for oyster larvae in offshore wind farms (see Chapter 4). It yet remains to be determined how exactly the various elements of scour protection in offshore wind farms can be used or attuned to positively influence oyster reef development, and only by putting interventions into practice one can study their effects. Fact is, the presence of stable hard substrate by means of scour protection provides settlement opportunities for the flat oyster larvae (Smyth *et al.*, 2018), and it is to be expected that an increase in its habitat complexity by bringing in more variety in use of materials, shapes and dimensions (see Chapter 4), will result in a higher oyster abundance, as is the case for epibenthic biodiversity in general (Lapointe and Bourget, 1999; Firth *et al.*, 2014).

Merely deploying favourable settlement substrate and creating suitable settlement conditions is likely not sufficient to initiate oyster reef development in offshore wind farms due to the absence or low abundance of flat oysters (see Chapter 4). There's often a lack of connectivity between existing oyster beds and the newly developed wind farms (Kamermans *et al.*, 2018b; Rodriguez-Perez *et al.*, 2020). This results in a lack of recruitment to initiate oyster reef development, despite the presence of hard substrate for settlement. Currently, the focus lies on deploying oyster broodstock in offshore wind farms, to serve as local larvae pumps for initiation of oyster reefs (Didderen *et al.*, 2019; Schutter *et al.*, 2021). However, the observed higher settlement rates in a spatting pond could support decision-making in setting an alternative strategy to pro-actively introduce oysters in offshore wind farms. Deploying substrate that is already pre-settled with oyster spat could become the preferred strategy to kickstart oyster reefs, knowing that spat densities on the used substrate will be high when settlement occurs in a controlled environment such as a spatting pond.

The selection of the type of substrate for pre-settlement can also be made based on cost-efficiency and suitability for the offshore environment. Making use of the infrastructure of the wind farm is the most cost-effective (see Chapter 6), as it is part of the construction process and existence of the wind farm itself without additional costs, which is even feasible with optimizations such as calciferous rock material as scour protection. Another cost-effective measure relates to the use of pre-settled spat on substrate. High settlement of oyster larvae was observed on mussel shells, a substrate with a high surface:volume ratio. The high surface:volume ratio of shells takes less volume of substrate to host a higher number of spat, during both spat collection and transportation to the wind farm. It is also for these reasons that mussel shells are commonly applied in oyster cultivation practices as spat collectors (van den Brink *et al.*, 2020). On the other hand, the high surface:volume ratio of shell material leads to a high chance of the shells to wash away by currents, once deployed in wind farms. A heavier material with a lower surface-volume ratio such as rock will be more stable once deployed, and provides hard substrate for oyster reef development over a longer period of time. The final selection of suitable interventions however needs to be based on a case-by-case assessment, making a trade-off between desired impact and costs.

5.5 Conclusions

The reinstatement of large European flat oyster reefs in the North Sea could benefit from the rapid increase in offshore wind farms. The use of hard substrate as scour protection in the infrastructure of the wind farms provides suitable settlement conditions for oyster reefs to develop. Our results show that oysters preferentially settle on stony substrates such as granite and concrete. Granite would be the most favourable substrate for use as (additional) substrate to facilitate oyster reef development in offshore wind farms, being a material from natural origin and already commonly applied as scour protection, simplifying its implementation. The initiation of oyster reef development in offshore windfarms likely requires the pro-active introduction of oysters, either spat pre-settled on substrate or adults, due to the lack of connectivity with existing oyster beds. Settlement rates in the spatting pond were much higher than in the natural bay, implying that deploying substrate pre-settled with spat under controlled conditions, could be an efficient strategy worth to consider for kickstarting oyster reefs.

Our results provide insight in the settlement preference of the European flat oyster for different types of substrate under both controlled and natural conditions, and allow for the selection of measures to initiate oyster reef development in offshore wind farms. Implementation of these findings can contribute to establishing the return of a large flat oyster population in the North Sea.

6 Achieve scale

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Five golden principles to advance marine reef restoration by linking science and industry

ter Hofstede R, Bouma T J, Van Koningsveld M

Chapter 6 – Achieve scale

To achieve system-scale impact through nature-friendly marine infrastructure, scientific knowledge should be paired with industry-based approaches. In this Chapter, five principles are presented to do so, illustrated for reef restoration. Synergizing practices by science and industry is needed to upscale restoration efforts and truly improve the condition of marine reef ecosystems. By consciously connecting novel scientific insights and the long-standing experience of marine contractors executing large-scale projects, the likelihood increases that marine infrastructure development and promoting targeted ecosystem components can be aligned successfully and have a significant impact on the system.

Research Question

How to achieve positive ecological impact at system-scale using nature-inclusive marine infrastructure?

6.1 Introduction: Advancing reef restoration

Reef ecosystems such as oyster and coral reefs have declined rapidly worldwide (e.g., Beck *et al.*, 2011; Eddy *et al.*, 2018). Restoration efforts in terms of "assisting the recovery of an ecosystem that has been degraded, damaged or destroyed" (SER, 2004), are undertaken to protect biodiversity, secure food provision, and mitigate climate change through carbon storage (Sala *et al.*, 2021). However, these don't keep pace with the ongoing changes in our world caused by coastal urbanization, warming temperatures, and rising sea levels (Suding, 2011; Bellwood *et al.*, 2019). Moreover, while restoration efforts have shown increased provision of biodiversity and ecosystem services, these are typically lower than in intact reference ecosystems (Rey Benayas *et al.*, 2009). A key challenge identified to achieve more effective ecosystem restoration is the development of scalable restoration methods (Rinkevich, 2008; Abelson *et al.*, 2020; Duarte *et al.*, 2020). This is where industry can be of support, having the capability and experience of executing large-scale operations. For industry it is also of interest to invest in restoration practices, in order to build a track record that allows industry to be able to include nature-based solutions in future contracts, to improve reputation, and to offer employer attractiveness.

Marine construction works modify seascapes by replacing natural habitats and changing environmental conditions critical to habitat persistence (Bugnot *et al.*, 2021). However, they can be designed to incorporate ecological principles that benefit marine life (Dafforn *et al.*, 2015; Laboyrie *et al.*, 2018). By no means this should be used as excuse to ignore or down-play the negative impact that infrastructural developments may have on a marine system (Firth *et al.*, 2020) or as argument to restrict restoration efforts only to where infrastructural works take place. However, nature restoration goals and marine construction works can be synergized much better to not miss out on unique nature-enhancing opportunities. In this Chapter we present five golden principles how marine contractors can support reef ecosystem restoration.

6.2 Five golden principles to advance marine reef restoration by linking science and industry

Principle I. Pursue upscaling – use industry-based techniques

Current practices for restoration are often too small in scope to combat the extent of anthropogenic threats driving habitat loss (Hughes *et al.*, 2017; Bellwood *et al.*, 2019). Hence, there is urgent need to move to cost-effective solutions that can be implemented at the kilometre-scale or above (Airoldi *et al.*, 2021). Such innovative solutions might be borrowed from industries, as they have already discovered economy of scale (Price and Toonen, 2017) and can provide technological advances leading to efficiencies of scale (Abelson *et al.*, 2020). Large scale and good connectivity of restoration sites is important for their sustainability, as it affects both biotic and abiotic interactions (Menz *et al.* 2013). For example, small and isolated restoration sites will have less genetic diversity, resulting in reduced resilience. Connectivity with remnant ecosystems, through proximity, stepping stones or corridors, allows for the exchange of species and genes, potentially resulting in enhanced biodiversity and resilience of the restored areas (Vaughn *et al.*, 2010). For restoration practices to become both ecologically successful and cost effective, interventions should be executed at a large enough scale and include remediation of degraded ecosystems if necessary (Abelson *et al.*, 2020).

Example upscaling assisted recruitment

Upscaling reef restoration is illustrated by the concept of using industry-based techniques for harvesting of coral larvae over vital reefs, and releasing these on degraded ones along the Great Barrier Reef (Figure 6-1). The concept entails large scale collection of coral spawn slicks with oil booms, pumping these slicks into storage tanks of commercial trailing suction hopper dredgers, culturing billions of larvae while being transported to degraded reefs, and once the larvae become settlement-competent, deploying them on these degraded reefs to initiate restoration (see Doropoulos *et al.*, 2018). This restoration method is estimated to be much more cost-effective than restoring the same vast geographical area with garden-grown corals (Doropoulos *et al.*, 2019). Also, the effect on the maintenance of natural populations is minimal, as it accesses an insignificant fraction of gametes released during a spawning event and refrains from any physical loss of the reef skeleton (Doropoulos *et al.*, 2018). In potential, it provides the means for increasing coral settlement and assisting gene flow between isolated populations to increase coral recruitment at unprecedented scale on strategically important reefs

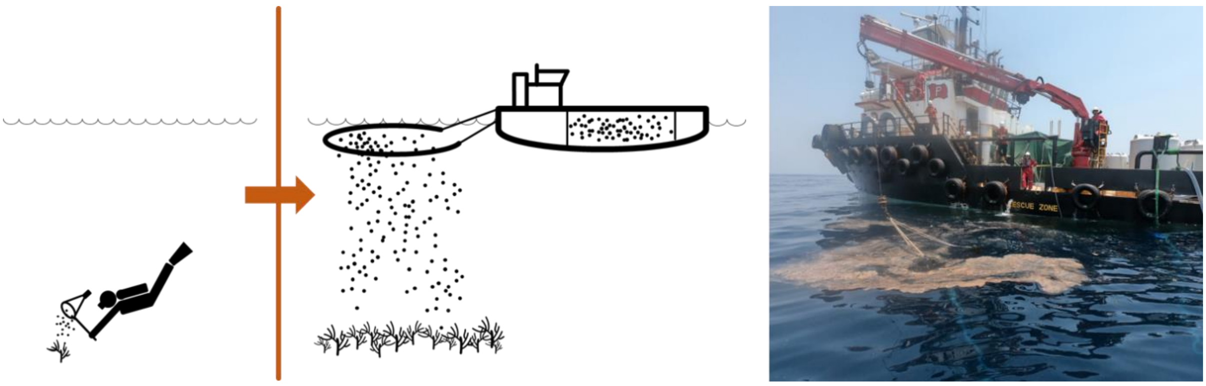

Figure 6-1: Principle I. Pursue upscaling: Changing from manually collecting coral gametes to harvesting using industry-based techniques to achieve positive impact at scale. Photo credit: Van Oord.

Principle II. Landscaping – optimizing marine infrastructure as habitat
Restoring reef ecosystems is often done through the installation of artificial reef structures, to provide hard substrate in varying three-dimensional shapes to promote biodiversity (Baine, 2001; Vivier *et al.*, 2021). These structures are tailor-made for a local system, targeting specific species groups, such as corals (Higgins *et al.*, 2022) or fish (Paxton *et al.*, 2020). Often concrete is used as their main construction material, allowing variation in both micro- and meso-habitat complexity (see Chapter 4). Downsides of using concrete include its toxicity, as the cement mortars often leach trace metals over time (Hillier *et al.*, 1999; Wilding and Sayer, 2002), and emissions of carbon dioxide during its fabrication process (Fennell *et al.*, 2021). Moreover, for artificial reef structures to achieve impact at scale, they need to be deployed in huge quantities, as biomass and species richness of the associated marine life is proportional to their extent (Bohnsack and Sutherland, 1985).

Besides restoring habitat by consciously adding artificial reef structures, it should also be considered to achieve the desired impacts by optimizing existing or novel marine infrastructure. This landscaping could serve similar restoration goals, be it at a much larger scale, even by using the same or only marginal additional materials. Marine construction works such as coastal breakwaters, quay walls in ports, and scour protection in offshore wind farms, already inherently provide artificial habitat. Their long-term presence allows nature development, and designs can be optimize to target desired species. For example, if concrete is used as construction material, its texture can be roughened to mimic natural rock which promotes colonization by pioneering species (Moschella *et al.*, 2005; Potet *et al.*, 2021), and its toxicity can be reduced by using nature-friendly adhesives (Perkol-Finkel and Sella, 2014). Improved reef habitat can be achieved at a far larger scale, more cost-efficient and with a lower carbon-footprint when optimizing the marine infrastructure than by just adding artificial reef structures.

It is recognized that a location for infrastructural development is typically selected for human needs, not for nature goals. Marine reef restoration is required at scales far beyond these locations. Therefore, optimizing marine infrastructure for reef development will never be able to fully replace targeted restoration, but it does provide a valuable extra opportunity to restore marine reefs at scale.

Example ecological enhanced marine infrastructure
Landscaping infrastructure to serve as habitat for marine species can be illustrated by designing nature inclusive scour protections at the base of wind turbines in offshore wind farms. These scour protections are layers of rock material, to prevent the seabed from scouring due to monopile induced turbulence and flow acceleration (Guan *et al.*, 2022). They generally resemble a flat pancake, composed of a filter base layer consisting of small-sized quarried rock, such as granite, topped with an armour layer of larger rocks (see Chapter 3). The rocky material acts as an artificial reef, hosting a broad range of marine species (Coolen *et al.*, 2018; see Chapter 3). Conventional scour protection can be adjusted to increase the habitat complexity by bringing in more variety in use of materials,

shapes and dimensions (Figure 6-2; see also Chapter 4), and is expected to result in a higher biodiversity (Lapointe and Bourget, 1999; Firth *et al.*, 2014). The use of calciferous rock such as limestone or marble will trigger increased settlement by shellfish (Hidu *et al.*, 1975; Soniat *et al.*, 1991). Irregular extensions in both vertical and horizontal directions, making heaps and berms, will increase surface area and provide leesides for shelter. Narrowing down the rock grading will result in more crevices, and variation in rock size at different locations will increase habitat diversity, serving a wide range of rock-dwelling species. If considered early in the design process such changes can easily be incorporated to ecologically enhance marine infrastructure, often at marginal additional cost.

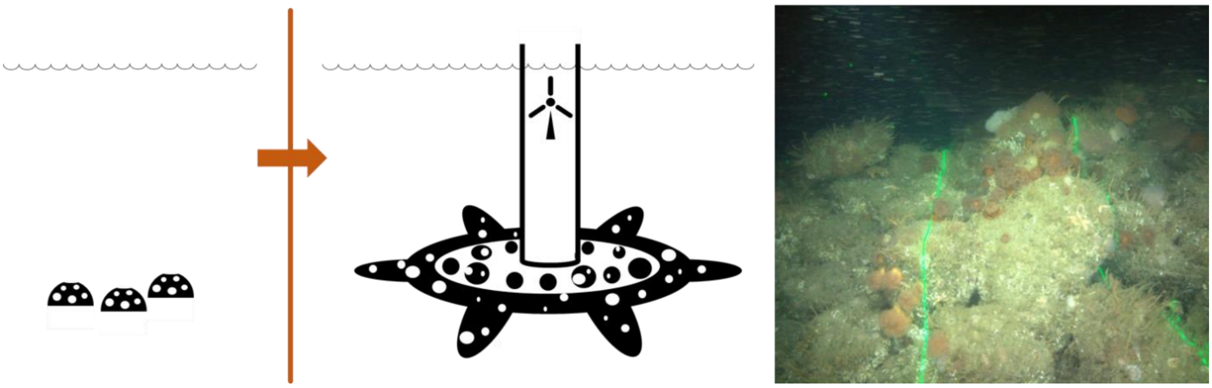

Figure 6-2: : Principle II. Landscape infrastructure: Changing from using artificial reef structures to nature-friendly designs of marine infrastructure to establish habitat complexity. Photo credit: Van Oord.

Principle III. Induce life – kickstart and steer community composition

Any new-built marine structure provides hard substrate habitat and is prone to be colonized by marine organisms (e.g. Komyakova *et al.*, 2022). The development of the benthic community at a new structure can be guided into a desired direction, not only by optimizing the habitat conditions, but also by pro-actively bringing in targeted species. This so-called priming is essential when there is no connectivity between the new structure and a natural system hosting the preferred species (see Chapter 4), and is advisable when one desires to influence competition in favour of targeted species (McCook *et al.*, 2001). Bringing in oyster or coral broodstock, for example, is a means to provide a local source of larvae to mitigate connectivity issues and increase the probability of settlement at the infrastructure. The installation of broodstock requires careful design and timing, taking into account species-specific life-history traits, to increase the likelihood of survival and long-term reproduction success.

Example using broodstock to kickstart and steer community composition

Introducing reef-building species can kickstart reef-development at remote locations that lack connectivity with natural reef systems. In the North Sea this is practiced via active introduction of flat oyster broodstock in offshore wind farms, with the aim to produce larvae that can settle locally and develop into thriving reefs (e.g. Didderen *et al.*, 2019; Schutter *et al.*, 2021; Figure 6-3). The broodstock is fixed on tailor-made structures that increase survival rates under governing local environmental conditions, such as providing stability, offering access to nutrients and oxygen, and avoiding burial by sedimentation. Two types of structures can be used: liftable ones installed with a crane (Van Rie, 2020), and droppable ones side-casted (Siderius, 2022), both having their pro's and con's. Liftable broodstock structures are large and stable, provide maximal security for the oysters, and can be replaced to other locations after the reef development has been kickstarted. However, installation of liftable broodstock structures is an expensive operation due to the required equipment. Droppable broodstock structures can also designed to be stable and robust during deployment and operation, but are smaller in size, allowing more cost-effective manual installation. However, being smaller in size, they may provide less security against sedimentation and predation, and they cannot be easily re-used at other locations. Despite the con's, the use of either broodstock structure is preferred over the distribution of lose mature oysters, as it protects the oysters from sedimentation and wash-out, resulting in a local high density of broodstock needed to ensure reproductive success.

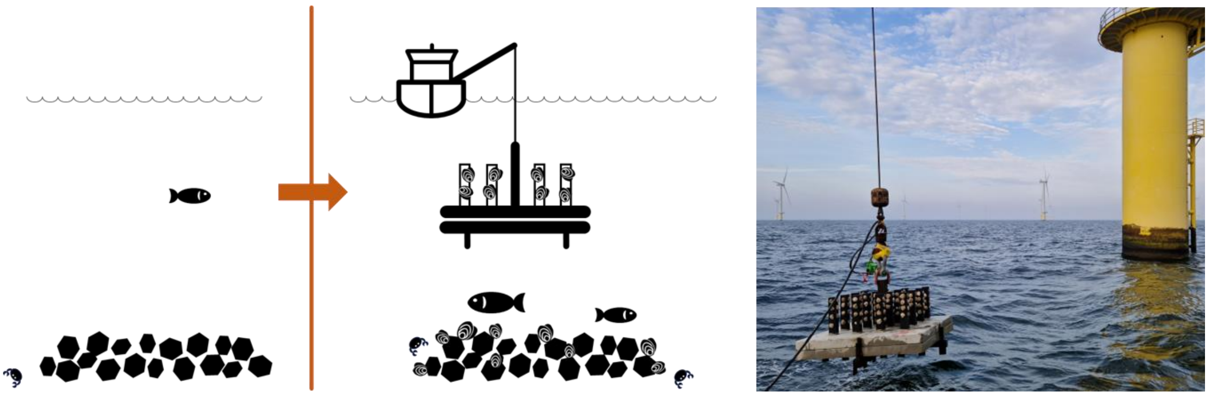

Figure 6-3: Principle III. Induce life: Changing from lack of recruitment to installation of broodstock to overcome connectivity bottle-necks and kickstart reef development. Photo credit: Van Oord.

Principle IV. Support self-sustainment – create the conditions

Natural recovery of an ecosystem is preferred over active restoration interventions (Abelson *et al.*, 2015). If interventions are needed to initiate the recovery, one would ideally achieve a self-regulating and self-sustaining ecosystem without the need for future human intervention to further steer restoration outcomes (Palmer and Steward, 2020). This aim for this so-called rewilding of a system (Perino *et al.*, 2019) has both economic and ecological benefits. If the targeted system becomes self-sustaining, costly interventions are no longer needed. Self-sustainment also indicates good health, the ecosystem being able to maintain its structure and function over time in the face of external stressors (Costanza and Mageau, 1999; Tett *et al.*, 2013). However, restoration efforts often remain far below reference conditions in terms of ecological metrics such as biodiversity, even after decades of maturing (Palmer and Steward, 2020). To become self-sustainable, the natural interactions between biota and abiotic physical features should be restored within the system (Suding *et al.*, 2015), and connectivity with remnant healthy ecosystems should be established (Mokany *et al.*, 2020). Only then are the restoration efforts likely to result in truly self-sustaining ecosystems in which human interventions are no longer required.

Example creating self-sustaining reefs

An example of an intervention to establish self-sustainment, is the concept of installing vertical bivalve reefs in the water column, from which living and dead bivalves will drop, to stimulate biogenic reef formation at a sandy seabed. That is, an agglomeration of shells at the seabed forms a complex matrix for settling juveniles and associated fauna, ensuring reef persistence over time (Mann and Powell, 2007; Schulte, 2009). This self-sustaining production concept has been designed for offshore wind farms in the North Sea, in which a vertical reef consisting of strings of blue mussels (*Mytilus edulis*) hanging in the water column produces a continuous supply of shell material to the seabed (Figure 6-4). It is based on structures used for commercial farming purposes, and comprises a longline anchored to the seabed, provided with vertical culture ropes at a depth suitable for mussel growth. Blue mussel larvae are abundant in the North Sea and known to attach rapidly to suitable substrates when offered (Coolen *et al.*, 2018; 2020). After installation of the structure, these larvae are expected to naturally settle on the culture ropes and grow into thriving mussel reefs with a rate of at least 5 cm shell length in the first 5 years (Bayne and Worrall, 1980). Once the mussels die or fall off, their shells are expected to sink and accumulate at the seabed, providing substrate suitable for reef development at the seafloor. By utilizing proven approaches from the mussel-aquaculture industry this design concept has a high likelihood of success at a large scale, and even a partial commercial setup seems conceivable.

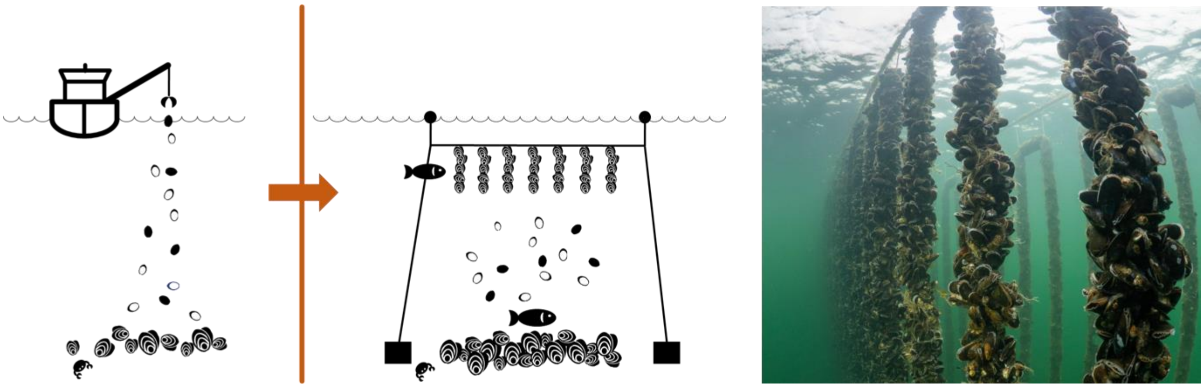

Figure 6-4: Principle IV. Support self-sustainment: Changing from ad hoc human interventions to continuous nature-steered supply of materials to create suitable conditions for reef restoration. Photo credit: Oscar Bos.

Principle V. Ensure continuity – active stakeholder involvement beyond initiation

Timescales for ecological restoration rarely match the timescales of both marine construction and active restoration projects. Large marine infrastructure projects generally last for a couple of years, from design to completion. Activities and resources, such as equipment and people on site, peak during the construction phase. Once the construction works come to an end, the activities on site will fade. The same will typically hold for imposing active restoration measures, for which activities are also concentrated in a limited time frame. However, reaching long-term overarching restoration objectives may require more time than foreseen for the initiated measures, and the need for continuation of activities is probable (see Figure 6-5). Also, restoration efforts should be monitored for a fair number of years (15-20), to allow for a solid evaluation whether recovery of the ecosystem and its associated functions and services has been reached (Bayraktarov *et al.*, 2016; Abelson *et al.*, 2020). Ensuring such continuation of restoration activities and their evaluation, requires the involvement of local partners who are willing to take responsibility beyond the initiation phase. Ideally partners that have an intrinsic interest in the success of the restoration efforts should be already involved during the design phase, thus way before starting marine construction or active restoration. Early involvement is important to ensure that partners take ownership of the activities, and to ensure that sufficient resources to continue monitoring and maintenance after the work have been put in place. Involving industry partners in ecological restoration practices will generate momentum and scale that would otherwise be inconceivable, while close involvement of local stakeholders will ensure the long-term continuation of the activities.

Example stakeholder involvement beyond project boundaries

Involving local parties to ensure long-term continuity of restoration efforts initiated as part of a marine construction project, took place at the island New Providence, Bahamas in the years 2015-2017. Along with port upgrade works, a so-called 'Coral Engine' was developed to promote local reef rehabilitation (ter

Hofstede *et al.*, 2019). Alignment with the construction works allowed the restoration works to make use of essential logistical capacity on site. The Coral Engine comprised an in-situ coral nursery that was filled with hundreds of fragments of opportunity obtained from the field, and tens of thousands of sexual recruits reared in a mobile breeding facility (Van Koningsveld *et al.*, 2017). Having these corals 'in stock' in the nursery, a continuous supply of genetically diverse corals for quick reef restoration is ensured, e.g. following hurricane disasters. Local NGO’s, government, and a recreational diving centre, were involved at an early stage for the long-term operation of the Coral Engine, using its benefits for tourism, research, education, and local employment. Following the project development until today, the Coral Engine is continued by the local stakeholders and demonstrates that initiating reef restoration activities coupled to an infrastructural development project can provide a long-term contribution to a local natural and socio-economic system well beyond the traditional time-scale of construction projects.

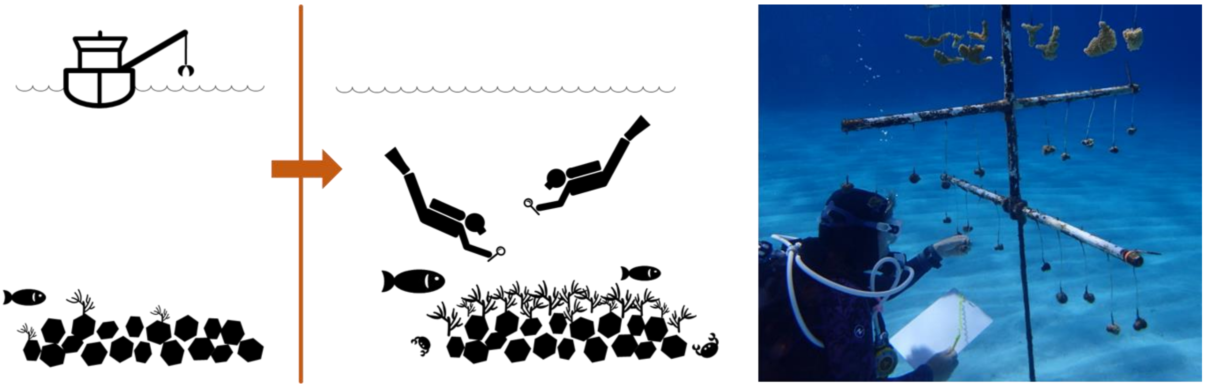

Figure 6-5: Principle V. Continue by stakeholder engagement: Changing from short-term restoration efforts during construction projects to long-term gains through stakeholder engagement beyond project boundaries. Photo credit Van Oord.

6.3 Discussion: Collaboration over conflict

The rapid decline of reef ecosystems requires a change of current restoration practices, and the development of novel approaches (Svejcar *et al*, 2022). Common key players to catalyse restoration actions are funding organizations, governmental bodies, scientists and citizens (Gann *et al.*, 2019; Danovaro *et al.*, 2021). The engagement of private companies, however, has recently been identified as critical in the implementation phase (Danovaro *et al.* 2021). Taking an interdisciplinary approach has been identified as a key feature in successful ecosystem restoration (Gann *et al.*, 2019; Saunders *et al.*, 2020). The five golden principles presented in this Chapter show how including the expertise of industry partners can promote effective marine reef restoration. It complements the science-based knowledge of the functioning of targeted species and their associated habitats, which is fundamental for restoration efforts to last long-term (Bayraktarov *et al.*, 2016; Fraschetti *et al.*, 2021). The synergy between science and industry requires a new way of thinking, acting and interacting (De Vriend and Van Koningsveld, 2012), as the incentives of both parties are fundamentally different. Exaggeratedly said, while 'classic restoration ecologists' aim for highest nature values within the margins of the foreseen ecosystem, 'conventional civil engineers' seek for solutions that minimise risks and costs. Also, negative past experiences have led to mutual mistrust, as green science has halted infrastructural development (Grorud-Colvert *et al.*, 2021) and grey industry irreversible harmed pristine seascapes (Bugnot *et al.*, 2021).

Both parties should set aside their differences and take a cooperative approach to find common ground in marine reef restoration. Win-win solutions should be embedded in the early phases of both restoration and infrastructural projects, to allow for upscaling restoration practices with maximum benefits against minimal costs, and to incorporate nature-benefitting features in the design of marine infrastructure (Pioch *et al.*, 2018). Over the past decades, our general perception about what is acceptable for the marine environment has normalized towards it being degraded and in an artificial state (Strain *et al.*, 2019). But we should refuse to adhere to this and join forces to turn the tide. If we now start by synergizing scientific insights and industry-based approaches, we can still reverse the degradation at the scale needed to regain healthy marine reef ecosystems for future generations.

7 General Reflection and Conclusions

7.1 Reflection

This dissertation comprises studies on the process to identify, select and implement design measures for marine infrastructure in order to enhance targeted components of the ecosystem. The components could be species, habitats or ecosystem processes, and enhancement refers to improvement in comparison to their condition prior to the infrastructural development. Conceptual approaches for nature-inclusive marine infrastructure have been developed, and applied on determining potential design measures to initiate flat oyster reefs in offshore wind farms in the Southern North Sea.
The studies come with certain assumptions and uncertainties, of which the main ones are described here. Future work should take these limitations into consideration, when applying the outcomes or when continuing the research.

In Chapter 2 a stepwise approach is presented, which can be used to **define** operational **objectives** for the design of nature-inclusive marine infrastructure aiming to achieve impact at system-scale. The final step of the approach entails to reach an achievable agreed ambition between the relevant stakeholders for implementation of the selected measures. When applying the stepwise approach to the case of the flat oyster reef development in Dutch offshore wind farms, the study assumed perspectives of the relevant stakeholder groups, instead of performing an actual stakeholder engagement process. Although these perspectives are highly probable, the outcomes of the case study should only be considered illustrative and not factual. The results fit an illustrative purpose within the scope of the study, but once the stepwise approach will be applied in practice, the relevant stakeholders should be engaged in reality to ensure the establishment of true stakeholder commitment to the agreed ambition.

In Chapter 3 a study is presented to **identify** the potential **effect** of conventional offshore wind farm infrastructure on epibenthic biodiversity. Conclusions are derived from video footage collected during an ROV monitoring survey executed at and around the scour protection in four Dutch offshore wind farms. The survey was uniquely dedicated to collect data on epibenthic species communities, which is an improvement compared to similar studies on offshore installations that had to use footage opportunistically obtained from technical inspection surveys (e.g. van der Stap, 2016; Schutter, 2019). However, the technique used in our survey merely collected video footage taken roughly at 0.5 m above the substrate, failing to provide information on small sized organisms (<1 cm) or epibenthic species living in the cavities of the scour protection. Also, all data was only collected during 1 week in September 2021, therefore information on seasonality or temporal changes is lacking. Furthermore, the selection of the four wind farms monitored was driven by permission to access the areas, not based on ecological motivations, for example to cover a wider spatial area.

In Chapter 4 a stepwise procedure is presented to guide the selection of measures and to determine their required scale for pro-actively facilitating flat oyster reef development in offshore wind farms in the Southern North Sea. When applying the procedure, the potential **effect** of interventions at different scales was **quantified**, using data available from previous research. However, as the data required to make the estimates is scarce, the estimates have a reasonable amount of uncertainty. Assumptions were made at all scales when estimating quantitatively the potential effect of measures for developing oyster reefs in offshore wind farms, and refinement is needed. Predicted effects of interventions such as proposed in Chapter 4 only become certain once being put into practice and properly monitored. Also, it should be taken into account that variation in impact is to be expected between locations where interventions are to be implemented, as the environmental subsea conditions differ throughout the Southern North Sea. Nevertheless, when using the procedure as presented in Chapter 4 in future exercises, calculations can be updated using the most recent, location-specific data, and it will provide insight into the available options and required magnitude of interventions to reach a desired impact.

In Chapter 5 research on a nature-inclusive measure for potential **application** as an **intervention** is presented, namely a study on what type of hard substrate as scour protection or as part of it would offer most favourable conditions for oyster larvae settlement. A broad range of materials was selected, based upon their application as scour protection, use in shellfish restoration activities, and use for commercial spat collection. The results indicate preference of oyster larvae for settlement upon stony substrate. It should be taken into account that this conclusion is based on investigating only a few types of stony substrate, while when implementing in practice, there are many types to choose from. Furthermore, in Chapters 4 and 6 it is suggested to use calciferous rock material such as marble and limestone to promote oyster larvae settlement. However, the experiment presented in Chapter 5 did not include such substrate, so the added benefit of using calciferous rock material for larvae settlement has not been confirmed. Furthermore, surface texture is nowadays known to be an important factor underlying settlement preference by flat oysters (Potet et al., 2021). It should be addressed that this factor was not included in the study presented in Chapter 5, although deliberate as the objective was to test the materials as 'available for use' to allow for easier scalable implementation in practice.

In Chapter 6, five golden principles are presented to link the academic and private sector in order to **achieve scale** in marine restoration efforts. Their purpose is to align specialist knowledge about ecosystem functioning with long-standing experience in executing projects at an industrial scale, complementing the expertise of both disciplines. Though adherence to these five principles should be considered essential for effective marine restoration at a large scale, the gap is currently wide between basically 'classical restoration ecologists' and 'conventional civil engineers'. A fundamental change in thinking and interacting is required to overcome mistrust and to establish collaboration. It should be acknowledged that such a change will be hard to achieve, possibly more difficult than presumed in Chapter 6. To bridge the gap, first recognition, commitment and investment are needed, and this will likely be an extensive and time-consuming process.

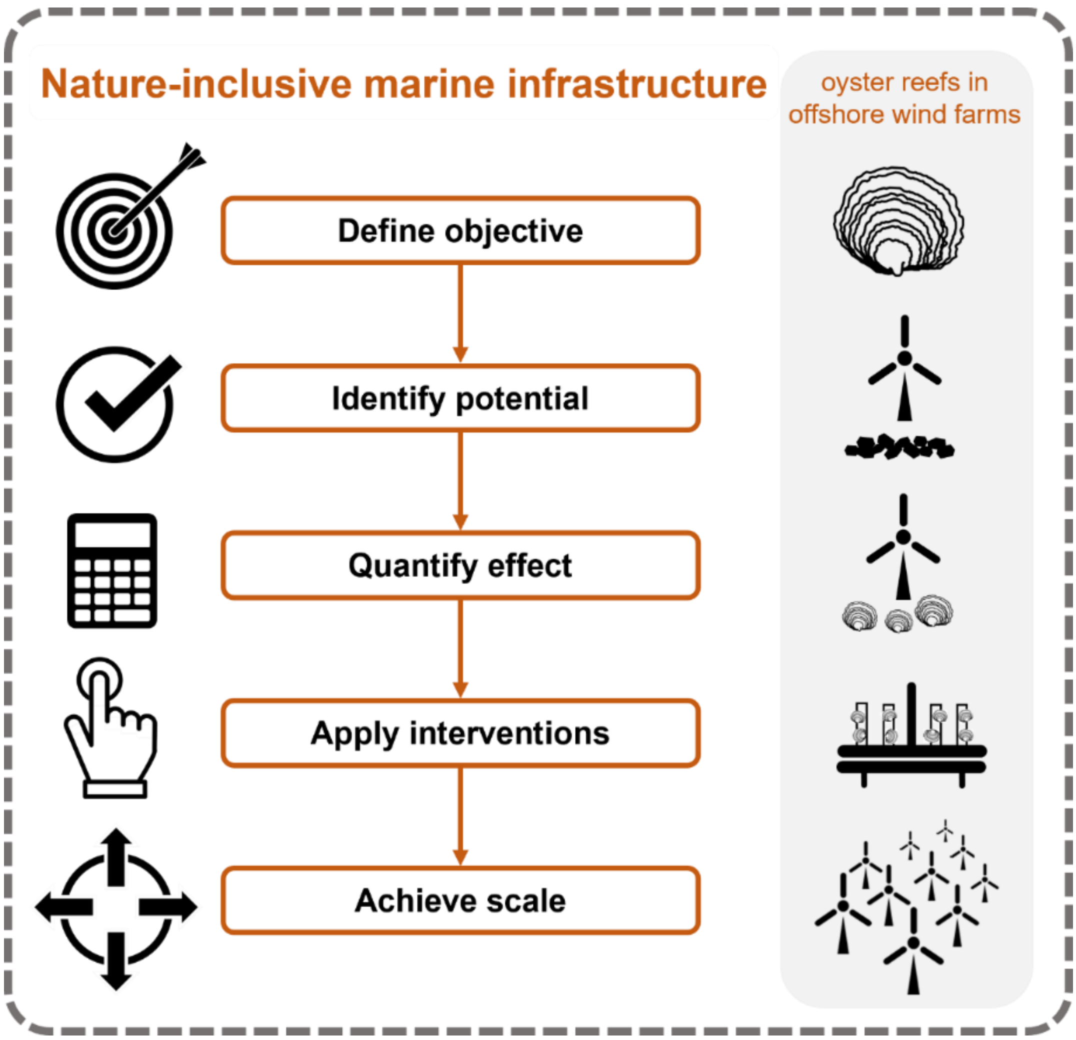

Figure 7-1: Process of consecutive steps to realise nature-inclusive marine infrastructure, illustrated when applied to oyster reef development in offshore wind farms.

7.2 Conclusions

Marine infrastructure modifies seascapes by replacing natural habitats and changing environmental conditions (Bishop *et al.*, 2017; Bugnot *et al.*, 2021). Their designs can incorporate ecological principles that benefit marine life (Dafforn *et al.*, 2015b; Laboyrie *et al*., 2018), but achieving impact at scale is challenging (Abelson *et al*., 2020; Duarte *et al*., 2020). Promoting ecosystem components, i.e. species, habitats or ecosystem processes, using infrastructural development can be achieved when following a process of executing consecutive steps as outlined in this dissertation (see Figure 7-1). The process is illustrated through application for European flat oyster reef development in offshore wind farms in the Southern North Sea. Herewith, this dissertation meets the main research question:
"How can marine infrastructure be designed to enhance ecosystem components effectively at a system-scale, with a focus on the European flat oyster (Ostrea edulis) in the Southern North Sea."

Enhancement refers to improvement in comparison to the condition of a targeted ecosystem component prior to the infrastructural development, and system-scale is the seascape dimension required to achieve the set objective for it effectively.

The conclusions of this dissertation provide guidance to develop nature-inclusive marine infrastructure, illustrated for promoting flat oyster reef development coinciding the growing offshore wind energy production in the Southern North Sea.

The process to design nature-inclusive marine infrastructure starts with **defining objectives** for the enhancement of targeted ecosystem components, in which ruling policies, environmental conditions and the potential offered by marine infrastructure are aligned. For doing this, one needs to know:
"How to define operational objectives for promoting ecosystem components using marine infrastructure?"
In Chapter 2, an approach is presented that supports defining operational objectives for nature-inclusive marine infrastructure. After finding a match between the ruling policies, environmental conditions and the foreseen infrastructural development, the approach includes a step in which stakeholders jointly select the most effective measures to reach shared targets towards impact at system-scale, meaning a seascape of the dimension required to achieve the desired impact. The involvement of relevant stakeholders is a key element of the approach to ensure that all required knowledge and expertise from various disciplines are covered, and to achieve commitment to the jointly established objectives. Finding mutual ground and reaching agreement on achievable ambitions between all relevant parties is essential to establish effect at a system-scale. Otherwise, there's a risk of an uncoordinated fragmentation of well-intended though ineffective measures to promote the targeted ecosystem component, failing to meet the desired impact.

The application of the approach is demonstrated for defining operational objectives to promote oyster reef development in offshore wind farms in the Dutch part of the North Sea. A coordinated basin-wide vision is required to reach connectivity between natural oyster beds and the to be developed reefs in the offshore wind farms. It is concluded that the policy, environment and infrastructure have a most suitable match for oyster reef development in future offshore wind farms in the area around the 54º latitude and between 4º and 6º longitude. Considering the interests of the main stakeholders, it is highly probable that an agreement on achievable ambitions to reach impact can be established. This would likely result in the operational objective to optimize settlement habitat in all future offshore wind farms in the designated area and to actively introduce oysters to establish an initial self-sustaining population.

Once the overarching objectives for promoting targeted ecosystem components have been defined, one should **identify the potential** of the foreseen infrastructural development to facilitate this. In Chapter 3 of this dissertation, this is studied by the research question: *"What is the potential of offshore wind farms to benefit targeted ecosystem components?"*
The construction of offshore windfarms in the North Sea includes the introduction of hard substrate by means of scour protection around the foundation of wind turbines. A monitoring survey in Dutch offshore wind farms was dedicated to investigate whether the conventional scour protection contributes to marine biodiversity, by comparing the epibenthic community present at the scour protection with the one living at the surrounding seabed. Epibenthic species abundance was found to be higher on the scour protection than on the surrounding seabed. Also specific species that are associated with a rocky habitat, were observed to dwell at the scour protection present in the furthermore mostly sandy seabed environment of the Southern North Sea. Assessment of the data collected during the dedicated monitoring survey revealed that presence of scour protection in offshore wind farms results in a higher abundance and diversity of epibenthic species, as these provide rocky habitat that would otherwise not be available in the area. Knowing this potential effect of the offshore wind farm infrastructure on the epibenthic community can support decision-making on including components to enhance the ecological value of existing and future offshore wind farms.
The implication for oyster reef development in offshore wind farms remained unconfirmed from this monitoring survey, as the actual presence of flat oysters at the scour protection had not been observed. However, the scour protection in its mere existence does offer stable hard substrate, which is known to be essential for oyster larvae to settle upon and successively grow into reefs. It is therefore assumed that the scour protection in offshore wind farms offers suitable habitat for oyster reef development. The current absence of oysters could be considered an incentive to take pro-active measures that initiate oyster reef development in offshore wind farms in the Southern North Sea. Interventions to introduce oysters in offshore wind farms and to facilitate reef development are addressed in Chapter 4, see the following section.

Integrating nature-inclusive design elements in marine infrastructure could contribute to their ecological value. In Chapter 4, a stepwise procedure is presented to **quantify the effect** of design interventions that can be taken to promote targeted ecosystem components. The Chapter addresses the research question: *"How to quantify the effect of interventions to enhance ecosystem components using offshore wind farms?".*

The stepwise procedure involves quantification of the effect of potential interventions at a range of scales, from micro-scale (materials used) to mega-scale (connectivity between systems). Knowing the potential effect of interventions is needed to determine the required order of magnitude for their application to make a significant impact. At a micro-scale, small adaptations in material use, texture, and shape can improve the conditions for settlement, growth and use by a variety of marine life, without affecting the functionality of the marine infrastructure. At a mega-scale, the spatial arrangement of how near or far marine infrastructure is located from each other determines their impact on the larger system, as it will affect the connectivity of marine organisms. For example, the deployment of scour protection in offshore wind farms in the Southern North Sea results in the creation of isolated rocky habitats, between which small-sized marine organisms such as larvae will be passively distributed by the hydrodynamics of the system, and larger species such as fish will actively migrate. The rapid expansion of offshore wind farms in the Southern North Sea may increase the movements of rock-dwelling species, as the rocky scour protection provides stepping stones for the marine organisms in a mostly sandy seabed environment.

The application of the stepwise procedure to quantify the effect of measures to enhance nature values at a range of scales is demonstrated for potential measures to promote oyster reef development in offshore wind farms in the Southern North Sea. The results indicate the most promising interventions and the required order of magnitude for implementation to achieve the desired impact. This includes identification of interventions that could be most suitable for oyster reef development but are little feasible in practice, like creating permanent reefs of shell material to maximize oyster densities (see Figure 7-2). It also reveals knowledge gaps, which may guide future research needed to promote flat oyster reef development. An important conclusion is that active introduction of oyster broodstock is likely required to initiate reef development in offshore wind farms in the Southern North Sea, due to the lack of their connectivity with natural oyster populations (see Figure 7-2). Another conclusion is that presence of hard substrate by means of scour protection and absence of seabed disturbing activities are main components to enable flat oyster reef development in offshore wind farms in the Southern North Sea. The presence of hard substrate provides settlement opportunities for the flat oyster larvae and successively may lead to reef development. The absence of bottom disturbing activities such as fisheries avoids destruction of the newly build reefs. A range of measures can be implemented in the offshore wind farms to promote oyster reef development, in particular in the design of the scour protection by modifying material, shape and dimension (see Figure 7-2). In Chapter 5, a study is presented on determining a substrate type that can promote oyster larvae settlement, but more studies on the effect of other measures are required to overcome current uncertainties to allow for the quantitative estimate of their potential effect.

Changing the design of marine infrastructure can be optimized to stimulate its use by targeted ecosystem components. One **intervention** that can be **applied** is using materials that provide suitable substrate for colonisation. The availability of hard substrate is often crucial for initial colonisation of the infrastructure by marine organisms, for example the settlement of larvae that start the development of thriving reefs. Different types of hard substrate can be found in marine infrastructure, ranging from natural materials such as rock to manufactured materials like steel and concrete. Chapter 5 presents a study that supports the selection a materials that could promote colonisation by marine life, in this case oyster larvae settlement, addressing the research question: *"What infrastructural design interventions can be applied to promote oyster reef development in offshore wind farms in the Southern North Sea?"* Offshore wind farm infrastructure generally offers hard substrate by means of quarried rock placed at the base of the wind turbine foundations and on top of cable crossings to prevent scouring of the seabed.

For oyster reef development, the availability of hard substrate is crucial for initial settlement of the larvae. The study presented in Chapter 5 investigated the settlement rates of oyster larvae on different types of hard substrates. The selection of studied materials was based on their potential application as scour protection itself in offshore windfarms, or as an add-on to the infrastructure. The results indicate that oyster larvae prefer to settle on stony substrates such as granite and concrete. Granite was concluded to be the most favourable substrate for use as scour protection, as it is already commonly applied as such, simplifying its further implementation. Note however that in Chapter 4 it was suggested to use a more calciferous rock material such as limestone or marble to increase settlement rates of oyster larvae. These materials, however, were not tested for settlement preference in the experiments presented in Chapter 5.

All efforts to establish nature-inclusive marine infrastructure should aim to be implemented at a scale large enough to make significant impact at system-scale. Chapter 6 addresses the research question to **achieve scale**: *"How to achieve positive ecological impact at system-scale using nature-inclusive marine infrastructure?"*.

Scalable restoration methods are required to improve the condition of targeted ecosystem components and achieve the desired impact at system-scale. Nature-inclusive marine infrastructure can provide the solution, but for its designs to be effective, it is required to pair scientific insights in restoration methods with the industry-based way of working for infrastructural development. In Chapter 6, five golden principles are presented to consciously connect science and industry, and to unify their complementing expertise. It is concluded that common ground should be sought and found between these key players to realise effective nature-inclusive design measures. As addressed in Chapter 2, achieving an agreed ambition between relevant stakeholders on objectives for nature-inclusive marine infrastructure is fundamental for its success.

The five golden principles to achieve nature enhancement at scale by linking science and industry, are illustrated with examples to advance reef restoration. Three principles are illustrated with examples specifically addressing oyster reefs development in offshore wind farms. These examples comprise the better use and optimization potential of the offshore wind farm infrastructure to serve as suitable habitat for oyster reefs (principle II), taking interventions that are aimed at establishing self-sustainment of the oyster reef development (principle IV), and the initiation of oyster reefs in wind farms by actively introducing broodstock (principle III).

The first, examples of a better use of the wind farm infrastructure, is also addressed in Chapter 4, mostly focussing on offering suitable habitat for reef development, by adding complexity through materials, shapes and dimensions (see Figure 7-2). For example, the use of calcareous rock such as limestone and marble, or better even adding shell material, will trigger increased larvae settlement, and extension of the scour protection will increase surface area for the oyster reefs to grow upon.

The second, an example of an intervention aimed to establish self-sustainment of oyster reef development, is the installation of vertical mussel reefs (see Figure 7-2). This concept, as introduced in Chapter 6, consists of a longline anchored to the seabed and holds strings of blue mussels (*Mytilus edulis*), forming a vertical reef in the water column. Over time, the mussels produce a continuous supply of shell material to the seabed, facilitating the suitability of the seafloor for larvae settlement (see also Chapter 4).

The third, actively introducing broodstock, is often required to ensure the local presence of larvae production, overcoming the lack of recruitment due to poor connectivity between offshore wind farms and natural reef systems. The introduction of broodstock is presented in Chapter 6 by use of tailor-made structures on which mature oysters are attached. These structures can be, installed with a crane (‘liftable’), or side-casted manually (‘droppable’) (see Figure 7-2), both having their advantages and disadvantages. Alternatively, adult oysters can be introduced ‘loose’, but this would have a higher risk for the oysters to be smothered by sediment or wash-out, requiring a higher initial amount of broodstock to ensure similar reproductive success. This makes ‘liftable’ or ‘droppable’ structures with oyster attached on it a preferred method for deploying broodstock compared to ‘loose’ oyster dump, as it reduces the demand for supply of adult oysters, limiting damage to existing populations (wild stocks) or excessive demands on commercial hatcheries (farmed stocks) (e.g. Helmer *et al.*, 2020). Also, the ‘liftable’ and ‘droppable’ structures ensure densely aggregated oyster broodstock at the designated locations, which will benefit recruitment success. That is, oyster recruitment is determined by broodstock density, as the fertilization success increases with density (Gercken and Schmidt, 2014), and oysters with a nearest neighbour ≤1.5 m were found to brood significantly more larvae than individuals with nearest neighbours ≥1.5 m (Guy *et al.*, 2018). Alternatively to installation of mature broodstock, local reef development can be initiated by deploying oyster spat, pre-settled on substrate offsite (see Figure 7-2). Rearing and settling of larvae under controlled conditions would avoid impact on wild or cultured oyster populations and offers even the opportunity to using larvae from a pre-selected source, e.g. those from a disease-tolerant population (Kamermans *et al.*, 2023). Support to select a material most suitable to use this spat-on-substrate is addressed in Chapter 5.

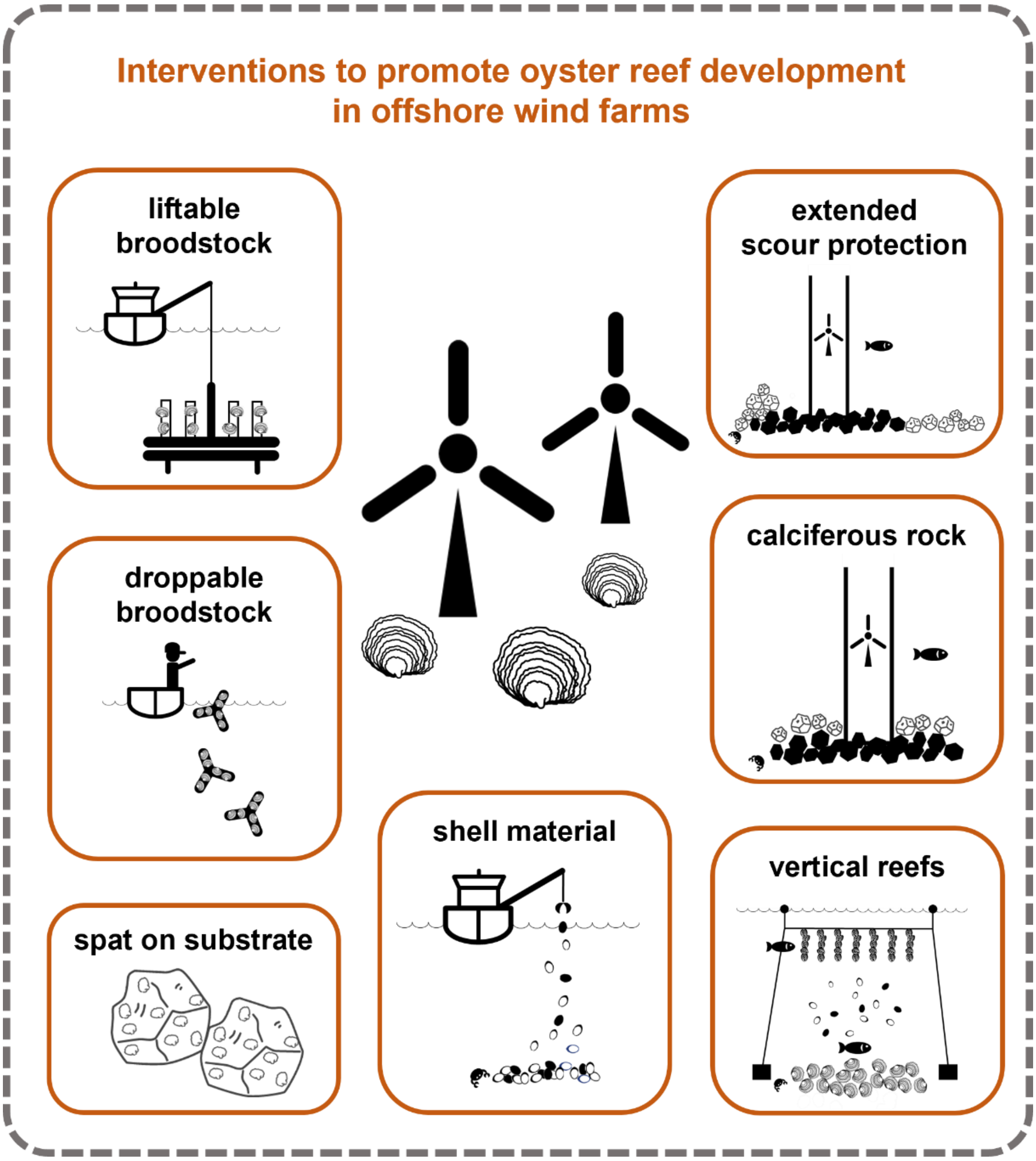

Figure 7-2: Examples of interventions to promote oyster reef development in offshore wind farms, as discussed in this dissertation.

To end, the establishment of nature-inclusive marine infrastructure is increasingly encouraged worldwide. However, many well-intended initiatives to promote targeted ecosystem components remain ineffective in meeting their desired impact, as they are not aligned under an overarching strategy for the wider seascape. The conclusions of this dissertation provide guidance to develop nature-inclusive marine infrastructure to achieve impact at system-scale. Tangible approaches are presented to identify, select and realize design measures for impactful nature-inclusive marine infrastructure. The process is illustrated by what is currently one of the most prominent examples of nature-inclusive marine infrastructure, namely promoting flat oyster reef development in offshore wind farms in the Southern North Sea. Application of the outcomes of this dissertation could lead to the realisation of truly effective nature-inclusive marine infrastructure, seizing the opportunity offered by infrastructural developments to have a positive impact on the marine environment.

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List of publications

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