De
Rijke
Noordzee

Options for biodiversity enhancement in offshore wind farms

Photo: Udo van Dongen

Knowledge base for the implementation of the Rich North Sea Programme

Bureau Waardenburg
Ecologie & Landschap

Options for biodiversity enhancement in offshore wind farms

Knowledge base for the implementation of the Rich North Sea Programme

Bureau Waardenburg

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Preface

A Rich North Sea - Where wind energy and biodiversity enhancement complement each other

A healthy North Sea, rich in marine biodiversity and full of life, which functions also as a source of sustainable energy, that is the dream. The concept is simple: offshore wind farms can act as sources of marine biodiversity.

The aim of the Rich North Sea programme is to enhance nature within offshore windfarms in the North Sea by developing and implementing biodiversity enhancement measures. In this study we will use “biodiversity enhancement” instead of “nature enhancement” as a most appropriate ecological term for the increase in species richness and ecosystem functioning.

At the end of the nineteenth century natural reefs, formed by flat oysters, occurred in a substantial part of the Dutch part of the North Sea, and provided natural hard substrates in a sea which was dominated by soft sediments. These reef areas provided a habitat for numerous sessile and mobile species, including soft coral, anemones, worms, crabs, lobsters and fish. However, intensive bottom trawling first targeting oysters and later a variety of fish species caused the disappearance of the natural reefs have reduced the biodiversity of our largest natural area. Interventions are necessary if we want to bring back the past variety of habitats and associated biodiversity.

In the coming years, many new wind farms will be built in the North Sea. As bottom-trawling is not allowed in these farms and scour protections provide hard substrate, these areas can function as a source of marine biodiversity. The natural development of areas rich in biodiversity is a lengthy process and may in some cases be unsuccessful. For example, to bring back vulnerable oyster reefs a ‘kick-start’ is needed: only if a suitable source of oysters is created, then the oysters will be able to settle on natural and artificial substrates and independently maintain living reefs with associated species. The idea is that this can be done in OWFs that contribute to the development of biodiversity in the North Sea. The aim of the Rich North Sea programme is to enhance biodiversity by restoring and enhancing biogenic reefs and improve nature-inclusive design of artificial hard substrates in offshore wind farms.

This report will provide a source of knowledge and inspiration for biodiversity enhancement measures that will be explored together with the offshore wind farm industry and NGOs.

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The following persons are thanked for their comments: Peter Herman, Jan Jaap Poos, Han Lindeboom, Tinka Murk, Hein Sas, Guido Schild, Christiaan van Sluis, Nathalie Strookman and Mark Collier.

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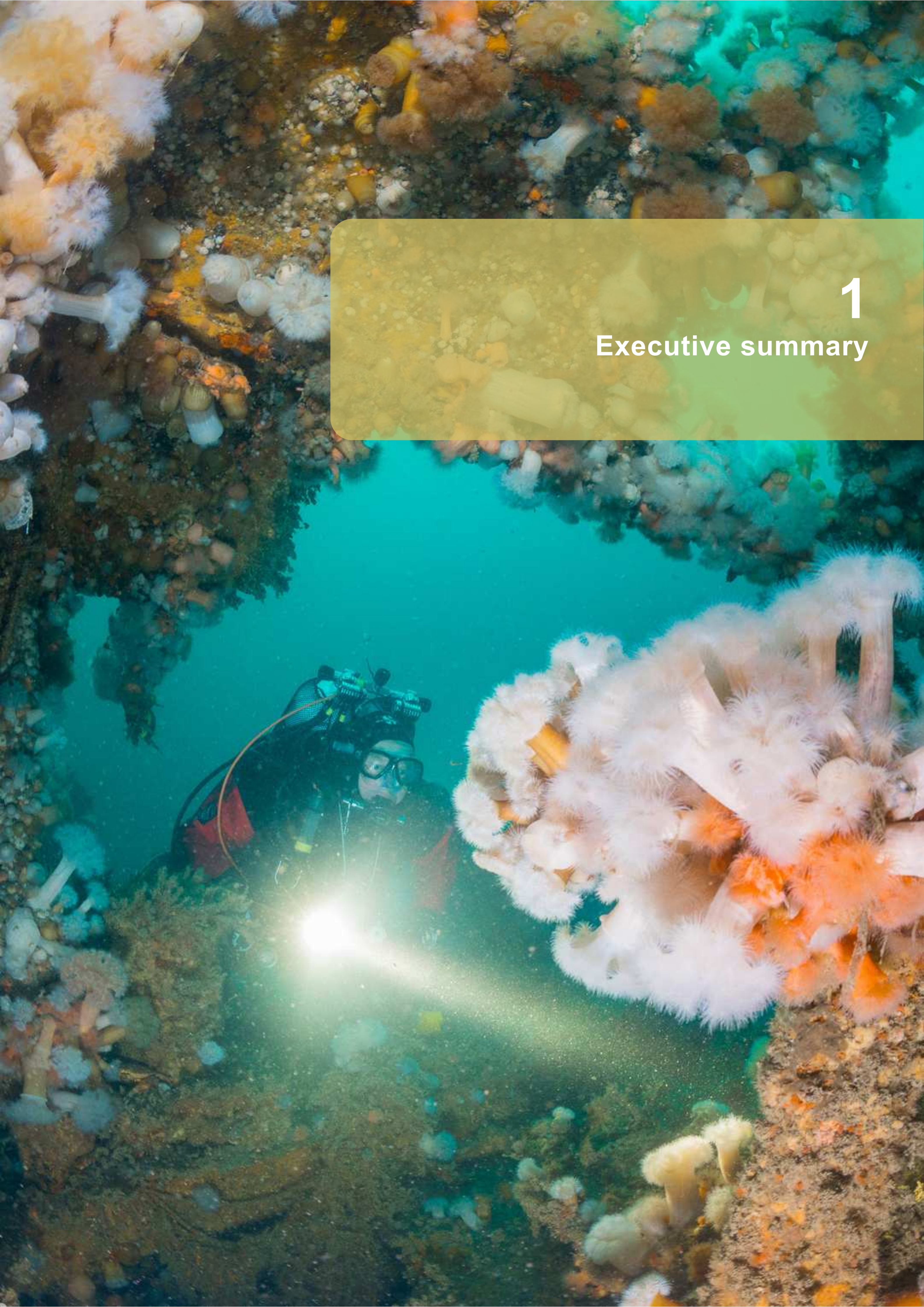

1

Executive summary

1 Executive summary

Aim

The main aim of the Rich North Sea Programme is to enhance nature within offshore wind farms (OWFs) in the North Sea by developing and implementing biodiversity enhancement measures. The programme focusses on enhancement of biogenic reefs and associated species, which provide critical ecosystem functions within OWFs and the wider North Sea.

The programme is looking for synergies in wind farm construction and biodiversity enhancement, resulting in best practices that can be implemented in future developments in OWFs. The ultimate goal is that offshore wind farms are a source of sustainable energy, but also contribute to marine biodiversity in a healthy North Sea.

Approach

The knowledge developed during the next years will be made available through an open-source website with the 'Toolbox for Biodiversity Enhancement in Wind Farms'. This Toolbox website contains best practices for wind farm developers to implement reef restoration, biodiversity enhancement and Nature Inclusive Design. The Toolbox includes a 'Learning by Doing' approach, that is, implementation, measuring success and evaluation.

Biodiversity enhancement options for native reef building species and species associated with and benefitting from natural and artificial reefs are implemented at five locations in Dutch offshore wind farms. These five projects will give insight in the success and cost-efficiency of measures and materials and at the same time highlight processes, like planning and legal requirements. The focal areas are the scour protection zones around wind turbine foundations and the soft sediment areas between the wind turbine foundations at the scale of the OWF. More technical and ecological information about Nature Inclusive Design of artificial structures within OWFs can be found in Hermans *et al.* (2019)[1], which is in part complementary to this report.

This programme is carried out in close cooperation with the wind- and offshore sector and scientific research partners. The future growth of wind farms in the North Sea provides an opportunity for nature development if these biodiversity-enhancing measures were to become the new standard in the construction and exploitation of offshore wind farms.

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[1] Hermans, A, Bos, O.G. & I. Prusina. 2019. Nature Inclusive Design: a catalogue for offshore infrastructure. Technical Report, Witteveen + Bos, Deventer.

Motivation

At the end of the nineteenth century natural oyster reefs occurred in a substantial part of the Dutch part of the North Sea and provided natural hard substrates in a predominantly soft sediment environment. These reef areas offered a habitat for numerous sessile species, including sponges, soft corals, anemones and worms, and mobile species such as crabs, lobsters and fish. However, intensive bottom trawling first targeting oysters and subsequently a variety of fish species, caused, in combination with oyster diseases, the disappearance of the natural reefs and reduced the biodiversity of the Dutch Continental Shelve (DCS) in both reef and soft sediment areas.

Offshore wind farms provide opportunities for the enhancement of North Sea biodiversity. The addition of hard substrates such as scour protection and the exclusion of bottom disturbance by bottom trawling, gives soft sediment habitats and hard substrate communities the opportunity to develop into more diverse communities. In addition, biodiversity enhancement measures, for example by deployment of empty shells at the scour protection around the wind turbines and on the soft sediments between the wind turbines, provides hard substrate that may promote the development of reefs formed by living organisms. The hard substrate itself and its associated community partly compensates the loss of natural hard substrates due to the loss of oyster reefs.

Biodiversity enhancement is defined as the process of assisting a general increase in the number of species or species richness. From this definition it follows that the common denominator of the enhancement options is that they all enhance biodiversity compared to the current impoverished state of the North Sea marine habitats.

Nr	Full name	Abbreviation
1	Buitengaats	Gemini
2	Zee-energie	Gemini
3	Offshore Wind farm Egmond aan Zee (OWEZ)	Egmond aan Zee
4	Prinses Amalia wind farm	Prinses Amalia
5	Wind farm Eneco Luchterduinen	Luchterduinen
6	Hollandse Kust (zuid) Wind Farm Zone	Hollandse Kust Zuid
7	Hollandse Kust (noord) Wind Farm Zone	Hollandse Kust Noord
8	IJmuiden Ver	IJmuiden Ver
9	Hollandse Kust (west 2) Wind Farm Zone	Hollandse Kust W2
10	Hollandse Kust (west 3 Wind Farm Zone	Hollandse Kust NW3
11	Hollandse Kust (west 4) Wind Farm Zone	Hollandse Kust ZW4
12	Borssele Wind Farm Zone I-II	Borssele I-II
12	Borssele Wind Farm Zone III-IV	Borssele III-IV
12	Borssele Wind Farm Zone V	Borssele V

Figure 1.1. The scope of this study explores the possibilities of biodiversity enhancement in actual and planned offshore wind farms at twelve locations roughly from north to south in the Dutch part of the North Sea.

Enhancement strategies

Three strategies for biodiversity enhancement can be distinguished, which operate at different scales and vary in the resulting biodiversity. We consider these as either obligatory (A) or optional (B & C; Figure 1.2):

A. **Detect and protect biodiversity already present (considered as obligatory).** Resilient reefs of short-lived species, such as sand mason worm, may already present and relatively easy to protect and rehabilitate. Expected biodiversity outcome: Moderate. Scale: Large.
B. **Introduce and restore natural reefs with reef building species (optional).** Vulnerable or extinct reefs of long-lived species (e.g. oysters) may be costly to develop or reintroduce. Expected biodiversity outcome: High. Scale: Intermediate.
C. **Construct artificial reefs (optional).** Hard-substrates at OWF result in rich communities of hard-substrate associated biodiversity. This can be optimized by adding artificial reef structures in between wind turbines or with nature-inclusive design of scour protection. Expected biodiversity outcome: High. Scale: Small.

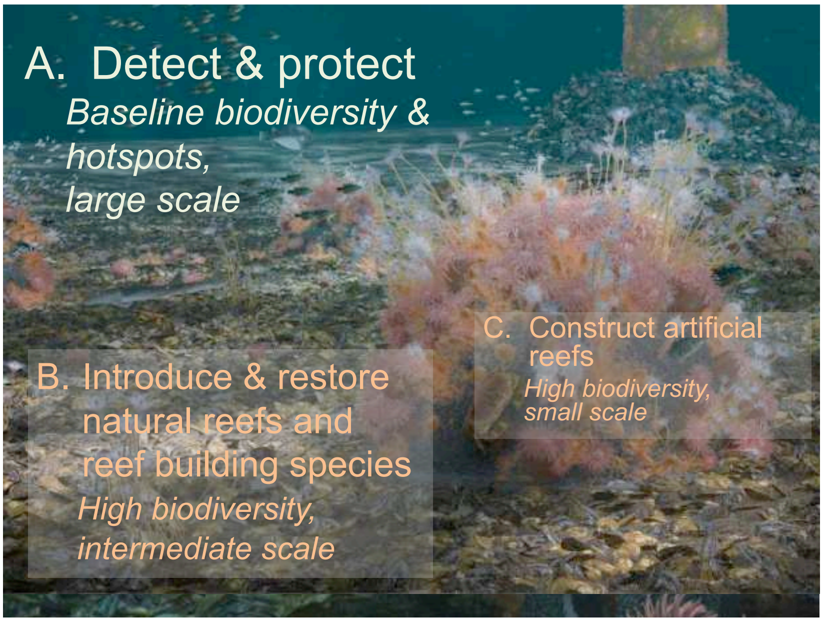

Figure 1.2. Three strategies for biodiversity enhancement in OWFs, which we consider as obligatory (white) or optional (orange) and operate at different scales.

Implementing these three strategies results in the following options of biodiversity enhancement measures for OWF (we consider the first two as obligatory, the others are optional):

1. *Base line*: Biodiversity survey of natural and artificial substrates present in OWF.
2. *Biodiversity hotspots*: Locate existing reefs / other biodiversity hotspots in OWF and develop conservation measures.
3. *Natural substrates deployment:* Add reef-stimulating natural substrates such as shells, gravel.
4. *(Re-)introduction and facilitation of reef building species:* For example, oysters or Ross worms (*Sabellaria spinulosa).*
5. *Artificial substrates deployment for artificial reefs on soft sediments*: Add artificial structures (various materials, biomimetic 3D-printing, nature-inspired design and materials), tests hydrodynamic performance, monitoring of biodiversity.
6. *Artificial substrates deployment for artificial reefs at scour protection:* Add artificial structures (various materials, biomimetic 3D-printing, nature-inspired design and materials), tests hydrodynamic performance, monitoring of biodiversity.

Biodiversity Enhancement Options

In Figure 1.3 the schematic representation is given of the selection process of biodiversity enhancement options in OWFs and the evaluation of their success.

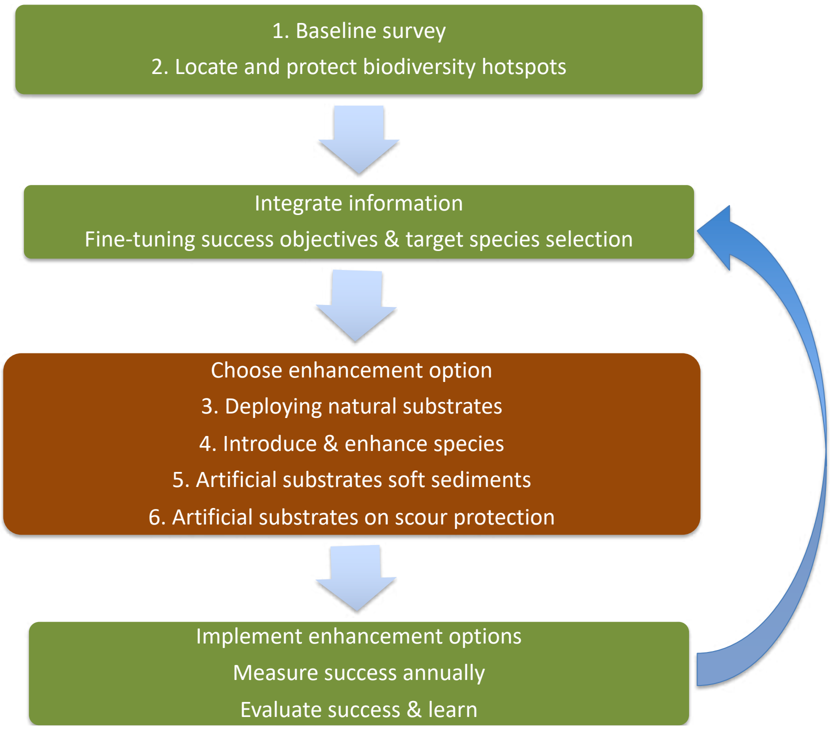

Figure 1.3. Selection process of Biodiversity enhancement Options in OWFs as part of a "learning by doing" approach, that is, implement and measure and evaluate success.

Biodiversity targets

Reef biodiversity is a broad term representing a large group of different organisms, with different habitat requirements and thus requesting different enhancement strategies. Three species groups can be distinguished in reef biodiversity:

Reef building species are the keystone habitat altering organisms. They can turn a soft (dynamic) seabed, colonised by endo-benthos, into a hard and stable environment colonised by both endo- and epi-benthic communities. Important reef building species in the North Sea are the flat oyster *Ostrea edulis*, the blue mussel *Mytilus edulis*, and various tubeworms (Ross worm and sand mason worm).

Reef associated species can only be present when there is a reef, because one or more life stages depend on it. Examples are anemone species that only grow on hard substrates, fish species that builds a nest in a reef, or shark and ray species that need a reef structure to attach their eggs to. This group represents a vast number of species, that give more structure, function and colour to a natural and artificial reef, ranging from hydroid polyp species to cold-water corals, crabs, lobsters and species of fish.

Reef benefitting species are species that can also live in the soft sediment habitats of the North Sea, but whose habitat is improved by adding reefs. Good examples of reef benefitting species are cod and sea bass, which are found on various sediments, but are known to congregate near reef structures and eat reef-associated prey when available. Furthermore, young cod are known to hide in crevices of reef structures.

Natural reef enhancement

Natural settlement of biogenic reef building species depends on the availability of larvae in the water column and the availability of suitable substrate in the period that larvae are ready to settle. For sand mason worms and blue mussels, the abundance of larvae is not limiting for the recruitment. Therefore, it is not necessary to introduce these species. Deployment of empty shells on soft sediment habitats will facilitate their settlement and formation of reefs. Large mussel populations are present along the tideline of most wind turbines at sea and sand mason worm is a very common species in the southern North Sea. Enhancement of these species is feasible by creating suitable conditions for settlement and survival. The flat oyster, however, is absent from large parts of the North Sea and has a very limited dispersal potential compared to the other species. Therefore, live oysters are introduced with suitable and clean settlement substrate. Biodiversity hotspots, such as shipwrecks, could function as source areas for epifaunal species with more limited dispersal capabilities.

Artificial reef deployment

Hard substrates provide a settling substrate for many plants and animals, attachment surface for eggs of various organisms and shelter for juvenile fish and mobile invertebrates. Eco-friendly design principles for scour protection in planned wind farms include (1) Adding larger structures (in comparison to conventional scour protection); (2) Adding more small-scale structures (than conventional scour protection); (3) Providing natural biogenic substrates (or bio-mimetic substrates). The target species of enhancement options which provide artificial substrates are primarily reef associated species and reef benefitting species. The first group requires hard substrate for settlement (e.g. sponges, cold water coral, anemones, hydroids, echinoderms) or for shelter and egg depositions (crabs, lobster, fish). The latter group includes mainly large, mobile species, which find food in or around artificial reefs, including Atlantic cod, pout, Atlantic wolffish, rock gunnel, sea bass. Reef building species may also settle on or among the scour protection or on artificial reefs (in particular bivalves such as blue mussel, flat oyster).

Offshore Wind Farm characteristics

The most important abiotic and biotic factors, which characterise the OWFs and are relevant for biodiversity enhancement are presented. The general characteristics, including abiotic and biotic conditions, ownership, size, number of turbines, artificial substrate type, are listed for each OWF. Additionally, the characteristics and environmental parameters, which are most relevant to the ecology of the focal species and enhancement options, are also presented.

The substrate type, shear stress and seabed motility determine to a large extent the scope for settlement and survival of recruits and the stability of natural and artificial hard substrates. Bottom shear stress, stratification regime and food abundance influence the dispersal of larvae and survival of all life stages. The soft sediment habitats vary from fine sand in areas with a rather stable seabed to coarse sand in areas with sand waves and mega-ripples. Morpho-dynamic modelling of seabed motility is important for the site selection of the pilot locations. The average concentration of Suspended Particulate Matter (SPM) is generally low and not detrimental for filter feeders in any OWF.

Temperature stratification, the absence of mixing between surface and bottom layers, only occurs in IJmuiden Ver, Borssele and Gemini. All other OWFs are permanently mixed and have lower salinities caused by freshwater outflow from the Rhine. In areas with stratification the food availability (phytoplankton abundance), as indicated by the chlorophyll-a content in spring and summer is lower due to the lower mixing and availability of nutrients (Gemini and IJmuiden Ver), but not in Borssele.

Biodiversity enhancement requirements

The requirements for the six biodiversity enhancement options are analysed and integrated with the OWF characteristics to evaluate the opportunities for biodiversity enhancement (Table 1.2).

*Table 1.2. The potential for Biodiversity Enhancement Options in Dutch OWFs in the North Sea is based on the OWF characteristics and biodiversity requirements and indicated by a number: 1=unsuitable, 2=moderately suitable, 3=favourable, 4=promising, 5=highly promising. We consider "enhancement options" 1-2 as obligatory, the measures under 3-6 are optional. All reef building species are combined in option 4, based on Bos et al. (2019) and Kamermans et al. (2018). An asterisk * indicates that hydro-dynamical testing is required for deployment at scour protection and suitability could be higher.*

	OWF	**Gemini (Buitengaats)**	**Gemini (Zee-energie)**	**Egmond aan Zee**	**Prinses Amalia**	**Luchterduinen**	**Hollandse kust - Z**	**Hollandse kust-N**	**IJmuiden Ver**	**Hollandse kust-W 2**	**Hollandse kust-W 3**	**Hollandse kust-W 4**	**Borssele**
Enhancement options	1. Baseline	5	5	5	5	5	5	5	5	5	5	5	5
	2. Biodiversity hotspots	4	4	4	4	4	4	4	4	4	4	4	4
	3. Natural substrates deployment	5	5	3	5	5	5	5	5	5	5	5	5
	4. (Re-)introduction of reef building species	5	5	4	4	4	5	4	4	4	4	4	5
	5. Artificial substrates deployment for artificial reefs on soft sediments	4	4		3	3	3	3	3	3	3	3	3
	6. Artificial substrates deployment for artificial reefs at scour protection	4*	4*	4*	4*	4*	4*	4*	4*	4*	4*	4*	4*

Measuring success

The aim of the Rich North Sea Program is to develop a Toolbox for biodiversity enhancement. Therefore, it is important to know if the implemented biodiversity enhancement options are successful in enhancing reef communities and biodiversity within and outside the studied offshore wind farms. Measuring success will reveal the conditions, potential and knowledge gaps of the different options. Which options are feasible at which location and which factors are relevant for the success? What is the efficiency of the enhancement options? And are these options also applicable outside OWFs?

This report presents specific success parameters to measure the efficiency of the biodiversity enhancement options. These parameters vary from the number species as a general representation of biodiversity to very specific parameters of population change and success of reef building species (e.g., growth, reproduction, survival, settlement, density). The success of the enhancement options can be measured by comparing the biodiversity before and after their implementation. Therefore, the first two obligatory steps, detect and protect the present biodiversity, are crucial in determining the reference situation (T_0). In addition to the monitoring design, an overview is given of cost-effective biodiversity monitoring methods together with crude cost estimates.

This report

Within the Rich North Sea Programme the focus will be on the enhancement of biodiversity within OWFs at the Dutch Continental Shelf (Figure 1.1). This report is intended as a first step in the programme and forms the basis of existing knowledge of reef and biodiversity enhancement in the North Sea. It provides a framework for selecting enhancement options for different OWF locations. It will be used in future activities within the programme, that will be explored together with the offshore wind farm industry and NGOs. It forms a basis for the design of five offshore projects within the Rich North Sea Programme.

2

Introduction

2 Introduction

2.1 The Rich North Sea Programme

2.1.1 Goal

The main aim of the Rich North Sea Programme is to enhance biodiversity within offshore wind farms (OWFs) in the North Sea by developing and implementing biodiversity enhancement measures. The programme focusses on enhancement of biogenic reefs and associated species, which provide critical ecosystem functions within OWFs and the wider North Sea.

The programme is looking for synergies in wind farm construction and biodiversity enhancement (Box 1), resulting in practices with the best of both worlds that can be implemented as the new standard in future developments in offshore wind farms. The ultimate dream for the future is that offshore wind farms are a source of sustainable energy, but also contribute to marine biodiversity in a healthy North Sea.

Box 1. Offshore wind energy and marine biodiversity

Reductions in CO_2 emissions are needed to combat global warming and we therefore need to switch to large-scale exploitation of sustainable energy. Offshore wind farms are our best option to make this switch. These wind farms impose both risks and opportunities for nature. The Rich North Sea Programme focuses on seizing the opportunities. However, its initiators – The North Sea Foundation and Stichting Natuur & Milieu – also work on reducing the risks. The Rich North Sea Programme focuses on biodiversity enhancement within OWFs and aims to contribute indirectly to ecosystem restoration in the wider North Sea.

https://www.noordzee.nl/beschermde-gebieden/

https://www.noordzee.nl/natuurvriendelijkeenergie/

https://www.natuurenmilieu.nl/themas/energie/projecten-energie/zeekracht-3/factsheets-wind-op-zee/

2.1.2 Approach

The knowledge developed during the next years will be made available through reports and an open-source website with the 'Toolbox for Biodiversity Enhancement in Wind Farms' (cf. Dafforn *et al.*, 2015). This Toolbox website contains tools for wind farm developers to easily and effectively implement natural reef development and Nature Inclusive Design, which is obligatory in newly built offshore wind farms (Wind Energy Act, 2017). The approach is based on 'Learning by Doing'. The Rich North Sea programme implements biodiversity enhancement options at five locations in Dutch offshore wind farms for native reef building species (shellfish and tubeworms) and species associated with and benefitting from natural and artificial reefs. Reefs formed by stones or living organisms serve both as a settlement base, shelter and a source of food for marine biodiversity (e.g., Naylor *et al.*, 2012). These five projects will give insight in the success and cost-efficiency of measures and materials and at the same time highlight the process, like planning and legal requirements. The success of biodiversity enhancement will be measured with biodiversity monitoring before and after the deployment of materials and species.

The focal areas of this report within OWFs are the scour protection zones around wind turbine foundations and the soft sediments areas between the wind turbine foundations at the scale of the OWF. More technical and ecological information about Nature Inclusive Design of artificial structures within OWFs can be found in Hermans *et al.* (2019) and which is in part complementary to this report.

In case natural reef development is somehow limited, natural substrates may facilitate and enhance the development of marine biodiversity. In addition, the ecological function of the artificial hard substrate around wind turbines (scour protection) will be increased by nature-inclusive design (similar to ecological enhancement of coastal infrastructure, Chapman & Blockely, 2009; Dafforn *et al.*, 2015; Loke *et al.*, 2017). Such artificial reef structures are designed and tested in laboratory conditions, consist of hard materials on which various species can attach themselves. By introducing reef building species and creating optimal circumstances for their development, such organisms can form living reefs that sustain themselves and the associated biodiversity.

This programme is carried out in close cooperation with the wind- and offshore sector and scientific research partners. The future growth of wind farms in the North Sea forms a potential for nature development if these biodiversity-enhancing measures will become the new standard in the construction and exploitation of offshore wind farms.

2.1.3 Motivation

At the end of the nineteenth century natural oyster reefs occurred in a substantial part of the Dutch part of the North Sea and provided natural hard substrates in a sea which was (and still is) dominated by soft sediments (Christianen *et al.*, 2017; Smaal *et al.*, 2015). These reef areas can be considered as a *reference ecosystem* (see Box 2 for a list of definitions for the terms below in italics) and provided a habitat for numerous sessile species, including sponges, soft corals, anemones and worms, and mobile species such as crabs, lobsters and fish. However, intensive bottom trawling, first targeting oysters and later a variety of fish species, caused the disappearance of the natural reefs and reduced the biodiversity of hard and soft sediment habitats in the Dutch Continental Shelve (DCS). Areas with stones and gravel, also known as geogenic reefs as opposed to biogenic reefs formed by living organisms, are relatively rare in the DCS, but also negatively impacted by bottom trawling (e.g., Cleaver Bank, Borkum Reef Ground).

Offshore wind farms provide opportunities to enhance the North Seas biodiversity, not only for the disappeared oyster reefs and the hard substrate they provided for the associated biodiversity, but also for the impoverished soft sediment habitats and degraded geogenic reefs formed by gravel and stones. Bottom disturbance, including bottom trawling, is not allowed in OWFs. This provides an opportunity for recovery of soft sediment habitats. Shells deployed at the scour protection around the wind turbines and on the soft sediments between the wind turbines provides hard substrate, which compensates the loss of natural hard substrates due to the loss of oyster reefs. Flat oysters themselves have a complex life cycle and a limited dispersal capacity and, therefore, introductions or *translocations* (Box 1) are necessary if we want to bring back sources for the development of natural oyster reefs, their *structural diversity* (Box 2) and their associated biodiversity.

Biodiversity enhancement is defined as the process of assisting a general increase in the number of species or species richness (adapted from Chapman & Blockley, 2009; Loke *et al.*, 2017). From this definition it follows that the common denominator of the above-mentioned activities is that they all enhance biodiversity compared to the current impoverished state of the North Sea marine habitats. In areas with historic occurrences and/or a *reference ecosystem* this could be indicated as *ecological restoration* (Box 2). If such a reference is lacking the result of biodiversity enhancement could be indicated as a *designer ecosystem*.

In addition, these biodiversity enhancement options will strengthen the *ecosystem functions* of the new or recovered habitats (e.g., Chapman & Blockley, 2009; Naylor *et al.*, 2012) and the *ecosystem services* (Box 2), as well. Enhancement of biodiversity and ecosystem functions and ecosystem services are an important motivation for ecological restoration (Hagger *et al.*, 2017, Naylor *et al.*, 2012).

Box 2: List of definitions (adapted from McDonald *et al.* (2016)

Baseline inventory – a description of current biotic and abiotic elements of site prior to enhancement or restoration, including its structural, functional and compositional attributes and current condition. The inventory is implemented at the commencement of the enhancement or restoration planning stage, to inform planning including enhancement or restoration goals, measurable objectives and treatment prescriptions.

Designer ecosystem – an ecosystem that is primarily created to achieve mitigation, conservation of a threatened species, or other management purpose rather than achieve the re-establishment of a reference ecosystem.

Ecological restoration (syn. ecosystem restoration) – the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed.

Ecosystem services – the direct and indirect contributions of ecosystems to human well-being. They include the production of clean soil, water and air, the moderation of climate and disease, nutrient cycling and pollination, the provisioning of a range of goods useful to humans and potential for the satisfaction of aesthetic, recreation and other human values.

Functions, of an ecosystem – the workings of an ecosystem arising from interactions and relationships between biota and abiotic elements. This includes ecosystem processes such as primary production, decomposition, nutrient cycling and transpiration and emergent properties such as competition and resilience. Functions represent the potential that ecosystems will be able to deliver ecosystem goods and services to humans.

Reference ecosystem – a community of organisms and abiotic components able to act as a model or benchmark for restoration. A reference ecosystem usually represents a non-degraded version of the ecosystem complete with its flora, fauna, abiotic elements, functions, processes and successional states that would have existed on the restoration site had degradation, damage or destruction not occurred – but should be adjusted to accommodate changed or predicted environmental conditions. An alternative term for reference ecosystem is ‘ecological reference’.

Structural diversity – Ecosystem structure refers to the physical organisation of an ecological system including density, stratification, and distribution of species (their populations, habitat size and complexity), canopy structure and pattern of habitat patches, as well as abiotic elements.

Translocation – the intentional transporting (by humans) of organisms to a different part of a given landscape or aquatic environment or to more distant areas. The purpose is generally to conserve an endangered species, subspecies or population.

2.2 Reefs: State of the art

Reefs are defined as rocky and biogenic concretions that support a zonation of benthic communities of algae and animal species littoral and sublittoral (EU, 2013). In temperate waters biogenic reef-forming species commonly include worms (polychaetes) and mussels and oysters (bivalves) (Ayata *et al.*, 2009). Subtidal reefs have important ecological functions and related ecosystem services such as nursery and feeding grounds for various fishes, crabs and lobsters and as settling substrate for sessile animals, in an otherwise mostly sandy environment (Coen *et al.*, 2007; Grabowski *et al.* 2012; McCoy *et al.*, 2017; Wahl, 2009) with. In open sea reefs in the Netherlands, like the Cleaver bank and Borkum reef, fauna associated with these reefs is categorised as of importance for biodiversity conservation (Lindeboom *et al.*, 2005; Bos *et al.*, 2014; Coolen *et al.*, 2015).

Shellfish reefs, consisting mainly of flat oysters (*Ostrea edulis*), once occurred in substantial areas of the Dutch part of the North Sea, which extended in the north to Germany (e.g. Olsen 1883) and in the south to the gravel areas of the Hinder Banks (Houziaux *et al.*, 2008, 2011). These reefs were absent in the dynamical, sandy areas in between (Smaal *et al.*, 2015). A study of the Belgian-Dutch part of the North Sea (including the Hinder Banks) in the early 19th century by Gilson (Houziaux *et al.* 2008, 2011) showed that such a natural hard substrate reef formed by live oysters and dead shells contained extensive and diverse reef communities. Furthermore, this reef of filter feeders would have had a major impact on sediment stability, visibility, water quality and carbon fluxes. The North Sea ecosystem would have differed substantially from that of today, being vastly more productive for hard substrate associated animals, however detailed knowledge on this reef ecosystem is not existent, with knowledge disappearing with the last shellfish reefs.

Globally, temperate biogenic reefs are at risk with 85% of all oyster reefs having been lost, making them one of the most degraded marine ecosystems on the planet (Beck *et al.*, 2011). Due to overfishing, habitat destruction and diseases, the North Sea epibenthic shellfish reefs have almost entirely disappeared, as is the case elsewhere in the world (Beck *et al.*, 2011; Smaal *et al.*, 2015). For a good hundred years, recovery was not to be expected, due to the absence of undisturbed areas. Epibenthic shellfish reefs take decades to develop, and human exploitation can destroy a shellfish reef entirely in a time period of years.

The time for restoration of biogenic reefs is right. Dutch and EU government policy now support reef protection for over a decade (92/43/EEC; European Commission, 1992, 2008/56/EC; European Commission, 2008). In addition, due to the designation of marine protected areas and the construction of offshore wind farms, areas with undisturbed seafloor are increasing. As a consequence, biogenic reef development and restoration is getting the attention of scientist and practitioners throughout the world. For example, European scientists have been focussing on the endangered status of *O. edulis* habitats and there is scope for restoration (Airoldi and Beck, 2007; Gercken and Schmidt, 2014; Sawusdee *et al.*, 2015; Smaal *et al.*, 2015; Smyth *et al.*, 2018). Moreover, *O. edulis* beds are now identified as a priority marine habitat for protection in the OSPAR region (OSPAR agreement 2008-6, OSPAR Commission, 2011). The discovery of a natural flat oyster bed in the North Sea (Christianen *et al.*, 2018) confirms feasibility of development and recovery of North Sea reefs.

The natural recovery of biogenic reefs is predicted to take tens to hundreds of years (Moore, 2009; Cook *et al.*, 2013). Therefore, active habitat restoration – or rehabilitation - is now investigated and developed throughout the globe. The aim is not to restore a pre-human reference point, but to develop techniques that will aid the development or recovery of these reefs after physical disturbance, thereby restoring the high levels of biodiversity they support. Since the field of work is only recently developing in the offshore, examples of published replicated studies with unambiguous effects are rare. For the most part general ecological theory, a few lab tests and lessons learned in pilots form the basis of the state of the art for each species and enhancement option. Therefore, testing biodiversity enhancement options provides an opportunity for a better understanding of nature via a powerful tool: large-scale field manipulations of habitats or populations. If implemented with a priori hypotheses and replicated designs this will yield useful feedback to inform future enhancement strategies.

Worldwide a few practical guidelines and handbooks for biogenic reef restoration and subsea biodiversity enhancement are available, including a handbook on Virginica oyster restoration (Eastern USA, intertidal species, Baggett *et al.*, 2014), Olympia oyster restoration (Western USA, intertidal and subtidal species, Wasson *et al.*, 2015), a managers and a practitioners guides to oyster habitat restoration (zu Ermgassen *et al.*, 2017; Brumbaugh *et al.*, 2006), and biodiversity enhancement options for scour protection in offshore wind farms (Lengkeek *et al.*, 2017).

2.3 This report

Within the Rich North Sea Programme the focus will be on the enhancement of biodiversity within OWFs at the Dutch Continental Shelf (Figure 2.1). This report is intended as a first step in the programme and forms the basis of existing knowledge of reef and biodiversity enhancement in the North Sea. It provides a framework for selecting enhancement options for different OWF locations. It will be used in future activities within the programme that will be explored together with the offshore wind farm industry and NGOs. It forms a basis for the design of five offshore projects within the Rich North Sea Programme. The document provides information on strategies and measures how to enhance biodiversity (Chapter 3) and where (Chapter 4) and how to learn by measuring success (Chapter 5). These texts are extensively referenced (Chapter 6) and the annexes provide additional background information.

Nr	Full name	Abbreviation
1	Buitengaats	Gemini
2	Zee-energie	Gemini
3	Offshore Wind farm Egmond aan Zee (OWEZ)	Egmond aan Zee
4	Prinses Amalia wind farm	Prinses Amalia
5	Wind farm Eneco Luchterduinen	Luchterduinen
6	Hollandse Kust (zuid) Wind Farm Zone	Hollandse Kust Zuid
7	Hollandse Kust (noord) Wind Farm Zone	Hollandse Kust Noord
8	IJmuiden Ver	IJmuiden Ver
9	Hollandse Kust (west 2) Wind Farm Zone	Hollandse Kust W2
10	Hollandse Kust (west 3 Wind Farm Zone	Hollandse Kust NW3
11	Hollandse Kust (west 4) Wind Farm Zone	Hollandse Kust ZW4
12	Borssele Wind Farm Zone I-II	Borssele I-II
12	Borssele Wind Farm Zone III-IV	Borssele III-IV
12	Borssele Wind Farm Zone V	Borssele V

Figure 2.1. *The scope of this study explores the possibilities of biodiversity enhancement in actual (dark green) and planned (light green) offshore wind farms at twelve locations roughly from north to south in the Dutch part of the North Sea (Source: rvo.nl).*

3

Enhancement of North Sea underwater nature

3 Enhancement of North Sea underwater nature

The focus of the Rich North Sea Programme is on the enhancement of biodiversity within offshore wind farms (OWFs) in the North Sea. The development of guidelines for biodiversity enhancement aims to facilitate the implementation of biodiversity enhancement measures. In this chapter the strategies for the Biodiversity enhancement will be explored (section 3.1), the enhancement options (section 3.2) and biodiversity target species (section 3.3) are detailed. In the final sections practical information is given about sources of reef building species (section 3.4) and materials for artificial reefs (section 3.5).

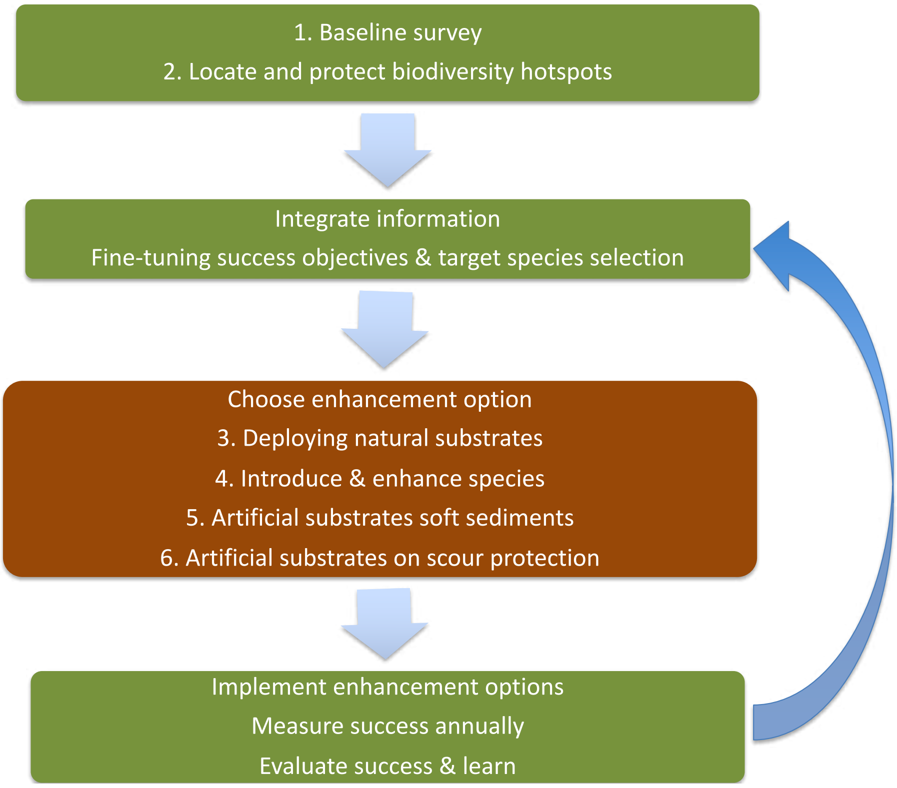

Figure 3.1. Schematic representation of the selection process of biodiversity enhancement options in OWFs as part of an overall "learning by doing" approach (See also Hermans et al., 2019, for the selection process of Nature Inclusive Design of artificial substrates).

3.1 Enhancement strategies

Biodiversity enhancement options broadly fall into three strategies (Figure 1.2). The type of biodiversity most fitting to the focal OWF and on the desired scale and ambition defines what strategy is followed. The strategies vary from less costly actions on a large scale with expected moderate increase in biodiversity, to moderately costly actions on an intermediate scale to costly, artificial hard-substrate additions on a small scale. When applicable in a specific OWF, maximum biodiversity outcome can to be obtained when all three strategies are implemented.

Three strategies for biodiversity enhancement:

A. **Detect and protect biodiversity already present (considered as obligatory).** Resilient reefs of short-lived species, such as Sand mason worm *(Lanice conchilega)*, may already present and relatively easy to protect and rehabilitate. Expected biodiversity outcome: Moderate. Feasible scale: Large.
B. **Introduce and restore natural reefs with reef building species (optional).** Vulnerable or extinct reefs of long-lived species (e.g. oysters) may be costly to develop or reintroduce. Expected biodiversity outcome: High. Feasible scale: Intermediate.
C. **Construct artificial reefs (optional).** Hard-substrates at OWF result in rich communities of hard-substrate associated biodiversity. This can be optimized by adding artificial reef structures in between wind turbines or with nature-inclusive design of scour protection. Expected biodiversity outcome: High. Feasible scale: Small.

Implementing these three strategies, results in the following options of biodiversity enhancement measures for OWFs of which we consider 1-2 as obligatory and 3-6 optional:

1. *Base line*: Biodiversity survey of natural and artificial substrates present in OWF. We consider this as obligatory, and therefore not a real option, but for completeness included in the list of options.
2. *Biodiversity hotspots*: Locate existing reefs / other biodiversity hotspots in OWF and develop conservation measures.
3. *Natural substrates deployment:* Add reef-stimulating natural substrates such as shells, gravel.
4. *(Re-)introduction of reef building species:* For example, oysters or Ross worms (*Sabellaria spinulosa).*
5. *Artificial substrates deployment for artificial reefs on soft sediments*: Add artificial structures (various materials, biomimetic 3D-printing, nature-inspired design and materials), tests hydrodynamic performance, monitoring of biodiversity.
6. *Artificial substrates deployment for artificial reefs at scour protection:* Add artificial structures (various materials, biomimetic 3D-printing, nature-inspired design and materials), tests hydrodynamic performance, monitoring of biodiversity.

In Figure 3.1 the schematic representation is given of the selection process of biodiversity enhancement options in OWFs and the evaluation of their success. In the next paragraph options 1 to 6 are elaborated in more detail.

All the enhancement options will be carried out to identify, create or enhance biogenic reefs and associated biodiversity. It is of major importance to determine the specific goal per OWF: which species do we expect and in how many years do we want to reach the goal? Setting an objective must be the starting point, and from here decisions can be made which specific enhancement options will be suitable or not for the focal OWF.

Not all enhancement options will be suitable in every wind farm, just as not all species introductions would be promising.

The choice as to which enhancement option should be carried out is largely dependent on the goals, objectives and ambition that are determined for the project. Relevant questions in this context are (in random order):

- Which reefs and associated species are suited for biodiversity enhancement?
- Is the project small or large scale?
- In how many years should the goals be reached?
- Enhancement of one species or a community of species?
- What are target species?
- What are the natural environmental circumstances?
- The use of natural or artificial materials as hard substrates?
- What is the available budget for biodiversity enhancement options?

In order to determine the goals and objectives per location information about (a)biotic factors and biodiversity are needed. Therefore, option 1 and 2 should be considered first, then determine the goals, and from there fine-tune the objectives and choose the optimal enhancement measures or combination (Figure 3.1).

3.2 Biodiversity enhancement options

1. Base line survey

The baseline for all enhancement options is a comprehensive biodiversity survey of all natural (shells, gravel) and artificial substrates (turbines, scour protection) and soft sediments within OWFs. This first step may seem trivial but the biodiversity present needs to be fully documented first and serves as a baseline for further enhancement. It also includes the biodiversity enhancement effects of existing OWF infrastructure by providing hard substrates in a predominantly soft sediment environment (Coolen *et al.*, 2019).

2. Conserve biodiversity hotspots

If the baseline survey has revealed the presence of biogenic reefs and shipwrecks, then it is recommended to carry out more targeted surveys, because these habitats are known to be biodiversity hotspots (Lengkeek *et al.*, 2013; Coolen et al 2018). In addition, specific conservation measures should be developed to protect these hotspots against disturbance. Potentially, these hotspots can serve as source populations for the enhancement measures in OWFs.

3. Natural substrates deployment

From the baseline survey it will be clear if natural hard substrates like shells (dead and alive) and gravel or stones are present within the OWF. If there is a general lack of settling substrate for epibenthic species like flat oyster, blue mussel, dead man's finger and anemones, then the deployment of shells, gravel or stones can be a cost-efficient biodiversity enhancement option. In a test environment adding hard substrate also proved to be the most promising technique for species like serpulid worms (e.g., calcerous tube worm *Serpula vermicularis*) and horse mussel (Cook, 2016)

Selection of suitable deployment locations can be based on the presence of cable crossings, shipwrecks, biogenic reefs in general and shellfish reefs in particular. Suitable deployment locations have intermediate bottom shear stress and current speed and low sedimentation rate and sand wave movement. This can be further evaluated with morpho-dynamic modelling (e.g., Hasselaar *et al.*, 2015) In areas with high sedimentation rate and current speed loose shells could be contained in metal gabions or biodegradable bags (see below, 3.4) or "glued" together with cement or bio-inspired adhesives. Calcereous worms (e.g., calcereous tube worm *S. vermicularis*) will colonise the shells and may contribute to 3D-stability (Todorova *et al.*, 2009) or even construct 3D-structures by themselves (Holt *et al.*, 1998). Shells may also enhance the occurrence of the reef building sand mason worm and Ross worm, which live in soft sediment habitats.

4. Re-introduction of reef building species

In order to develop natural reefs, the introduction of oysters is most promising. To build a new oyster reef, mature oysters or small spat are introduced and suitable substrate for larval settlement is placed in the period that larvae are swarming. Four translocation experiments currently take place in the offshore Dutch North Sea: the Voordelta, the Borkum Reef Grounds, Wind farm Luchterduinen and Wind Farm Gemini. A small number of adult oysters were deployed in racks and many thousands were placed on the sea floor, and empty shells were added as substrate. Survival in the Borkum Reef Grounds was high, and larvae were observed in the water column, indicating good health and reproduction (Didderen *et al.* 2019a,b). Crucial for survival and reproduction is the total absence of bottom disturbance by human activities, a sufficiently stable sea floor with low bottom shear stress, and presence of settlement substrate (Sas *et al.* 2019). Only offering settlement substrate is not sufficient, as flat oyster larvae have only a limited dispersal potential (<10 km) and will therefore not reach areas far away from their breeding grounds. Introduction of live flat oysters is therefore essential. Sand mason worms and Ross worms have a high dispersal potential and are widely distributed in the North Sea, and are able to colonise new, suitable areas. In the wider North Sea sand mason worm reefs occur only locally and Ross worm reefs are relatively rare. Deployment of shells, for example, may facilitate the formation of reefs.

5. Artificial substrates deployment for artificial reefs on soft sediments

Artificial reef structures (described in section 3.4), which are added to the soft sediment in an OWF, will create settlement opportunities for epibenthic fauna and thereby biodiversity hotspots and habitat for hard substrate associated species such as cod and lobster, hiding in crevices and feed on hard substrate associated organisms. To some extent they can replace the lost natural hard substrate of the once common oyster reefs in the North Sea. To these new artificial reefs, nearby shipwrecks are sources of hard substrate associated species.

6. Artificial substrates deployment for artificial reefs at scour protection

Scour protection and other parts of the wind turbine foundation also provide settlement substrate for epibenthic organisms and a hiding place for mobile species and already function as artificial reefs, with documented high productivity and biodiversity. The larger food abundance attracts fish species like cod and pout. However, improved nature inclusive design can increase habitat quality further for specific species groups. By adding *larger* structures species like edible crab and European lobster will hide in crevices and will increase in numbers. *Smaller* structures will favour smaller species of crab and fish.

3.3 Biodiversity: target species

The Rich North Sea Programme's main objective is to enhance North Sea reef habitats and associated biodiversity for which different options are available. Reef biodiversity is a broad term representing a large group of different organisms, with different habitat requirements, different life history traits, and thus requesting different enhancement strategies and options. To aid the development of effective enhancement, three species groups can be distinguished in reef biodiversity:

- **Reef building species**
- **Reef associated species**
- **Reef benefitting species**

Reef building species are the keystone habitat altering organisms. They can turn a soft (dynamic) seabed, colonised by endo-benthos, into a hard and stable environment colonised by both endo- and epi-benthic communities. Known reef building species in the North Sea are the flat oyster *Ostrea edulis*, the blue mussel *Mytilus edulis* (although limited by sea star predation), the horse mussel *Modiolus modiolus*, the Ross worm *Sabellaria spinulosa* and the sand mason worm *Lanice conchilega.*

Reef associated species can only be present when there is a reef, because the reef is essential to one or more life stages. Examples are anemone species that only grow on hard substrates, fish species, such as the goldsinny wrasse, that builds a nest in a reef, or shark and ray species that need a reef structure to attach their eggs to. This group represents a vast number of species, which give more structure, function and colour to a reef, ranging from hydroid polyp species to cold water corals, crabs, lobsters and species of fish.

Reef benefitting species are species that can also live in the soft substrate habitat of the North Sea, but whose habitat is improved by adding reefs. Good examples of reef benefitting species are cod and sea bass. Both species occur over sandy bottoms also, but they are known to congregate near reef structures and eat reef associated prey when available. Furthermore, young cod are known to hide in crevices of reef structures. In the next paragraphs, these species groups are presented in more detail, with most emphasis on reef building species, as vital keystone species of North Sea reefs.

3.3.1 Reef building species

In the Dutch part of the North Sea five species are able to build biogenic reefs: the flat oyster *Ostrea edulis*, the blue mussel *Mytilus edulis*, the horse mussel *Modiolus modiolus*, the polychaete *Sabellaria spinulosa* and the sand mason worm *Lanice conchilega*. Reefs of these species are known to provide substrate, shelter and food for other species. Distribution maps of these biogenic reef species are presented in Appendix 1. Observed and predicted presence in Dutch OWFs is presented in Table 3.1.

Table 3.1. Observed and predicted presence of reef building species in OWFs in the NCP, from long-lived (Mod=M. modiolus, Ostrea=O. edulis, left) to relatively short-lived (Mussel=Mytilus edulis, Sab=Sabellaria spinulosa, Lan=Lanice conchilega, right). Adapted from Bos et al. (2019): Obs= observed, 0=absent, 1= present; pred= predicted, - = unsuitable, + = suitable, ++ = highly suitable.

OWF (realised and planned)	Mod obs	Mod pred	Ostrea obs	Ostrea pred	Mussel obs	Mussel pred	Sab obs	Sab pred	Lan obs	Lan pred
Gemini (Buitengaats)	0	-	0	++	0	++	0	+	0	+
Gemini (Zee-energie)	0	-	0	++	0	++	0	+	0	+
Egmond aan Zee	0	-	0	+	1	-	0	-	0	+
Prinses Amalia	0	-	0	+	1	-	1	-	0	+
Luchterduinen	0	-	0	+	1	-	0	-	1	+
Hollandse kust - Z	0	-	0	+	1	+	1	+	1	++
Hollandse kust-N	0	-	0	+	1	+	0	-	0	+
IJmuiden Ver	0	-	0	-	0	+	1	++	1	+
Hollandse kust-W 2	0	-	0	-	1	+	1	+	0	+
Hollandse kust-W 3	0	-	0	-	1	+	0	-	1	+
Hollandse kust-W 4	0	-	0	-	1	+	1	-	1	+
Borssele	1	-	0	++	1	++	0	+	1	+

Flat oyster *Ostrea edulis*

English name	Flat oyster	
Scientific name	*Ostrea edulis*	
soft sediment	++	
natural hard substrate	+	
artificial hard substrate	+	
reef size	1-100 ha	
temperature range	temperate	
lifespan	10-50 y	
food	phytoplankton	

Distribution

The flat oyster *Ostrea edulis* once formed extensive reefs in the North Sea, but due to fishing activities and diseases these reefs have disappeared. In the Netherlands, they still occur in Lake Grevelingen, the Voordelta, and the Wadden Sea (Christianen *et al.* 2018; van der Have *et al.* 2017). The flat oyster occurs along the European Atlantic coast from Norway to Morocco, in the Mediterranean and in the Black Sea, mostly on sheltered hard substrate.

Life cycle

The flat oyster is an alternating hermaphrodite, which after one year reaches sexual maturity as male and thereafter, usually after three years switches between male and female. This switching between sexes occurs several times in their life and can even occur several times within one summer (Walne 1974). Water temperature seems to influence the sex ratio of a population, as cooler water temperatures cause a more even distribution of males and females (Eagling *et al.* 2017). The water temperature also controls the start and end of the breeding season, and the time of spawning (Joyce *et al.* 2013, Maathuis *et al.* submitted.). Oysters can survive in temperatures between 3-30ºC, optimum growth range is between 15-20º C (Buxton *et al.* 1981). Populations are able to adapt to local temperature ranges.

Females brood fertilized eggs for 6-8 days, after which the larvae are released into the water column. The larvae live for 7-10 days in the water column until they search for suitable hard substrate to settle on (Korringa 1940). The larvae tend to stay close to the sea floor and therefore larval dispersal is not far from the flat oyster reef (Knights *et al.* 2006). Successful spatfall and recruitment is irregular. Flat oyster reefs occur on sine sand and silty sand or gravel with shells and stones (Smaal *et al.* 2017). Oyster larvae tend to settle on or in the vicinity of other oysters, preferably on shells (Rodriguez-Perez *et al.*, 2019). Settled oysters are susceptible to burial under sand and sediment, therefore locations with little sediment movement is seen as optimal. Oysters may be able to dig themselves out of a fine layer of sediment, but this is likely energy demanding (T.M. van der Have, pers. comm). Therefore, they are vulnerable to burial by a high sedimentation rate, which can limit their feeding efficiency (Duchêne *et al.* 2015). They are also vulnerable to long periods of oxygen depletion and for parasites, especially *Bonamia*.

Ecology

Oyster reefs are biodiversity hotspots. The oyster reef in the Voordelta contained several crab species, bryozoans, fish, hydrozoans, starfish, sponges and a thornback ray (Didderen *et al.* 2018). Starfish and large crabs are potential predators of oysters (Didderen *et al.* 2019).

Restoration & enhancement

Flat oysters are currently used in nature restoration and biodiversity enhancement projects in the North Sea. In Dutch experiments flat oysters sourced from Norwegian oyster grounds were displaced in wind farms and an area closed for fishing activities. These oysters survived and showed growth, and some oysters developed gonads and contained larvae in their shell (Didderen *et al.* 2019). Sourcing oysters from other regions is not advised, therefore future projects may make use of spat on shell from oyster hatcheries (Sas *et al.* 2018). Flat oysters have irregular reproductive success, and experiments have only started in 2018 and 2019, therefore little is known of reproduction success in the Dutch North Sea.

Using flat oysters in biodiversity enhancement projects in the Dutch North Sea is likely a feasible option. First studies already showed positive results (Didderen *et al.* 2019). To build a regenerating and self-maintaining reef, it is important to introduce enough oysters of different life stages, and suitable substrate for oyster larvae to settle (Didderen *et al.* 2019). In previous experiments, oysters were placed directly on the sea floor and on substrates elevated from the sea floor, and both methods showed positive results.

Oysters can be sourced from other natural populations, from aquaculture and from hatcheries. The main limiting factor placing oysters in offshore areas is that these areas are free of parasites like *Bonamia* and it is illegal to introduce oysters infected with *Bonamia*. It is therefore required that the introduced oysters are *Bonamia*-free. Oysters from Norway are *Bonamia*-free, but still need to be extensively cleaned to prevent introduction of other unwanted species (Sas *et al.* 2019). A more feasible way of preventing the introduction of problem species is using oysters from hatcheries. There are currently several hatcheries that produce oysters for aquaculture and restoration purposes.

Blue mussel *Mytilus edulis*

English name	Blue mussel	
Scientific name	*Mytilus edulis*	
soft sediment	+	
natural hard substrate	+	
artificial hard substrate	++	
reef size	1-100 ha	
temperature range	temperate	
lifespan	7-18 y	
food	phytoplankton	

Distribution and life cycle

The blue mussel *Mytilus edulis* is a common and well-known reef building species in the intertidal zone. Intertidal mussel beds can be extensive and form an important food source for fish, crabs and birds. Less known is that mussels can also form beds in the subtidal: a large seed bed was found in the Voordelta which developed into a mature mussel bed (Didderen *et al.* 2018), and mussels were found on many locations on the sea floor in the Dutch North Sea during fish surveys (Bos *et al.* 2019).

Blue mussels are found along the coast of the northern Atlantic Ocean. They are acclimated to temperatures between 5-20ºC and have an upper temperature limit of 29ºC. They are tolerant to fluctuations in salinity and usually live between 1-10 m deep. Their length can range between 0.5-20,0 cm but they tend to be between 5-10 cm. Mussels are either male or female and reach sexual maturity in 1-2 years. They shed their egg and sperm cells in the water column, where the eggs are fertilized. The larvae that grow out of the fertilized eggs live 3-5 weeks in the water column (Wang & Widdows, 1991) and can therefore disperse far from the original mussel bed. The larvae then find a place to settle, on hard sediment, shells or other mussels. Predation on mussels is high, especially by birds in the intertidal and by crabs and sea stars in the subtidal. Mussels are susceptible to burial under sediments but can escape sediment layers of up to 2 cm (Hutchison *et al.* 2016; Cottrell *et al.* 2016).

Ecology

Blue mussels colonise hard structures of offshore platforms and wind farms. These hard substrates offshore create a new “intertidal” zone in the North Sea, and mussels are here the dominant species near the water surface (Krone *et al.* 2013). A windmill pile can be covered by as many as 4300 kg mussels (Krone *et al.* 2013). These reefs of mussel beds near the surface can significantly reduce phytoplankton stocks in the surface, which may lead to lower food availability for organisms living on the sea floor (Maar *et al.* 2009; Slavik *et al.* 2018). Mussels attached to platforms in the Dutch North Sea can create “reefs” of up to 60 kg/m^2 and enhance species richness (Coolen *et al.* 2018). These high densities of mussels may damage the turbine and sometimes need to be removed.

Nature restoration and enhancement

Due to their limitation to shallower depths (1-10 m), the blue mussel may not be a likely candidate for creating biogenic reefs in wind farms. However, mussels already create a vertical biogenic reef on poles in wind farms and should therefore be taken into account. In addition, individual mussels may survive among flat oysters, which prevent predation by seastars (Sas *et al.*, 2016, 2018).

Horse mussel *Modiolus modiolus*

English name	Horse mussel	 © Rob Cook
Scientific name	*Modiolus modiolus*	
soft sediment	+	
natural hard substrate	+	
artificial hard substrate	?	
reef size	< 1 ha	
temperature range	cold adapted	
lifespan	10-50 y	
food	phytoplankton	

Distribution

Due to their low optimum growth temperature, horse mussels only occur sporadic in the Dutch part of the North Sea (Bos *et al.* 2019). Dense beds of horse mussels do occur along the Scottish, Irish, Icelandic, Swedish and Norwegian coasts (Holt *et al.* 1998; Lindenbaum *et al.* 2008; Ragnarsson & Burgos 2012; Brown 1984). They require hard substrate to establish beds (Holt *et al.* 1998) but once established the beds also cover sediment.

Life cycle

The horse mussel *Modiolus modiolus* often forms biogenic reefs in sublittoral waters (3-100 m) but also in the intertidal. It is a slow-growing species that reaches sexual maturity around 3-8 years, and individuals can reach 100 years old (Jasim & Brand 1989). Horse mussels grow are generally 10-15 cm long but can grow to more than 20 cm. Spawning is sporadic and recruitment does not occur yearly, but larvae can live up to 6 months in the water column and dispersal is therefore usually over long distances. Horse mussels have an optimum growth temperature around 7-10 °C and an upper limit of around 15-20°C and are resistant to freezing (Davenport & Kjørsvik 1982).

Ecology
Horse mussels can form dense beds on cobbles and muddy gravel and build biogenic reefs through accumulation of shells and faecal deposits (Lindenbaum *et al.* 2008; Ragnarsson & Burgos 2012). These biogenic reefs have a high biodiversity and contain many hard-substrate species compared to the surrounding area (Ojeda & Dearborn 1989; Sanderson *et al.* 2008). They are patchy and heterogeneous, creating a habitat for the ocean quahog *Arctica islandica* (NL: noordkromp), the soft coral *Alcyonium digitatum* (NL: dodemansduim), starfish and sea anemones (Ragnarsson & Burgos 2012). Horse mussels are predated upon by the starfish *Asterias rubens*.

Restoration & enhancement
To build a horse mussel reef, clumps of horse mussels can be translocated, suitable substrate can be placed so larvae can settle, and horse mussels can be cultivated in a hatchery. An experiment along the North Irish coast showed that translocation in combination with suitable substrate placement resulted in high survival, reproduction and natural recruitment (Roberts *et al.* 2011). Only offering settlement substrate for larvae is not a viable option, as settlement mainly occurs on clumps of live mussels. There are at the moment no hatcheries that provide horse mussels, as cultivation is expensive due to the facts that horse mussels reach sexual maturity in 3-8 years, survival is low, and larvae and spat grow only slowly (Roberts *et al.* 2011).

Using horse mussels to build biogenic reefs in wind parks in the Dutch North Sea is likely not feasible, as horse mussels require colder water temperatures (7-10 °C), they grow very slow and reproduction is irregular. They are potentially interesting for wind parks along the northern and western British coast, as there are currently extensive mussel beds in Scottish and North-Irish waters (Roberts *et al.* 2011; Brown 1984).

Ross worm *Sabellaria spinulosa*

English name	Ross worm	 https://eu.oceana.org/
Scientific name	*Sabellaria spinulosa*	
soft sediment	++	
natural hard substrate	+	
artificial hard substrate	?	
reef size	1-100 ha	
temperature range	temperate	
lifespan	2-9 y	
food	phytoplankton	

Distribution
The Ross worm *Sabellaria spinulosa* is a polychaete that builds a tube of sediment particles. It is relatively tolerant to bottom disturbance and mostly occurs in areas with

high levels of suspended sediment (OSPAR 2010). The Ross worm can live solitary or in aggregations that form reefs up to 60 cm high and extend over several hectares. These reefs tend to form on hard substrate or mixed sediments of sand and gravel, and provide a habitat for calcareous tubeworms, crabs, amphipods, hydrozoans, bryozoans and sponges (OSPAR 2010). Recently, several large Ross worm reefs have been discovered in the Brown Bank area, which is intensively fished (van der Reijden *et al.* 2019). Ross worms occur in the Atlantic, the North Sea, Mediterranean Sea and the English Channel. Actual reefs are rare and in decline, likely as a result of human activities as fishing and sand extraction (OSPAR 2010).

Life cycle

The Ross worm has separate sexes and releases its egg or sperm cells into the water column where the egg cells are fertilized. The frequency and timing of spawning is unknown. The larvae live for six weeks to two months in the water column and therefore their dispersal is likely large (Wilson 1970). The larvae settle near adults or shells (Wilson 1970). Reproduction and recruitment are highly variable, and likely depends on the area (Rees & Dare 1993). Once settled, the worm produces a cement secretion to build a tube with sand, which can grow 2-3 cm a year. They reach sexual maturity in 1-2 years and can possibly live up to 9 years (Linke 1951; Marine Life Information Network).

Restoration & enhancement

The Ross worm is a likely candidate for creating biogenic reefs in offshore wind farms. Theoretically it could be possible to translocate or transplant reefs into wind farms. Due to high dispersal of larvae, however, it is likely that the Ross worm settles in wind parks independently. For successful colonisation, it is crucial to offer the right substrate (e.g. large shells like scallops; OSPAR 2010), little bottom disturbance and a certain amount of suspended sediment is required.

Sand mason worm *Lanice conchilega*

English name	Sand mason worm	
Scientific name	*Lanice conchilega*	
soft sediment	++	
natural hard substrate	-	
artificial hard substrate	-	
reef size	> 100 ha	
temperature range	Temperate	
lifespan	1-3 y	
Food	Phytobenthos	

Distribution

The sand mason worm is widely distributed along European coasts, from shallow intertidal to 1900 m depth. It occurs on sandy and muddy sediments and lives in aggregations or reefs of multiple individuals. There are multiple sand mason worm reefs in the Dutch part of the North Sea (Bos *et al.* 2019).

Life cycle

This species constructs tubes by gluing mainly shell fragments (60-80%) with sand grains. These tubes are buried in the sediments for several decimetres and protrude up to several centimetres from the surface of the sea floor. Sediment is deposited in areas with high worm densities, due to the current reduction among the tubes and the tubes grow upwards in pace with the sediment deposition (e.g., Alves *et al.*, 2017). Although the sand mason worm is short-lived (1-2 years), the tubes persist for several years and form a settlement substrate for young worms (Rabaut, 2009). If the densities are more than 500 worms per square meter and with c 5 cm elevation, then these concentrations qualify as a low biogenic reef (Rabaut *et al.*, 2009). These reefs can increase in densities and height up to more than 1500 worms /m2 and c 9 cm elevation. These high *Lanice*-reefs can cover large areas, persist for several years and are characterised by a high biodiversity (more than 30 species) in comparison to the soft sediments without *Lanice*-reefs (Bos *et al.*, 2014; Coolen *et al.*, 2015; De Smet *et al.*, 2015).

Ecology

The sand mason worm is a common species in the North Sea area and a typical species of the sandy areas permanently covered with water (Rabaut, 2009). Reproduction starts in spring and lasts until autumn. Eggs are fertilized in the water column and subsequent larval stages can stay there for several months (up to 60 days). The availability of habitat structures and hydrodynamic conditions determine where the larvae settle, usually near adults. The worms are suspension feeders in high densities and a deposit-feeders in low densities.

Restoration & enhancement

Bottom disturbance by trawlers has a negative impact on the quality and structure of existing *Lanice conchilega* reefs (Rabaut 2009). *Lanice conchilega* reefs can occur in a wide range of dynamic conditions and the best strategy is to prevent bottom disturbance in existing reefs or in suitable areas where the reefs are absent.

3.3.2 Reef associated species

The reef-associated species represent a vast number of species, that depend on hard substrate to settle, but also give more structure, function and colour to a reef, ranging from anemone and hydroid polyp species to cold-water corals and sponges (jewel anemone (*Corynactis viridis*), plumose anemone (*Metridium dianthus*), dahlia anemone (*Urticina felina*), dead men's fingers (*Alcyonium digitatum*), sea snails; Figures 3.2 – 3.3). Flat oysters can provide habitat for these species, but these species in turn provide habitat for yet other species, resulting in an extremely complex reef structure. Hydroid polyps for instance, need a hard structure such as an oyster to grow on. Several predatory sea snails (nudibranchs) species, need hydroids to live, because the eat them and lay their eggs on them. Many reef-associated species eat phytoplankton (filter-feeders), and thus this species group contributes substantially to the filtering capacity and secondary production of a reef.

It can be argued, if the soft coral Dead men's fingers (*Alcyonium digitatum)* is a reef building species or a reef associated species. Because it needs a hard substrate to grow on, and it cannot turn soft sediment into hard substrate by itself, in this study it is not considered as a reef building species. It does, however, contribute substantially to the 3-dimensional structure of a reef and is one of the most iconic reef associates in the North Sea. It prefers strong currents, has a low tolerance to sedimentary environments and is mainly found on hard substrate as bedrock and boulders (Bell 2001; Hiscock & Hoare 1975). Because of its low tolerance to sediment, it cannot be expected to flourish in all OWF locations.

Larger mobile species like edible crab, European lobster and species of fish, like gobies and blennies find shelter and a place to deposit eggs (Figure 3.4). Also, larger species of fish like the tadpole fish (vorskwab, *Raniceps raninus*), and ling (leng, *Molva molva*) forage among crevices and use them as a hiding place.

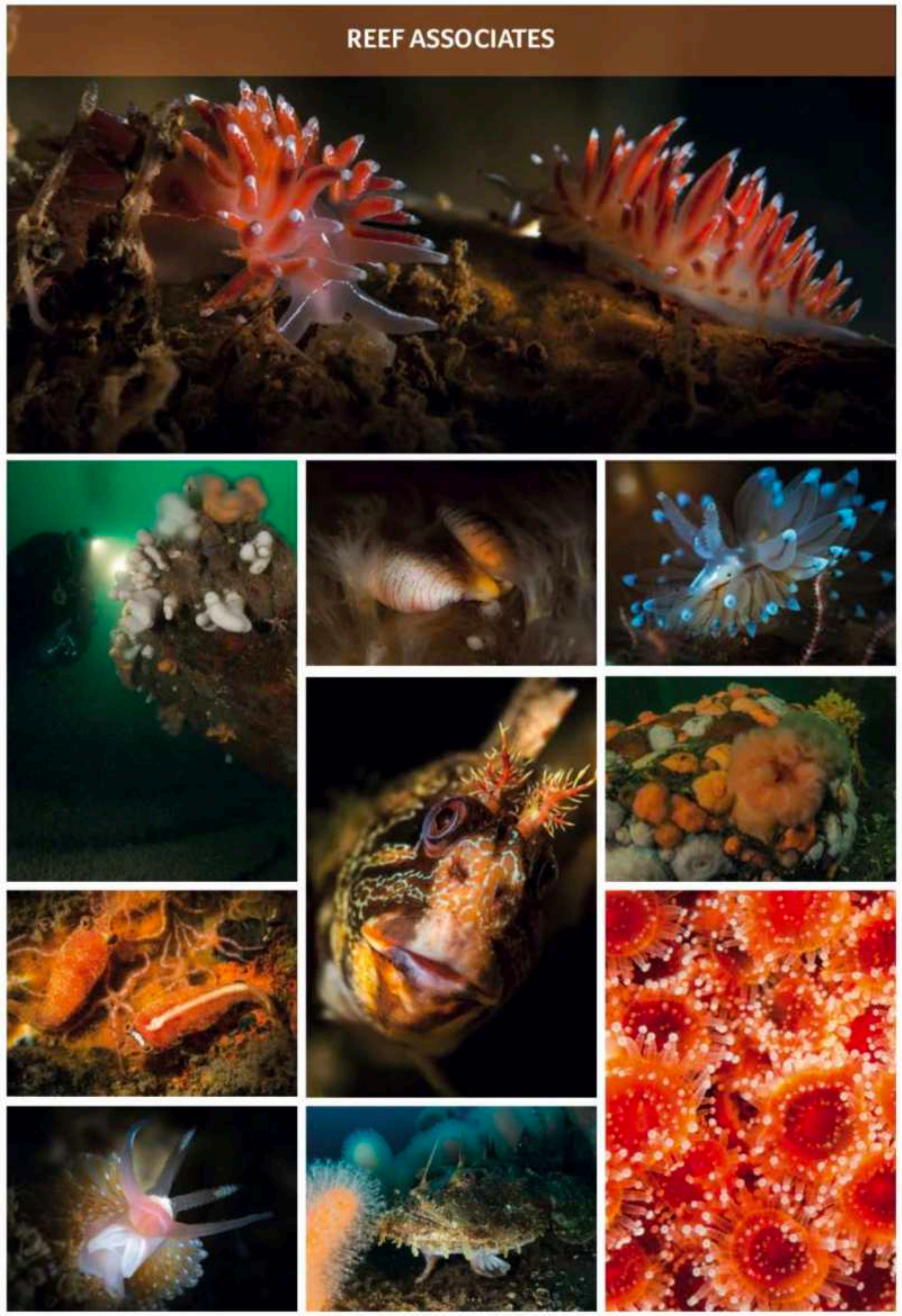

Figure 3.2. Reef associated species.

Figure 3.3. Reef associated species.

3.3.3 Reef benefitting species

These species include various large and mobile fish species, which are attracted to reefs for food and shelter. Several commercial, or otherwise policy-relevant or iconic species can be considered as reef-benefitting species. For instance, pout (*Trisopterus luscus*), Atlantic cod (*Gadus morhua*, Atlantic wolffish (*Anarhichas lupus*), rock gunnel (*Pholus gunnellus*) and sea bass (*Dicentrarchus labrax*), but also some shark and ray species and monkfish (*Lophius picatorius*) can be considered as reef-benefitting species (Plates). The lesser-spotted dogfish and the greater-spotted dogfish need structure on the seabed to lay their eggs in (Heesen *et al.*, 2015). Coastal seaweed and seagrass beds provide these habitats but also Ross worm reef structures in offshore locations. The greater spotted dogfish (*Scyliorhinus stellaris*) is known to have a strong preference for structure-rich habitat (Heesen *et al.*, 2015). Monkfish use reef habitats for yet another reason: They rely on camouflage for hunting. Their body is shaped in such a way that they are hardly visible when lying on or under a North Sea reef structure. For this reason, they prefer structures such as gravel beds and shipwrecks, although they are also occurring on finer sediments. Reefs also attract mobile molluscs such as common octopus (*Octopus vulgaris*; Figure 3.4) and various species of squid.

3.3.4 Sources and availability reef building species

The flat oyster is absent from large part of the North Sea and has a very limited dispersal potential compared to the other species. The methods and options for flat oyster introduction and the possible sources are discussed in Sas *et al.* (2019) and Kamermans *et al.* (2019). Biodiversity hotspots such as wrecks could function as source areas for epifaunal species with more limited dispersal capabilities.

Natural settlement of biogenic reef building species mainly depends on the availability of larvae in the water column and the availability of suitable substrate in the period that larvae are ready to settle. The number of larvae in the water column depends on the number of adults and the time period that the larvae are swimming and the dispersal potential increases with the pelagic period of the larvae. For sand mason worm, Ross worm, blue mussel and horse mussel, the abundance of larvae is not limiting for the recruitment. Therefore, it is not necessary to introduce these species. Large mussel populations are present along the tideline of most wind turbines at sea and sand mason worm is a very common species in the southern North Sea. Enhancement of these species is feasible by creating suitable conditions for settlement and survival (facilitation).

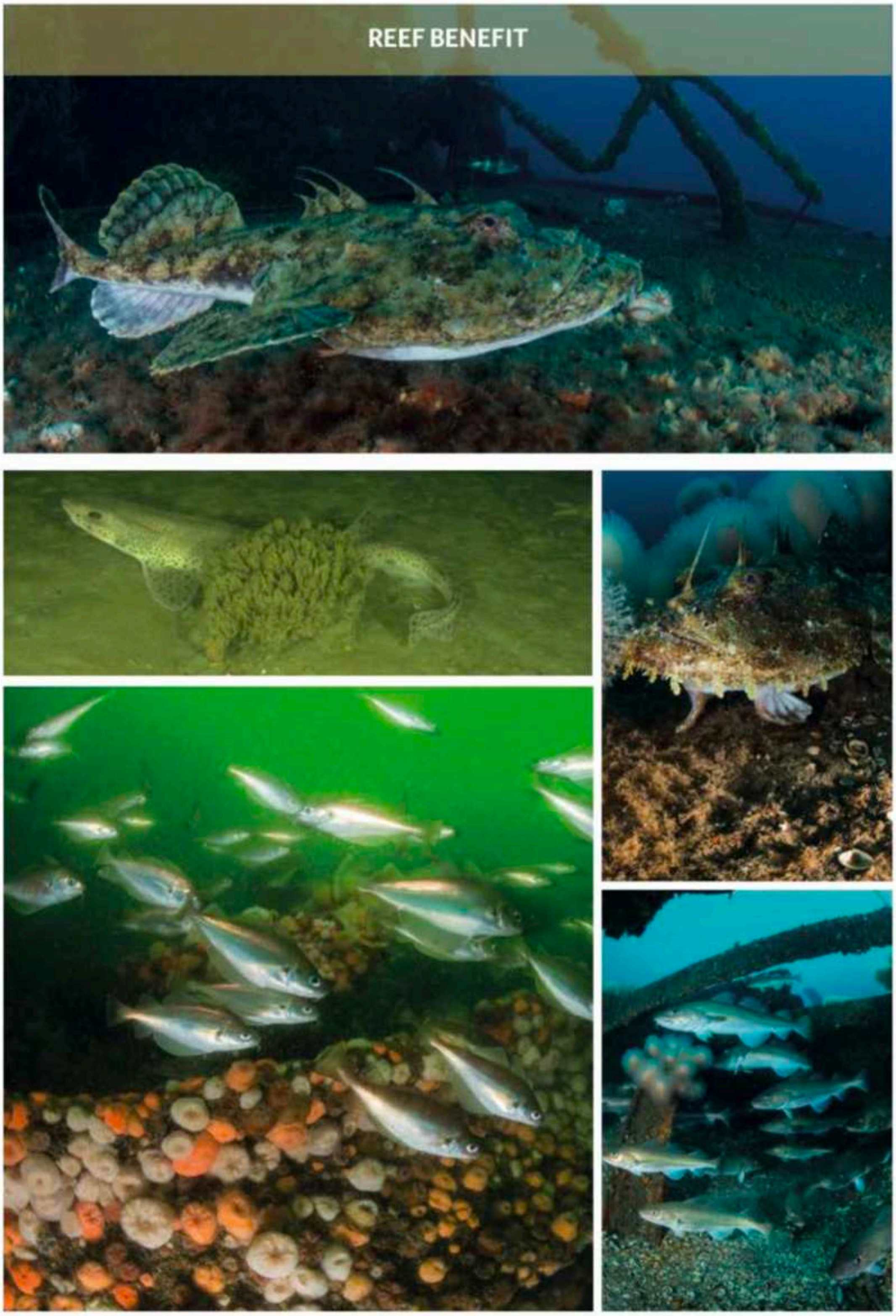

Figure 3.4. Reef benefitting species.

3.4 Materials for artificial reefs

Hard substrates have various ecological functions in a marine environment. Their main function is to provide a settling substrate for many species of algae and animals, attachment surface for eggs of various organisms and shelter for juvenile fish and mobile invertebrates. Reef organisms then also contribute to the structural complexity of these ecosystems.

From these basic ecological principles Lengkeek *et al.* (2017) derived a set of recommendations to implement eco-friendly design principles for scour protection in planned wind farms:

a) Adding larger structures (in comparison to conventional scour protection);
b) Adding more small-scale structures (than conventional scour protection);
c) Providing natural biogenic substrates (or bio-mimetic substrates);
d) Restoration of biogenic species by introduction.

The target species of enhancement options 5 and 6 (providing artificial substrates; section 3.2) are reef associated species (section 3.3.2) and reef benefitting species (section 3.3.3). The first group requires hard substrate for settlement (e.g. sponges, cold water corals, anemones, hydroids, echinoderms) or for shelter and egg depositions (crabs, lobster, fish). The latter group includes mainly large, mobile species, which find food in or around artificial reefs, including Atlantic cod, pout, Atlantic wolffish, rock gunnel, sea bass. Reef building species (3.3.2) may also settle on or among the scour protection or on artificial reefs (in particular bivalves such as blue mussel, flat oyster).

Table 3.2 and Figure 3.5 provide an overview of materials including materials that provide or mimic natural substrates (Category 1). Category 2 includes large structures, which provide holes (Figures 3.6 – 3.7) and category 3 contains smaller-scaled structures, which provide fine habitat complexity. For a catalogue of and technical description of nature inclusive materials and designs see Hermans *et al.* (2019).

*Table 3.2. Materials used for biodiversity enhancement and potentially suitable in OWFs. (Sources: Lindquist & Cessna ; www.ecocean.fr; reefballs.org; http://www.xbloc.com/; Peters & Werth 2012; TU Delft; EDF.com; arcmarine.org.uk/reef-cubes; reefdesignlab.com; Subcon.com; BESE-products.com; Reefcells.com. Adapted from Lengkeek et al., 2017, with additions. *materials also provide small scale structure). See also Hermans et al. (2019) for a technical description of these materials and designs.*

Category 1: Natural rocks or stones	
1	Boulders
2	Gravel
Category 2: Large, artificial structures providing holes	
3	Concrete with holes
4	Reef balls
4	Reef dome
5	Xblocs ®
6	Prefab collar
7	SeaCult Reef system
8	Biodegradable concrete reefs
9	3D-printed habitat modules
10	SubCon Artificial reefs and pelagic tower
11	ECOncrete ®
12	ReefCubes ®
12a	Fish hotels
12b	ReefCubes *
Category 3: Smaller-scale structures: fine habitat complexity	
13	Oyster Catcher
14	Biohut ®
15	Fibre mesh enclosed stone bundles
Category 4: Materials that provide or mimic natural substrates	
16	Loose (empty) shells
17	Shell material in bags or cages
18	Live oysters
19	Biorock ®

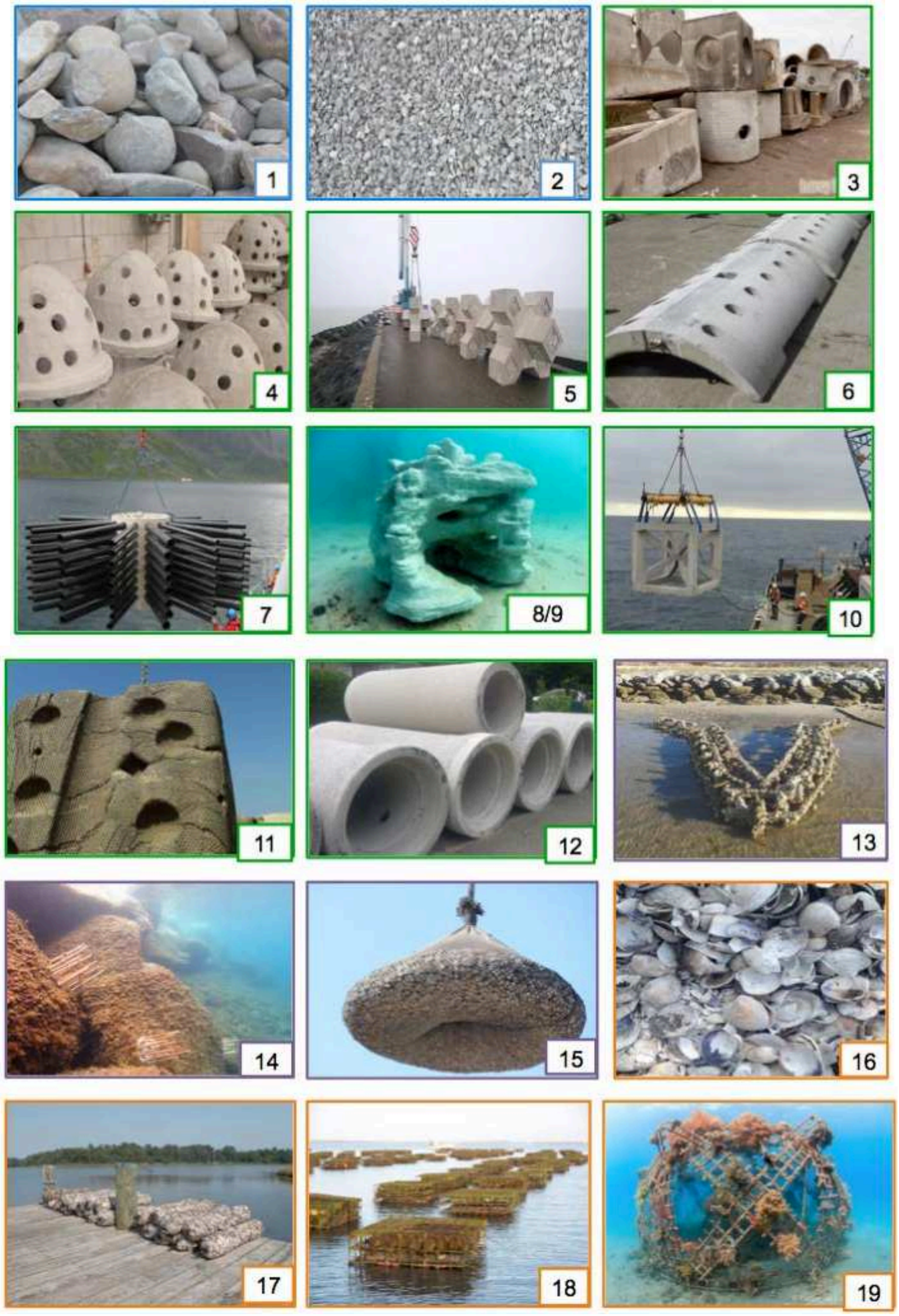

Figure 3.5. Overview of potential materials for active biodiversity enhancement in OWFs. (Source: Lengkeek et al., 2017).

Figure 3.6. Fish hotels, an idea of Tinka Murk, Wageningen University. Structures made of concrete with large holes and interlocking system with pins aimed at large fish. (Source: Wageningen University).

Figure 3.7. ReefCubes® designed by ARC Marine are systems with large holes and interlocking pins made from low-carbon concrete (Source: ARCMarine.co.uk).

4

Offshore wind farms and local conditions for active biodiversity enhancement and restoration

4 Offshore wind farms and local conditions for active biodiversity enhancement and restoration

The Dutch North Sea covers a large area and the abiotic conditions in this relatively shallow sea shows great variation between different locations. The local circumstances are important for the species that live there since they provide conditions for establishment, growth and reproduction. Survival of species and accessibility of substrate is of crucial importance for the success of any biodiversity enhancement project. Section 4.1 presents the most important abiotic and biotic factors, which characterise the OWFs and are relevant for biodiversity enhancement. The requirements for the six biodiversity enhancement options are discussed in section 4.2 and integrated with the OWF characteristics to evaluate the opportunities for biodiversity enhancement in the OWFs in section 4.3. It should be noted that very limited information is available about the ecology of the focal species of the Rich North Sea programme in relation to offshore wind farms, mainly because offshore wind farms are, on an ecological time scale, a very recent addition to the North Sea environment. Many interpretations are based on expert judgement. More specific knowledge will be developed by “learning by doing” in the various enhancement projects that will be initiated the coming years.

4.1 Description of current and planned OWFs until 2023

The present study includes twelve locations of offshore wind farms (see also section 2.4, Figure 2.1). These wind farms at the Dutch Continental Shelf (DCS) are currently in operation or being constructed till 2023. The general characteristics, including ownership, size, number of turbines, artificial substrate type and abiotic and biotic conditions of these OWFs are presented in Tables A1 to A5 in Appendix II. The abiotic factors, which are most relevant to the ecology of the focal species and enhancement options, are summarised in Tables 4.1 – 4.2, indicated in bold and briefly discussed below.

The **substrate type**, **shear stress** and **seabed motility** determine to a large extent the scope for settlement and survival of recruits. Bottom shear stress, stratification regime and food abundance influence the dispersal of larvae and survival of all life stages. The **soft sediment habitats** vary from fine in areas with a rather stable seabed to coarse sand in areas with sand waves and mega-ripples.

The average concentration of **suspended particulate matter** (SPM) varies from 5-10 mg/l in IJmuiden Ver, and Hollandse Kust West (2-4) to 20 mg/l in Egmond aan Zee, and 10 mg/l in the other OWFs. Higher concentrations of inorganic particles (e.g., >50 mg/l) are detrimental for filter feeders because it lowers phytoplankton content of ingested particles.
The average **bottom shear stress** is a measure of the pressure of currents and wind action on the sea floor expressed as Newton per square meter. It is relatively low in

Gemini (0,3 N/m^2) and high in Egmond aan Zee (0,8 N/m^2) and intermediate in the others (0,5-0,6 N/m^2).

Seabed motility is characterized by the presence of larger sand waves or smaller mega-ripples (Figure A.15; *e.g.*, Hasselaar *et al.*, 2015) and is discussed in more detail in Appendix II. The movement of sand creates sand waves in areas with high currents, and these sand waves can be stable or slowly moving. The seabed is stable in Gemini in the north, without sand waves in Egmond aan Zee, Hollandse Kust West-4 and Hollandse Kust Noord, and with sand waves in the other OWFs. The sand waves are relatively small and dynamic in Hollandse Kust Zuid, IJmuiden Ver, Hollandse Kust West-3 and Luchterduinen, but high and relatively stable in Borssele. Mega-ripples are detrimental for settlement and stability of flat oyster beds (and possibly also for mussel beds) and the succession of epibenthic fauna on the lower parts of artificial reefs, but suitable for *Lanice* and *Sabellaria* reefs. Further modelling studies on the morpho-dynamics and the height and speed of mega-ripples are needed for each project location to predict the influence of seabed motility on the enhancement measures.

The **temperature** regime is characterised by intermittent stratification (IJmuiden Ver, Borssele) and irregular stratification (Gemini) in the OWFs relatively far offshore (large difference between sea surface temperature and bottom temperature, mainly in spring and summer, with no mixing). All other OWFs are permanently mixed and have lower salinities caused by freshwater outflow from the Rhine (van Leeuwen *et al.*, 2015).

In the irregularly or intermittently stratified areas the food **concentration** (phytoplankton abundance), as indicated by the chlorophyll-a content in spring and summer is lower due to the lower mixing and availability of nutrients (Gemini and IJmuiden Ver), but not in Borssele. Flat oysters seem to be adapted to these areas as the historical distribution range largely overlaps with the area of irregular stratification.

Table 4.1. List of artificial substrates and conditions in OWFs, which are relevant for biodiversity enhancement options and are further detailed in Appendix 2.

Abiotic conditions	**Biotic conditions**
Substrate type	Food concentration
Spatial variation within OWFs	Larval retention
Water depth	Historical abundance of flat oysters
Water temperature (at the bottom)	
Sea bed shear stress	**Artficial substrates**
Sea bed motility	Scour protection
Suspended particulate matter (SPM)	Cables in the DCS
Salinity	Shipwrecks
Oxygen content	

The **artificial substrates** include the scour protection around the wind turbines, cables and shipwrecks. The scour protection and cables are present in all OWFs, shipwrecks are present in several of the planned OWFs (Appendix 2, Figures A7-8).

The biotic and abiotic characteristics of the OWFs are the main determinants of the potential for biodiversity in general and for biogenic reefs in particular (section 3.2.1, Table 3.1) and by implication also for the success of biodiversity enhancement measures. Six different options were identified: (1) baseline survey, (2) identification of biodiversity hotspots, (3) natural substrate deployment, (4) introduction of reef building species, (5) artificial substrate deployment on soft sediment, (6) artificial substrate deployment on scour protection. In this section first the requirements of the enhancement options are presented and discussed and in the last section the opportunities for the various options are evaluated for each OWF (Tables 4.3 – 4.5). These evaluations are based on expert judgements as the detailed relationships between the habitats within OWFs and the focal species of the Rich North Sea programme are largely unknown. More information will be acquired by the “learning by doing” approach of the enhancement projects in the near future.

4.2 Requirements of biodiversity enhancement options

In this section we present the requirements for the successful implementation of biodiversity enhancement measures in OWFs as six different options, of which we consider options 1 and 2, the baseline and hotspot study, as obligatory and essential for the selection process and evaluation (Figure 3.1).

1. Baseline: Carry out a base line survey of substrate and biodiversity

An important prerequisite for many marine species is the availability of suitable substrate for settlement. Therefore, a first step would be to map the substrate types and its availability and associated biodiversity. This option can be carried out in all OWFs and is independent of the OWF characteristics. In addition to available information (like Bos *et al.*, 2019 and/or investigation of wind farm explorers) investigations can be carried out using sonar, a remotely operated underwater vessel (ROV) and/or by taking samples. Detailed methods for the actual surveys are described in chapter 6.

2. Biodiversity hotspots: Locate and protect biodiversity hotspots

Besides the available substrate, it is important to know what reefs, reef building species and biodiversity hotspots are yet present in and near the wind farm area. This is important for biodiversity conservation, and for working with local species richness as a starting point. Existing hotspots can give insight into the suitability of the specific area for the different species, in terms of abiotic factors, larval distribution, recruitment options, predation and competition. Furthermore, a species-rich shipwreck or reef in the proximity will increase the chance of successfully creating a rich reef area within the OWF. If an area is specified as suitable and promising, the simplest measure is waiting, whilst implementing precautionary measures that will make sure there is no bottom disturbance in that area. If the area is not yet suitable, one or more advanced enhancement options should be considered. This type of survey can be carried out in every OWF and are particularly promising in OWFs where shipwrecks are located (Figures A.7 – A.8; Appendix 2).

Table 4.2. The characteristics of 12 actual and planned OWFs in the DCS, which are most relevant for biogenic reefs and enhancement options, substrate type (fine or coarse sand), the concentration of Suspended Particulate Matter (SPM, mg/l), average shear stress (N/m2), sea bed motion, temperature stratification regime and food abundance (indicated by the average Cholorophyll-a concentration in $\mu g/l$).

Name OWF	**Substrate type**	**SPM avg**	**Shear stress avg**	**Seabed motility**	**Stratification regime**	Chl-a avg
Gemini 1(= Buitengaats)	Fine sand	10	0,3	Relatively stable	Irregular stratification	1,60
Gemini 2 (= Zee-energie)	Fine sand	10	0,3	Relatively stable	Irregular stratifiation	1,56
Egmond aan zee (OWEZ)	Fine sand	20	0,8	No sandwaves	Semi-permanently mixed (ROFI)	2,27
Prinses Amalia	Coarse to fine sand	10	0,6	Two areas with sand waves, rest is stable	Semi-permanently mixed (ROFI)	2,23
Luchterduinen	Coarse to fine sand	10	0,6	Covered with low and stable sand waves	Semi-permanently mixed (ROFI)	2,45
Hollandse Kust Zuid	Coarse to fine sand	10	0,5	Low sandwaves 1-3 m	Semi-permanently mixed (ROFI)	2,52
Hollandse Kust Noord	Fine sand	10	0,6	No sandwaves in most parts, small area with low sandwaves 1-3 m	Semi-permanently mixed (ROFI)	2,13
IJmuiden Ver	Coarse to fine sand	5-10	0,5	No sandwaves northern part, southern part with low sandwaves 1-3 m	Intermittent stratificaton	1,71
Hollandse Kust West - NW2	Fine sand	5-10	0,5	Intermediate sandwaves 4-6 m	Semi-permanently mixed (ROFI)	2,33
Hollandse Kust West - W3	Coarse sand	5-10	0,5	Low sandwaves 1-3 m	Semi-permanently mixed (ROFI)	2,02
Hollandse Kust West - NW4	Coarse sand	5-10	0,5	No sandwaves in most parts, small area with low sandwaves 1-3 m	Semi-permanently mixed (ROFI)	1,87
Borssele	Coarse to fine sand	10	0,6	High sandwaves, low motility	Intermittent stratificaton	2,81

3. Natural substrates deployment

If a wind farm area seems suitable for the desired species, but the substrate is not yet optimal, natural substrate can be deployed. Implementation options include different types of shell material, stones or multiple shells/stones glued together with for instance concrete or biodegradable adherence substances.

The requirement for effective enhancement is that the substrate must remain in place without being covered with sediment. This means that the currents should not be too strong, and the seabed should not be too dynamic (e.g. no mobile sand waves). Furthermore, the desired species should be able to reach the area with substrate, by inflow of larvae through currents or because of the presence of a source population in proximity.

4. (Re-)introduction of reef building species

If larvae cannot naturally reach the desired location or if the settlement success of the larvae is largely dependent on the presence of an existing population close by, the target species can be introduced. In chapter 3 more information per species can be found. When introducing flat oysters, all relevant age classes should be introduced since young oysters exclusively or mainly function as male and only at 4-8 years old do they switch to function as female (Sas *et al.*, 2019). The timing of deployment of suitable settlement substrate in relation to larval presence is important (Sas *et al.*, 2019; Didderen *et al.*, 2018), because the window of opportunity for successful settlement is rather limited (Sas *et al.*, 2019).

Additionally, it is necessary to think about the possible predators and risks for the introduced species at a specific site, especially if only one species is introduced in a high density. Facilitating parts of the reef food web and specifically the allies (the predators of the predators) of the introduced species are additional measures. It is important to design an introduction from an ecosystem point of view and not only consider the requirements of the desired species itself.

Another relevant question is how much source material, e.g. flat oysters, is needed to kick-start a population? Also, is a small population in different years preferred over introducing a large population at once? From recent studies and restoration pilots in the Voordelta (Sas *et al.*, 2016, 2018; Didderen *et al.*, 2018), OWF Luchterduinen (Didderen *et al.*, 2019b) and Borkumse Stenen (Didderen *et al.*, 2019a) it is clear that a relatively small oyster population can produce larvae. However, it is still unknown if there is actual recruitment offshore in the North Sea. A sustainable reef means that enough larvae settle and survive up to the moment that they will reproduce and that they reproduce so effectively that they maintain a reef without help.

5. Deploy artificial reefs on soft sediment

A general remark for all the enhancement options with artificial substrates is: what is the technology readiness level of a specific artificial structure? Also, how large does the area need to be and how much substrate needs to be deployed to be able to reach the biodiversity enhancement objectives? To date, most biodiversity enhancement projects include small-scale pilots (e.g. Sas *et al.* 2016, 2018; Didderen *et al.*, 2018, 2019). Extrapolation to a larger scale in not yet feasible.

Option 5 includes adding artificial substrates on soft sediment. There are many examples of artificial substrates with nature-inclusive design, amongst others: Reefballs™, ReefCubes® (ARC Marine), biodegradable concrete reefs, 3D-printed concrete reefs, SubCon Artificial reefs, ECOncrete®, 'Fish hotels', drainage pipes and SeaCult reef systems (see section 4.4 and Lengkeek *et al.* 2017). Which artificial structure will be most suitable depends on the desired species, its material and its shape (large or small holes, rough or smooth surface)? Every artificial substrate has its own prerequisites, but in general they cannot cope with strong currents, and high sedimentation rates will decrease the chance of successful reef development. Additionally, for deploying artificial substrate on soft sediment, it is necessary to consider the possibility of erosion around the structure and the occurrence of sand waves. If biodiversity hotspots like wrecks are used as a structure or to enhance artificial reef performance, the regulations with respect to shipwrecks as cultural heritage may impose additional requirements for implementation. This enhancement option can be combined with the introduction of species (option 4), natural substrate (option 3) and conservation of biodiversity hotspots (option 2).

6. Deploy artificial substrates at scour protection

Scour protection is currently deployed at the base of all monopoles present in the DCS. This can be a suitable place for increasing habitat suitability and thereby enhancing biodiversity. For the most optimal design of scour protection it is advised to provide a combination of large and small-scale structures and to use substrate that mimics natural substrates, such as concrete with added chalk (Lengkeek *et al.* 2017). The scour protection of the wind turbines in the current OWFs already consists of different types of rock. Yet, to facilitate desired species, specific requirements can be met by deploying artificial substrates at the scour protection. In this way the scour protection itself and the artificial substrates can strengthen each other.

Additional to the requirements of option 5, for this option it is most important that the hydrodynamic performance of the structure is thoroughly tested. Furthermore, close to the pile currents are generally stronger, so it is advised to focus mostly on the outer edge of the scour protection (Lengkeek *et al.* 2017).

4.3 Enhancement options potential in OWFs

The opportunities for enhancement options depend on the environmental requirements of the enhancement options (focal species and substrates) on one hand and the relevant environmental characteristics of the OWFs on the other hand. The most limiting factors for the focal species and substrates in each OWF are briefly discussed. The resulting scores for the enhancement potential for the five different reef building species is presented in Table 4.3. As mentioned in section 4.1, these scores are based on expert judgements and the "learning by doing" approach of the enhancement projects will collect more detailed information in the near future.

4.3.1 Enhancement options focal species

Flat oyster

Flat oysters are mainly limited by their settlement requirements (ideally large shells on soft sediment) and short dispersal distance of the larvae. The opportunities for flat oyster enhancement in OWFs have been analysed in detail by Smaal *et al.* (2017) and Kamermans *et al.* (2018) and summarised in Bos *et al.* (2019). The relevant environmental factors are seabed shear stress, seabed motility, suspended sediment (SPM), food concentration and larval retention. The best conditions are found in Gemini and Borssele, where the larval retention is high and seabed shear stress and motility are relatively low. Moderately suitable conditions are found in Egmond aan Zee, Prinses Amalia, Luchterduinen, Hollandse Kust Zuid en Noord, where the larval retention is moderate. The larval retention in IJmuiden Ver and Hollandse Kust West 2-4 is too low and seabed motility probably too high.

Blue mussel

Blue mussels are found on all wind turbines, mainly around the intertidal zone. This implies that larvae and (off bottom) settlement substrate are available in all OWFs. There are a few limiting factors. Starfish predation, and perhaps seabed motility, limits the opportunities for development of mussel beds on the seabed. Scour protection and biogenic reefs (in particular flat oyster reefs) can provide settlement substrate and shelter to blue mussels. Therefore, all OWFs are at least moderately suitable for mussel bed development and favourable conditions will develop in areas where flat oyster reefs will develop (e.g., Gemini and Borssele).

Horse mussel

The major limiting factors of the horse mussel are its slow growth and adaptation to a cold climate. This implies that it is very difficult and time-consuming to produce source material. In addition, during part of the year the temperature regime in all OWFs is partly outside the optimal range of the horse mussel. Under the current climate-change predictions the DCS will become less suitable for this species.

Ross worm

The major limiting factors for Ross worm are not well known. The current distribution of Ross worm at the DCS is rather patchy and far offshore (van der Reijden *et al.*, 2019; Bos *et al.*, 2019). So far it is unknown if the distribution is related to specific habitat requirements, bottom trawling disturbance or both. Based on the current distribution in the UK part of the North Sea and in the Brown Bank (van der Reijden *et al.*, 2019; Bos *et al.*, 2019), IJmuiden Ver is promising for recovery or development of Ross worm reefs and Gemini, Prinses Amalia, Hollandse Kust Zuid, West 2 and 4 and Borssele are moderately suitable.

Sand mason worm

Sand mason worms are not very selective and have a broad habitat preference. Individual sand mason worms, therefore, occur commonly in most parts of the DCS (Bos *et al.*, 2019). The occurrence of well-developed reefs (densities >1500/ m^2) is patchy and depend on specific dynamic conditions of the sediment and currents. Sand mason worm reefs have been found within the Hollandse Kust West 2 (Bos *et al.*, 2019) and therefore this area is highly promising, all other OWFs are promising because of the presence of dynamic sandy habitats.

Table 4.3. Potential of the different OWFs for enhancement of the focal reef building species in this study (adapted from Bos et al., 2019) and expert judgement. Scope for restoration or enhancement: 1=unsuitable, 2=moderately suitable, 3=favourable, 4=promising, 5=highly promising.

OWF	Horse mussel	Flat oyster	Blue mussel	Ross worm	Sand mason worm
(realised and planned)					
Gemini (Buitengaats)	1	5	3	2	4
Gemini (Zee-energie)	1	5	3	2	4
Egmond aan Zee	1	2	2	1	4
Prinses Amalia	1	2	2	2	4
Luchterduinen	1	2	2	1	4
Hollandse kust – Z	1	2	2	2	5
Hollandse kust-N	1	2	2	1	4
IJmuiden Ver	1	1	2	4	4
Hollandse kust-W 2	1	1	2	2	4
Hollandse kust-W 3	1	1	2	1	4
Hollandse kust-W 4	1	1	2	2	4
Borssele	1	5	3	2	4

4.3.2 Enhancement options substrates

Table 4.4 presents the OWF potential for the deployment of different types of natural and artificial substrates on either soft sediment or scour protection, which is mainly based on the abiotic factors shear stress and seabed motion, since movement and sedimentation of added substrates should be prevented.

Baseline surveys (option 1) are indicated as “highly promising” and biodiversity hotspot surveys (option 2) as “promising” in all OWFs but are in fact no-regret options, which can be carried out in all OWFs. The presence of biodiversity hotspots is not certain in every OWF and therefore scored as promising. As mentioned before, option 1 and 2 are essential to measure the success of options 3 to 6.

Most OWFs are only moderately suitable for the deployment of loose shells (option 3), because of the relatively high bottom shear stress and seabed motility. In areas with low shear stress (Gemini) a higher sedimentation rate will cover small structures. Morpho-dynamic modelling of seabed motility (Hasselaar *et al.*, 2015) is needed to select the best locations within OWFs, the “learning by doing” approach with monitoring and evaluation (see also Chapter 5) will generate information to validate these models.

The deployment of larger structures of large shells (option 4, e.g. oysters) jointed by cement or other similar substances is favourable in all OWFs, because in high-dynamic conditions they are high enough to be influenced by sand movement and in low-dynamic conditions with a high sedimentation rate will remain protruded from the sediment. The Technology Readiness Level (TRL) of these “cemented large-shell structure” is currently intermediate, which mean that components are available but not yet assembled and tested.

Except for Egmond aan Zee (high bottom shear stress), most OWFs are favourable or promising (Gemini, low bottom shear stress) for the deployment of artificial substrates on soft sediment (option 5). Low sand waves occur in most OWFs, except for Gemini, Egmond aan Zee, Hollandse Kust Noord (no sand waves) and Borssele (high sand waves). This implies that within the OWFs with sand waves project locations should be selected with low motility.

The deployment of artificial structures on scour protection (option 6) is promising to highly promising in all OWFs but depends on the Technology Readiness Level (TRL), including certification with respect to safety and hydrodynamic conditions in the scour protection.

In the end, the enhancement option potential is a combination of many factors. The tables presented here should only be seen as rough indication since the final choice of an enhancement option or its design is more than simply the suitability of a substrate or a species. While looking into the different designs for artificial structures, it is very important to also consider which (community of) species will be facilitated and whether biotic and abiotic requirements of these species, in combination with the location characteristics, will be met.

*Table 4.4 Potential of the different types of substrate in combination with the different OWFs discussed in this report. 1 = not suitable, 2 = moderately suitable, 3 – favourable, 4 = promising, 5 = highly promising. * = if approved by a certifying body. The scores are based on expert judgement.*

Name OWF	**natural substrate on soft sediment**			**artifical structures**		
	small (loose shells)	**large (joint shells)**	**large stones**	**stand-alone on sediment**	**at scour protection**	**remarks**
Gemini	2	5	5	4	4-5*	probably suitable
Hollandse Kust Noord	2	5	3	3	4-5*	seabed dynamics unknown
Egmond aan zee (OWEZ)	1	3	3	1	4-5*	high shear stress and SPM
Prinses Amalia	2	5	3	3	4-5*	locally possible
Luchterduinen	2	5	3	3	4-5*	locally possible
Hollandse Kust Zuid	2	5	3	3	4-5*	seabed dynamics unknown
Borssele	2	5	3	3	4-5*	locally possible

*Table 4.5. Dutch OWFs in the North Sea and their potential for reef building species (5 species) and Biodiversity Enhancement Options (6 options). 1=unsuitable, 2=moderately suitable, 3=favourable, 4=promising, 5=highly promising. * Hydro-dynamical testing is required for deployment at scour protection and suitability could be higher.*

	OWF	**Gemini (Buitengaats)**	**Gemini (Zee-energie)**	**Egmond aan Zee**	**Prinses Amalia**	**Luchterduinen**	**Hollandse kust - Z**	**Hollandse kust-N**	**IJmuiden Ver**	**Hollandse kust-W 2**	**Hollandse kust-W 3**	**Hollandse kust-W 4**	**Borssele**
biogenic reefs	Horse mussel	1	1	1	1	1	1	1	1	1	1	1	1
	Flat oyster	5	5	2	2	2	2	2	1	1	1	1	5
	Blue mussel	3	3	2	2	2	2	2	2	2	2	2	3
	Ross worm	2	2	1	2	1	2	1	4	2	1	2	2
	Sand mason worm	4	4	4	4	4	5	4	4	4	4	4	4
enhancement options	1. Baseline	5	5	5	5	5	5	5	5	5	5	5	5
	2. Biodiversity hotspots	4	4	4	4	4	4	4	4	4	4	4	4
	3. Natural substrates deployment	5	5	3	5	5	5	5	5	5	5	5	5
	4. (Re-)introduction of reef building species	5	5	2	2	2	2	2	1	1	1	1	5
	5. Artificial substrates deployment for artificial reefs on soft sediments	4	4	1	3	3	3	3	3	3	3	3	3
	6. Artificial substrates deployment for artificial reefs at scour protection	4*	4*	4*	4*	4*	4*	4*	4*	4*	4*	4*	4*

5

Measuring success: monitoring and research

5 Measuring success: monitoring and research

5.1 Introduction

The first three steps of the management cycle of biodiversity enhancement projects, setting objectives, site selection and overview of enhancement options, have been discussed in Chapter 3 (Figure 3.1). The abiotic and biotic conditions and artificial substrates in the OWFs (Table 4.2; Appendix 2) in relation to the ecological requirements of the species building reefs and associated or benefitting from reefs have been discussed in the previous chapter. The resulting suitability scores for the reef building species (Table 4.3) and enhancement options (Tables 4.4 – 4.5) are based on expert judgement and require further validation and evaluation. This chapter provides guidelines for evaluating the ecological relationships of the focal species and success of the implemented enhancement options. From this “learning by doing” process, information can be gathered to adapt the enhancement options to the local conditions within OWFs.

In every OWF a variety of habitats are usually present, ranging from natural soft sediments (sand, silt), natural hard substrates (shells, rarely gravel and stones) and artificial hard substrates (turbines, scour protection and cable infrastructure). Biogenic reefs formed by sand mason and Ross worms may be present and blue mussels are present around the tideline of the turbines and between the scour protection. Shipwrecks may also provide artificial hard substrates. This implies that a baseline biodiversity, as identified by options 1 and 2, is already present within the OWF area.

This chapter further gives practical information on how to monitor success with an overview of methods and equipment and, because offshore field work is very expensive, give suggestions how to reduce monitoring costs by using simple techniques and combining as much activities as possible during campaigns.

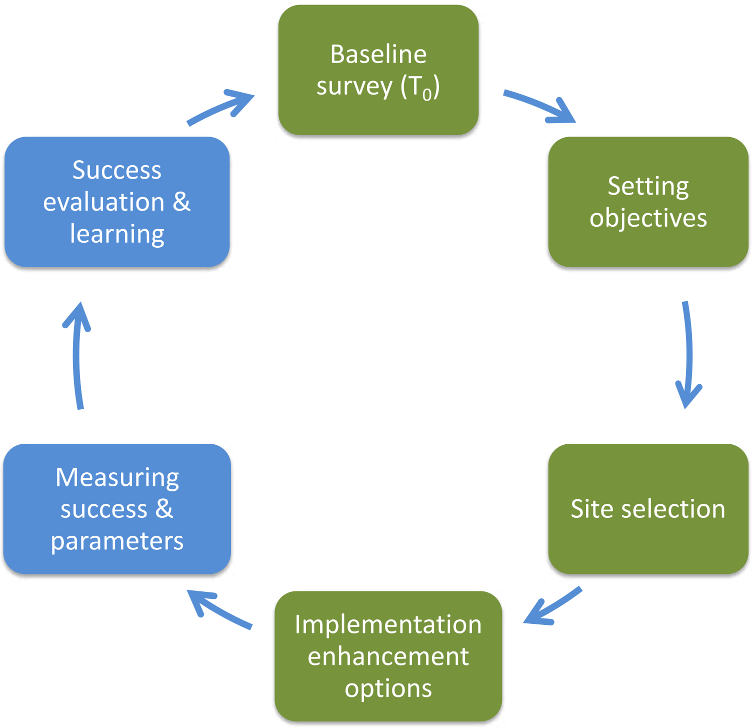

Figure 5.1. Schematic representation is given of the management cycle of biodiversity enhancement projects (adapted from Zu Ermgassen et al., 2017). The first four steps (in green) are discussed in Chapter 3. The final two steps, measuring success and learning (blue), are discussed in this chapter as part of the "learning by doing" approach.

5.2 Measuring success: Before After Control Impact comparison

Information about baseline biodiversity is important for several reasons.

- A generally accepted method to evaluate the success (or ecological impact) of interventions is to compare the biodiversity before the impact with the biodiversity after the impact. Simultaneously, the biodiversity before and after the impact is compared with a control area without the impact. This is known as the Before After Control Impact (BACI) method.
- In particular, the presence of artificial hard substrate may have already a positive impact on hard substrate related species, in particular fish and large crabs and lobsters (Coolen *et al.*, 2019).
- In addition, biogenic reefs and shipwrecks within the OWF area may need extra conservation measures against disturbance and pollution.
- Shipwrecks and biogenic reefs are excellent locations to implement enhancement options, including restoration projects.

The general advice to measure the success of enhancement options with biodiversity monitoring in OWFs is first of all an extensive general survey of all available substrates preferably before measures are implemented (also known as a T_0-survey). This type of information may already be available for existing OWFs (e.g. OWEZ, LUD, PA).

In addition, the goals and objectives of the biodiversity enhancement options should be clearly defined against the baseline biodiversity. These goals further define the specific research questions, hypotheses and monitoring activities to evaluate the success of the measures taken.

5.3 What is success?

The general aim of The Rich North Sea Programme is to enhance biodiversity within offshore wind farms (OWFs) in the North Sea by developing and implementing Biodiversity enhancement measures. The programme focusses on enhancement of biogenic reefs and associated species, which provide critical ecosystem functions within OWFs and the wider North Sea. Consequently, the general question about the success of implementing biodiversity enhancement options within OWFs is as follows:

- Is biodiversity enhancement option “x”, implemented by measure “y”, enhancing reef communities and biodiversity within and outside OWF “z”?

In other words, the success of the enhancement options can be measured by observing the biodiversity before and after their implementation. From this general question more detailed questions are derived about measuring the success of the various enhancement options, biogenic reefs, ecosystem services and ecological risks (Table A.6). These questions include the conditions, potential and knowledge gaps with respect to biodiversity enhancement options. Which options are feasible and which factors are relevant for the success? What is the efficiency of the enhancement options? And are these options also applicable outside OWFs?

The specific success parameters to measure the efficiency of the biodiversity enhancement options for both the general question and more specific questions are presented in Tables A.5 – A.6 (Appendix III). These parameters vary from the number species as a general representation of biodiversity to very specific parameters of population change and success of reef building species (e.g., growth, reproduction, survival, settlement, density). Information on the abiotic and biotic parameters, such as bottom shear stress and seabed motility which can be derived from morpho-dynamic modelling, is important for the general analysis and evaluation.

5.4 How to measure success? General step-by-step monitoring programme

The aim of the monitoring programme is to measure the success and efficiency of the specific biodiversity enhancement options implemented in the focal OWF. This implies that information about the baseline biodiversity with the OWF is essential and is most important to evaluate the impact of the measures taken.

When implementing a monitoring programme, the following steps should be taken into account:

- Assemble all available baseline biodiversity information of the focal OWF.
- If necessary, carry out a full baseline biodiversity survey, including potential biodiversity hotspots (biogenic reefs, shipwrecks).
- Specify detailed objectives for your biodiversity enhancement options.
- Define your enhancement strategy with respect to safety requirements in the focal OWF, legal requirements, scale, available funding and ambition level.
- Choose a set of biodiversity enhancement options for implementation and select the best localities within the OWF.
- Identify the research questions and hypothesis linked to the enhancement options.
- Quantify, as much as possible, the factors that indicate success for each measure.
- Define an experimental or BACI design.
- Select the monitoring parameters, which are linked to the objectives and experimental design.
- Set up a cost-efficient monitoring programme, including standardisation and cooperation with other OWF to reduce costs.
- Evaluate monitoring programme, measures and objectives.

5.5 Overview of monitoring methods[1]

Time, weather and financial constraints determine the opportunities for offshore activities including remote sensing, sampling and deployment of materials. Therefore, the monitoring methods as described below are ranked according to the costs, which are mainly determined by the type of ship required, dependence on weather and tide, number of staff, type of staff and research material needed. In addition, some tasks can be done simultaneously during a whole day at sea, others only can be carried out shortly before and after the turn of the tide. These requirements and conditions are summarised in Table 6.2.

Monitoring methods include (a) biodiversity observations with remote sensing techniques including sonar, video cameras and ROV, (b) biodiversity sampling by taking samples of water and sediments and (c) biodiversity research equipment including deploying and retrieving materials and research devices to study the performance of reef building species. Most of the collected images and samples are subsequently stored and analysed at, respectively desktop and in the laboratory.

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[1] Diving is arguably one of the most effective ways to carry out underwater observations, sample reef communities and place specialist research equipment. Diving however, is currently not permitted in Dutch offshore wind farms. Therefore, the monitoring techniques described in this chapter do not involve diving.

5.5.1 Biodiversity observations

Sonar

Large-scale “remote sensing” observations of the sea floor can be carried out by sonar equipment including side-scan sonar and multi-beam sonar (MBES) on a vessel. Most biogenic reefs, soft sediments, geogenic hard substrates (gravel, rocks, shells) and shipwrecks give a specific backscatter pattern (refs). Low acoustic frequencies carry deeper into the sediment and higher frequencies are better in detecting hard substrate structures. OWFs can be surveyed by sailing transects to reach full coverage. Regular offshore vessels and crew can carry out small-scale surveys, specialized companies usually carry out full coverage acoustic surveys of OWFs. Sonar surveys can be carried out independently from the tide and with high turbidity and low visibility.

Video camera

Video cameras in ROVs, sea drones, towing frames or attached to a frame and line (dropcam) can be used for biodiversity surveys of the sea floor, scour protection, turbine foundation and wrecks. Camera surveys can be performed during the time window around the turning of the tide and under conditions with low turbidity and high visibility. Observations are limited to epifaunal species attached to hard substrates and living on top of the soft sediments. Mobile species such as fish may be under-recorded due to disturbance by the camera. These observations can validate the habitat mapping by the sonar observations.

Baitcam

Mobile species such as fish, crabs and lobsters can be attracted to the camera with bait (baitcam). This prevents disturbance by the movement of the camera frame or ROV. Bait cam observations are even more efficient during the night with red light and can attract overall more species than during the day (ref). Cameras can be positioned in the morning and collected the following day. Therefore, baitcam operations can be done simultaneously with other activities.

5.5.2 Biodiversity sampling

Water

Water samples to determine various biotic factors can be taken within OWFs during the whole day independently from the tidal cycle. Chlorophyll-a content is measured as a proxy for the abundance of phytoplankton, an important food source of most biogenic reef species. Additional information of Chlorophyll-a content on a large scale is taken from a remote sensing databank. Special filtration will isolate eDNA for species detection in the laboratory. Larvae, phytoplankton and zooplankton can be isolated by filtration through a fine-meshed plankton net and identified and counted in the laboratory. Abiotic factors in the samples can be determined in the laboratory and include the concentration of suspended particulate matter (SPM) as a measure of turbidity, PH, O_2 content and salinity.

Sediment

Special grab equipment can be used to take sediment samples for further laboratory analysis. This type of sampling can give information on the animals in the sediment (infauna), grain size (sand or silt), organic content and density of dead shells (shelliness). The shelliness is an important factor for the settlement of marine animals (epifauna).

Live animals

Biogenic reefs can be kick-started by introducing live animals (in particular shellfish like flat oysters) directly on the sea floor or by deployment in contained units. The introduced animals can be followed visually with video cameras (dropcam or in a tow frame) or investigated in detail by retrieving the animals in contained units. The video camera observations can provide relatively low-cost information on growth, survival and recruitment of biogenic reef species, but only under excellent observation conditions (high visibility, moderate current, calm sea). The costly retrieval and laboratory analysis of animals in contained units can generate highly detailed information population change parameters (Tables A1-A2; Appendix 2). Retrieval is possible during favourable weather and independent of visibility.

5.5.3 Biodiversity research equipment

Data loggers

Data loggers can collect an environmental data in a cost-efficient way, such as sound, temperature, oxygen concentration, salinity and turbidity. The combination of bottom water temperature and oxygen concentration is important in relation to the occurrence of temperature stratification during the summer period. Data loggers can be attached to contained units (cages, racks) or to buoys with acoustic release.

Contained units

Live animals and settlement substrate can be deployed in contained units (basket, cage, rack) on the sea floor, which are designed to withstand high wind-driven current speeds and but also sand wave dynamics. The hydrodynamic performance of these units should be tested for safe deployment within OWFs. In addition, the mesh size of the units should be wide enough for exchange of water and phytoplankton to provide enough food for the filter-feeding biogenic reef species.

5.5.4 Laboratory and desktop analysis of biodiversity

Video camera observations

The analysis of video camera footage needs to be checked in the office. Automated image analysis software has been developed to assist in the identification and make video analysis more cost-efficient.

Analysis of live animals

Live animals, which are introduced to the sea floor directly of in research cages, are usually measured preferably shortly before deployment. After retrieval they have to be preserved (freezer and/or ethanol) for later analysis in the laboratory. For the determination of gonad development after retrieval, the animals are kept alive. These activities can be carried out after the major fieldwork.

Table 5.1. Overview of offshore biodiversity observations, sampling and equipment and onshore laboratory and desktop analysis.

Activity	**Method**	**Parameters**
Observation	MBES (sonar)	sediment type location substrate type biogenic reefs
Observation	Video camera	biogenic reefs epifauna shelliness
Observation	Baitcam	fish, crabs, lobster
Observation	ROV	epifauna biodiversity
Sampling	Water samples	SPM (turbidity) PH, O2, Salinity, eDNA (biodiversity)
Sampling	Water samples & plankton net	#larvae chlorophyll-a concentration plankton
Sampling	Sediment core sampling	benthos sediment
Sampling	Pods	fish, crabs, lobster
Sampling	Nets	fish
Retrieve units	Contained units live animals	whole animals
Retrieve units	Contained units substrates	substrates
Lab/ship	Measuring whole animals	size
Lab	Inspecting whole animals	sex ratio gonads fish guts diseases
Lab	Inspecting substrates, epifauna	biodiversity #recruits
Lab	Chemical analysis	isotopes trace elements
Lab	Identification benthic animals	biodiversity
Lab	Sediment analysis	grain size organic content shelliness

5.6 Cost estimates of measuring success, advice cost-efficient monitoring

The cost of offshore monitoring activities generally depends on the number of staff needed, the experience level and vessel size (Table 5.3, the mobilisation/demobilisation costs are not included because they highly depend on the size of the vessel). In addition, visual observations with video cameras and the deployment of research equipment highly depend on calm weather and a relatively short time window around the turn of the tide. Other monitoring activities, including acoustic observations with sonar and water and sediment sampling are less dependent on weather and tide.

The potential to combine activities is also an important factor and in Table 10 the cost estimate is expressed as the middle of a range (+/- €5000) if only a single activity would be carried out. The activities, which depend on the time window around the turning of the tide, are difficult to combine during this time window. However, before and after this time window most other monitoring activities can be carried out while waiting for the tidal time window. In general, remote sensing with sonar and video camera and sampling techniques require fewer and less qualified staff, while deployment of contained units with substrates and live animals requires more and highly qualified staff in the field and in the laboratory.

Additional reduction of costs can be achieved by combining research equipment (data loggers) and contained units with acoustic release options which can deployed by relatively small vessels and non-scientific staff.

Table 5.2. Cost estimate of measuring success with biodiversity observation, sampling, equipment and laboratory analysis is determined by number of staff, experience level of staff, vessel type, dependence on weather and tide and the potential to combine activity with other monitoring activities and excluding mobilisation/demobilisation costs. The (conservative) cost estimate (in K€/day)) is the median of a range (+/- K€5) and is based on one activity per day. Staff experience level: 1=low, 2=moderate, 3=substantial, 4=high; vessel type: 1=small, 2=intermediate, 3=large; weather and tide dependence and combination potential: 1=low, 2=moderate, 3=substantial, 4=high, n.r.= not relevant.

Activity	monitoring methods	#staff	experience level	vessel size	weather dependent	tide dependent	combination potential	Cost (K€/day)
observation	MBES (sonar)	1	1	1	1	1	4	10
observation	video camera	2	2	1	4	3	2	20
observation	Baitcam	1	2	1	3	3	4	10
observation	ROV	2	3	2	4	4	1	20
sampling	water samples	1	1	1	1	1	4	10
sampling	water samples & plankton net	1	1	1	2	2	4	10
sampling	sediment core sampling	1	1	1	3	3	4	10
sampling	Pods	1	1	1	2	2	4	5
sampling	Nets	1	1	1	2	2	4	5
retrieve racks	research cages live animals	2	2	3	4	4	1	30
retrieve racks	research cages substrates	2	2	3	4	4	1	30
lab/ship	measuring whole animals	1	3	n.r.	n.r.	n.r.	n.r.	1
lab	inspecting whole animals	1	4	n.r.	n.r.	n.r.	n.r.	1
lab	inspecting substrates, epifauna	1	4	n.r.	n.r.	n.r.	n.r.	1
lab	chemical analysis	1	2	n.r.	n.r.	n.r.	n.r.	1
lab	identification benthic animals	1	4	n.r.	n.r.	n.r.	n.r.	1
lab	sediment analysis	1	2	n.r.	n.r.	n.r.	n.r.	1

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Appendix I Distribution of biogenic reefs in the Dutch part of the North Sea

Figure A.1. Distribution of Horse mussel observations in the Dutch part of the North Sea (Bos et al., 2019).

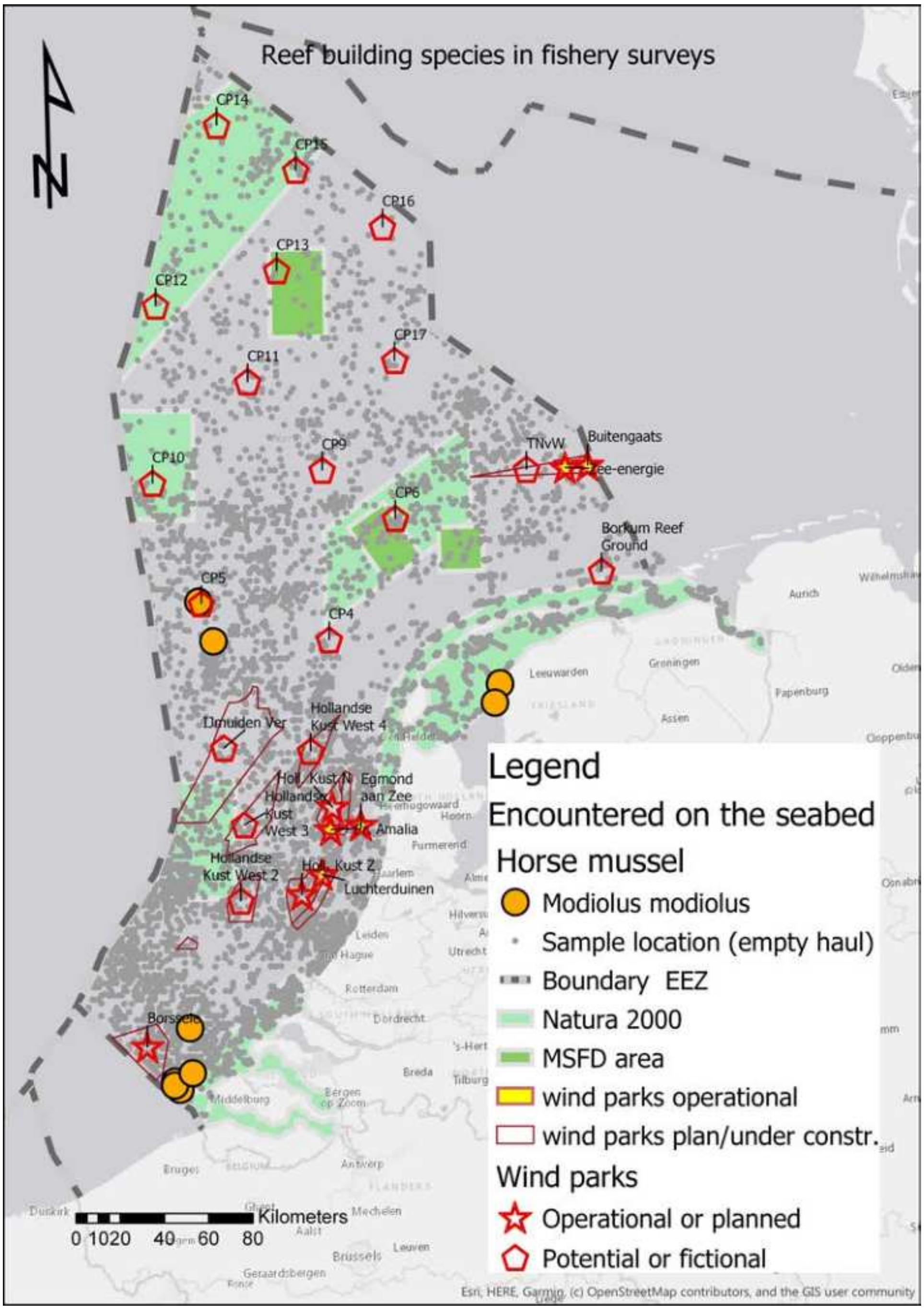


Figure A.2. Suitability of selected locations in the Dutch part of the North Sea (Bos et al., 2019).

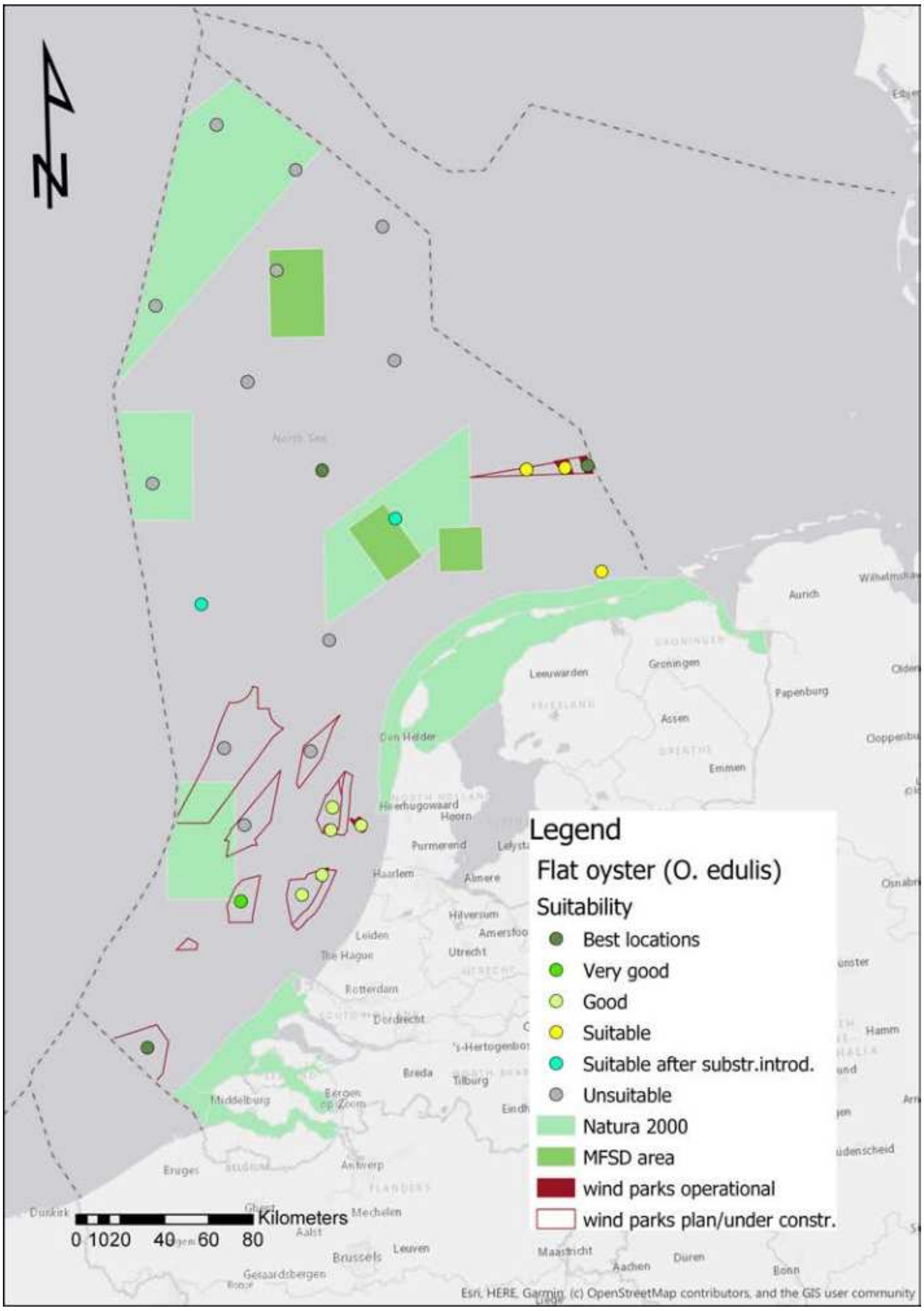


Figure A.3. Habitat suitability of the Dutch part of the North Sea for the Blue mussel (Bos et al., 2019).

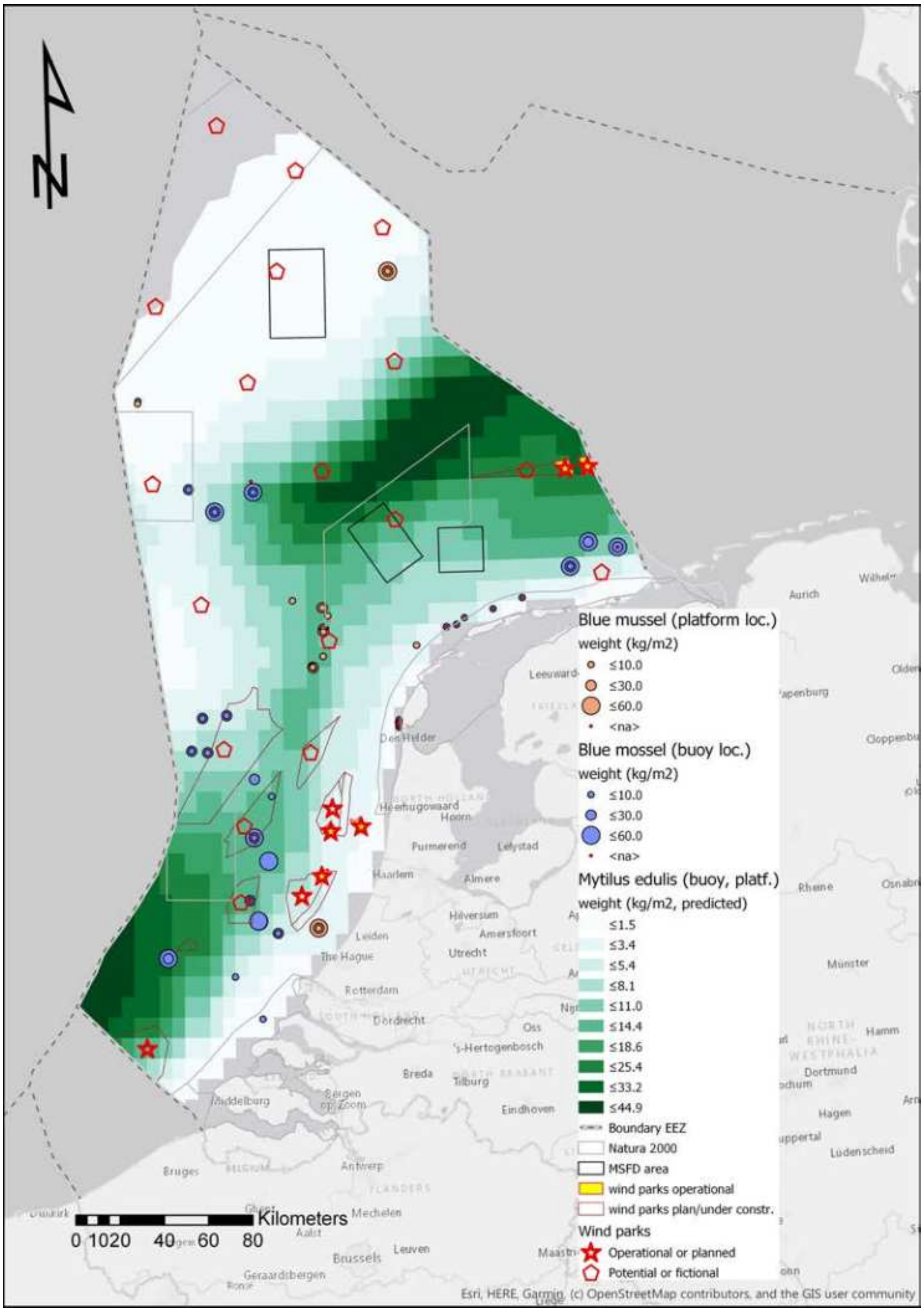


Figure A.4. Distribution of biogenic reefs formed by Ross worms and suitability of selected locations in the Dutch part of the North Sea (Bos et al., 2019).

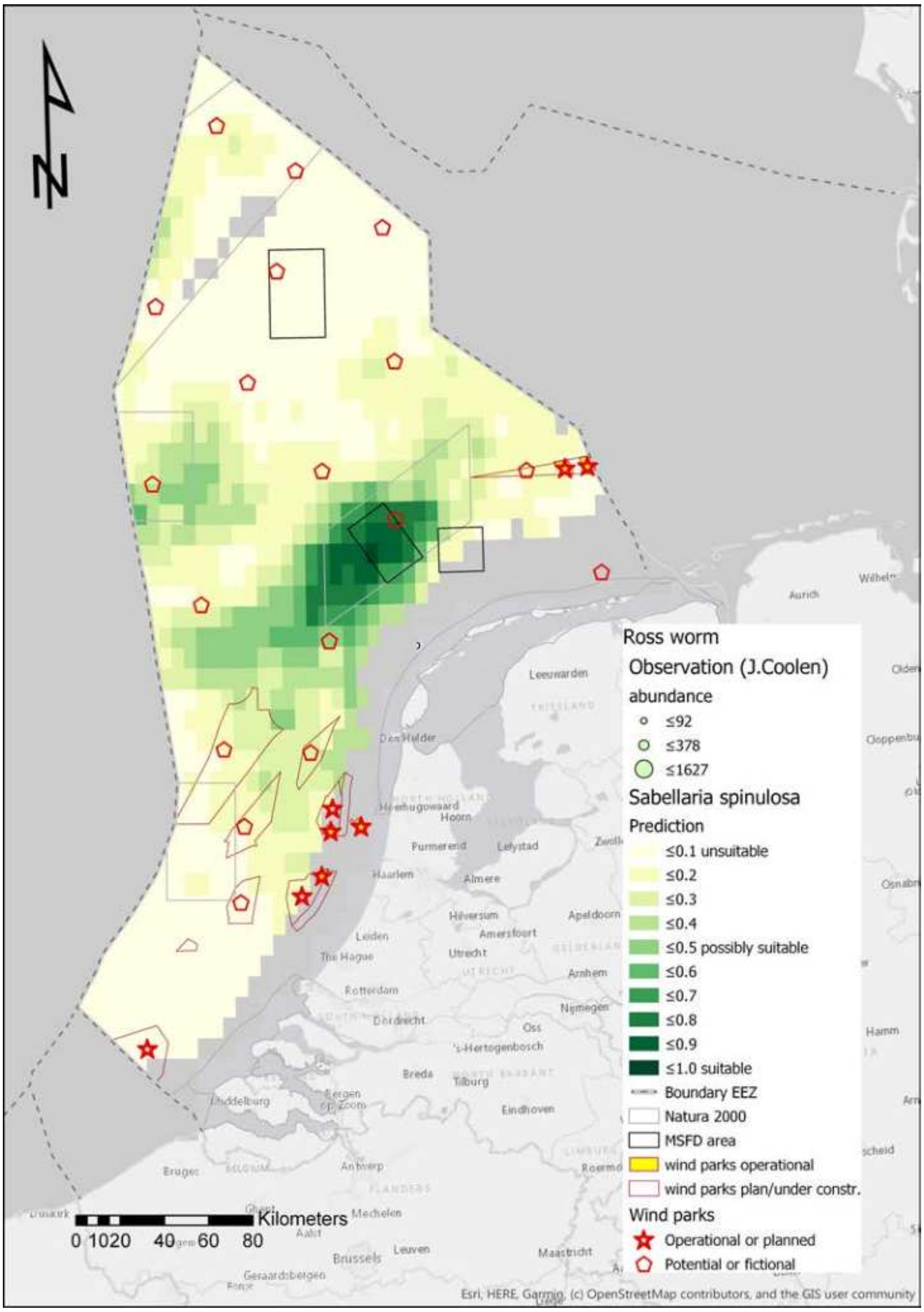
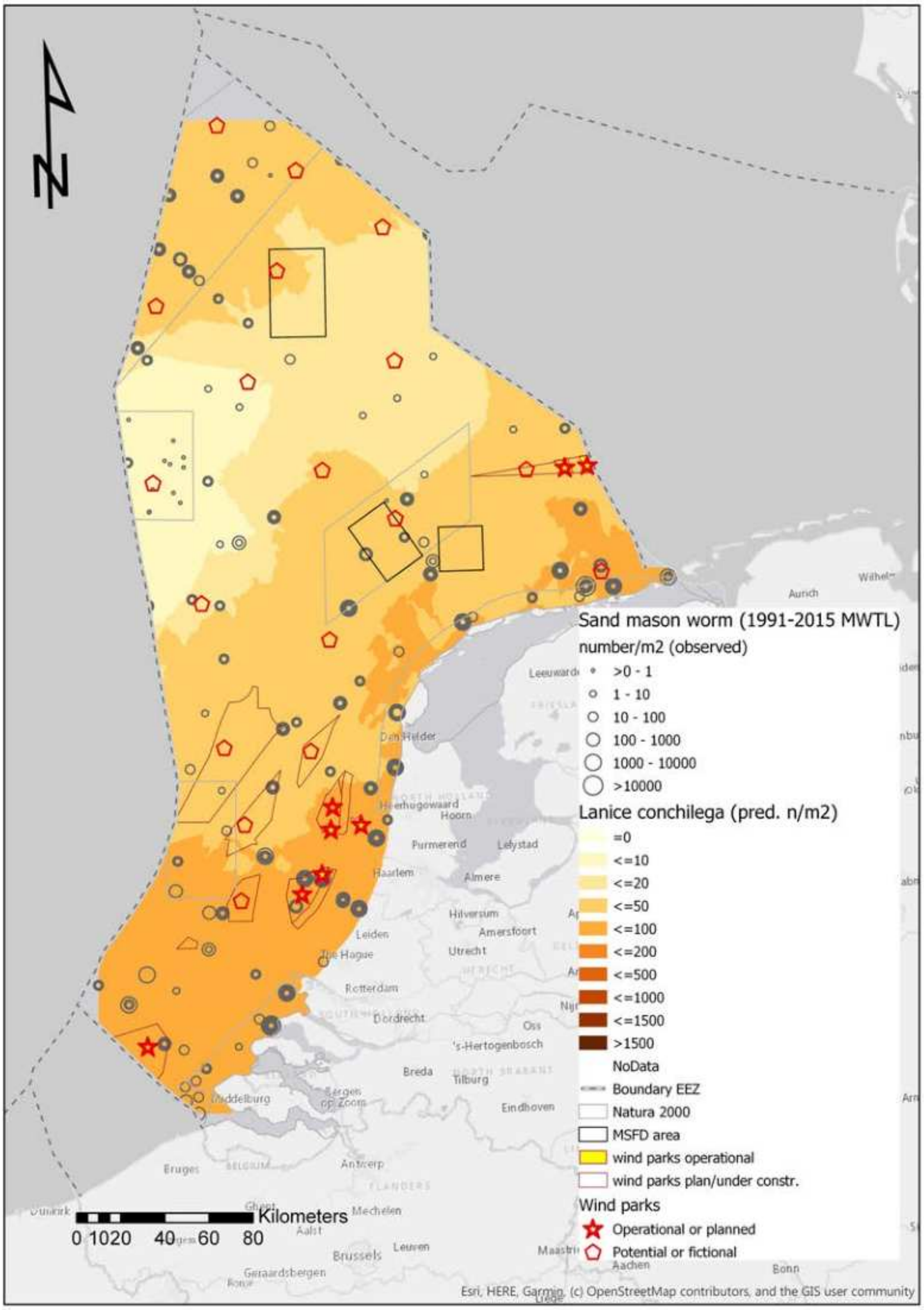


Figure A.5. Distribution of biogenic reefs formed by sand mason worms and suitability of selected locations in the Dutch part of the North Sea (Bos et al., 2019).



Appendix II OWF characteristics

Artificial substrates

Scour protection

To prevent erosion around the windmill piles, scour protection was deployed at all Dutch wind farms currently in operation. The combined action of currents and waves around a monopile creates high flow velocities and different turbulent structures (vortices). Because of these flows, the bed shear stress increases, which typically extends up to one pile diameter from the pile (Lengkeek *et al.*, 2017). There are differences in scour protection between the different wind farms, but most commonly applied scour protection methods consist of a few layers of rock. The armour layer is the top layer and consists of sufficiently heavy loose stones. Next, a filter layer with smaller rocks is applied to prevent material escaping from underneath. The extent of the layers is typically 3 to 4 times pile diameter for the armour layer and 5 to 6 times the pile diameter for the filter layer. The general trend is that the grain size of the armour rocks is getting smaller from the first OWF onwards, since the stones were located more sheltered (Lengkeek *et al.*, 2017). In addition to the scour around the pile, there is edge scour. In the wind farms off the Dutch coast the flood velocities are dominant over the ebb velocities, causing erosion North-East of the scour protection (Lengkeek *et al.*, 2017).

Cables in the DCS

There are different cables present at the bottom of the North Sea (Figure A.6). For instance, direct current transmission cables between the Netherlands and Norway and the Netherlands and the UK. Additionally, all OWFs are connected to shore and have infield cables to connect the turbines to offshore transformer stations. The electromagnetic field strength of the export direct current cables is 100-300 μT, export alternating current cables is 5-50 μT and alternating current infield cables is about 5 μT (Snoek *et al.* 2016).

Figure A.6 Top: cables (green) and pipelines (blue) in the DCS (from Snoek et al 2016). Bottom: Typical layout of a OWF, a) wind turbines b) infield cables c) export cables d) transformer station e) converter station f) meteorological mast g) onshore station (figure from Rodrigues, 2016).

Shipwrecks at the DCS and their biodiversity

Shipwrecks in the North Sea are part of our cultural heritage and many have been present since decades or even centuries. They provide artificial hard substrate in a predominantly soft sediment environment and give shelter against bottom disturbance and are as result important marine biodiversity hotspots (Didderen *et al.*, 2013; Lengkeek *et al.*, 2013). The distribution of 100 relatively large shipwrecks in the DCS in given in Figure A.7 & A.8 relative to the position of the actual and planned OWFs. Shipwrecks are present in the plan wind farms in Hollandse Kust Zuid, Hollandse Kust Noord en Hollandse Kust West 3.

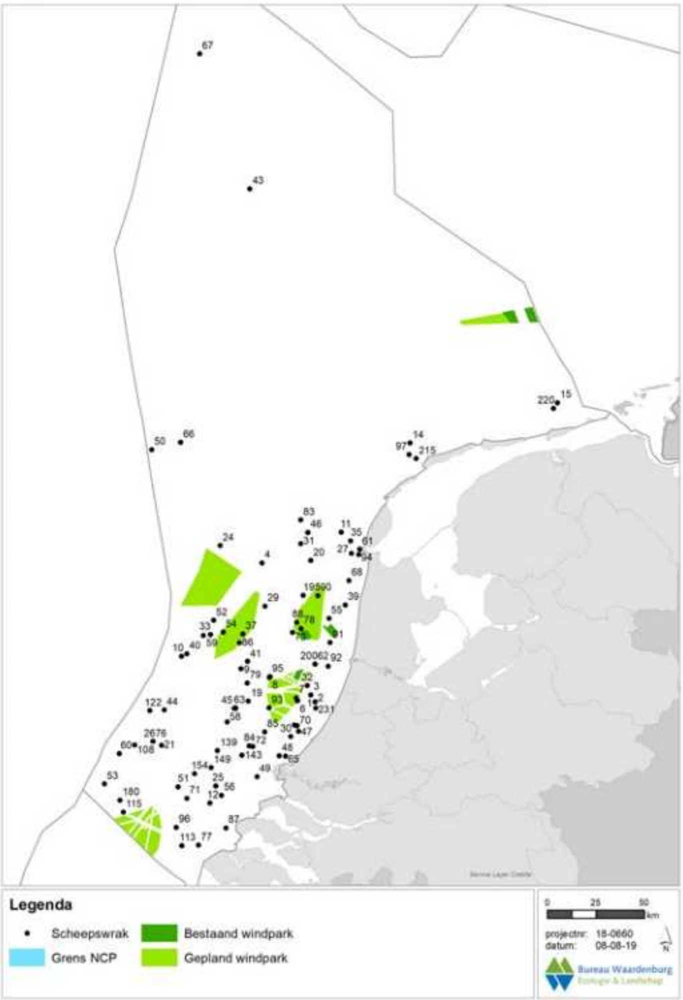


Figure A.7. Distribution of relatively large shipwrecks in the DCS and the position of actual and planned OWFs (source: Didderen et al., 2013; Lengkeek et al., 2013).

Figure A.8. Distribution of relatively large shipwrecks in the DCS and the position of actual and planned OWFs shown in more detail for the southern North Sea (source: Didderen et al., 2013; Lengkeek et al., 2013).

Abiotic habitat characteristics

In this paragraph a number of relevant physical characteristics are discussed which are important for biodiversity enhancement in OWFs. The factors are shown independently, without considering the interactions between factors.

Substrate type

The substrate type and sediment composition determine amongst others the suitability for occurrence and recruitment of biogenic reefs. The availability of shells and the sediment grain size are important parameters. In general grain sizes vary according to local currents, with coarser sand in the south of the DCS and finer sand of mud to the north (Figure A.9-A.10).

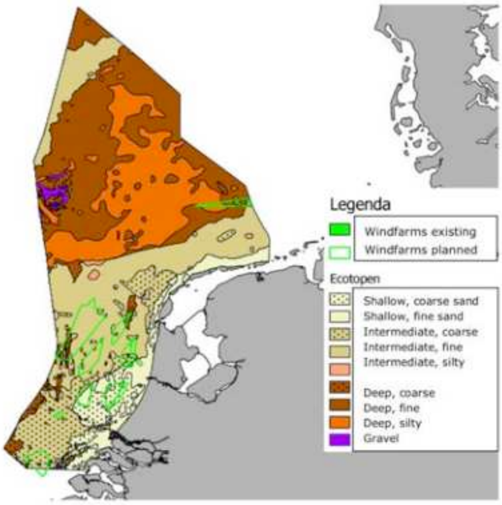


Figure A.9 Sediment composition in the Dutch Continental Shelf, with windfarm areas depicted in green (from Smaal et al, 2017).

Figure A.10 EUNIS habitat map of the Dutch coastal zone (data: EUSeaMap 2019 EMODNET). Yellow shades represent sand, brown shades coarser sediment and green shades sandy to fine mud.

Water depth and water temperature at the bottom

The North Sea is a relative shallow sea. Most OWF are constructed at depths between 20-40 meters (Figure A.11). The average temperatures near the seabed are between 3 in winter and 20 degrees Celcius during summer (Figure A.12). Depth and water temperature mainly affect growth, condition and survival and the latter also being important for the reproduction of many organisms, among which flat oysters.

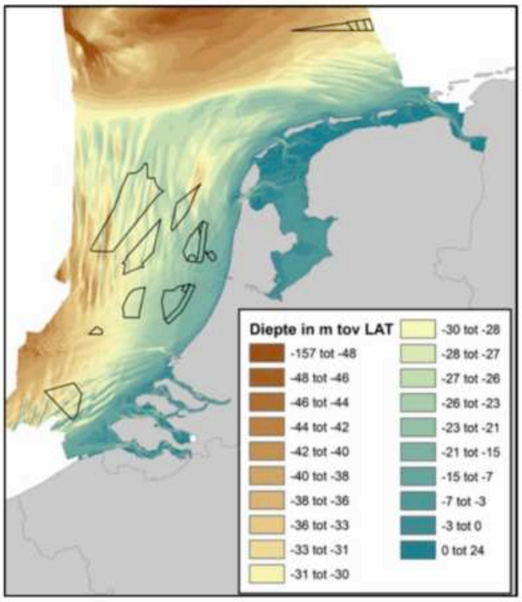


Figure A.11 Water depth (m) within the DCS relative to Lowest Astronomical Tide, black lines indicate the wind farm sites seabed (from Smaal et al. 2017).

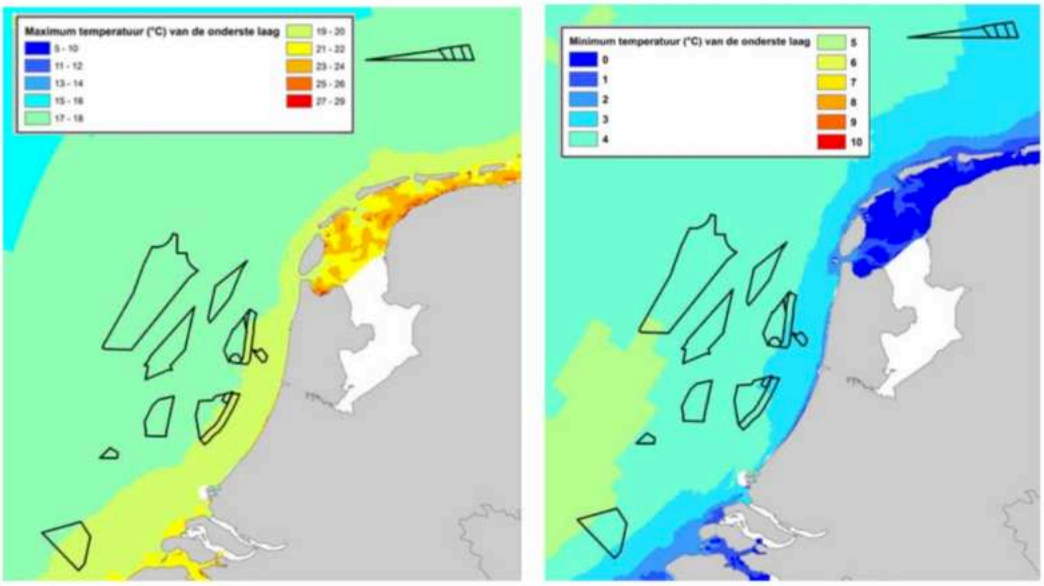


Figure A.12 Modelled maximum (left) and minimum (right) annual water temperatures (°C) near the seabed (from Smaal et al. 2017).

Seabed shear stress

Since the DCS has predominantly a soft sediment seabed and generally lacks rocky substrate or geogenic reefs, sediment dynamics and hydrodynamics play an important role in shaping the physical conditions characterising the North Sea.

Bottom shear stress is used as a measure for local bed dynamics, depending of surface roughness and current velocity. The current velocity depends on the tidal movement and the extent in which wave energy reaches the seabed. In general, in the DSC and especially close to the coast, waves are responsible for most forces on the seabed. The average and maximum seabed shear stress is high in the English Channel, along the coast and at the Dogger Bank (Figure A.13-A.14). Although the maps shown here give the general picture, it is possible that local conditions may provide shelter from hydrodynamic forces, such as stones or reefs.

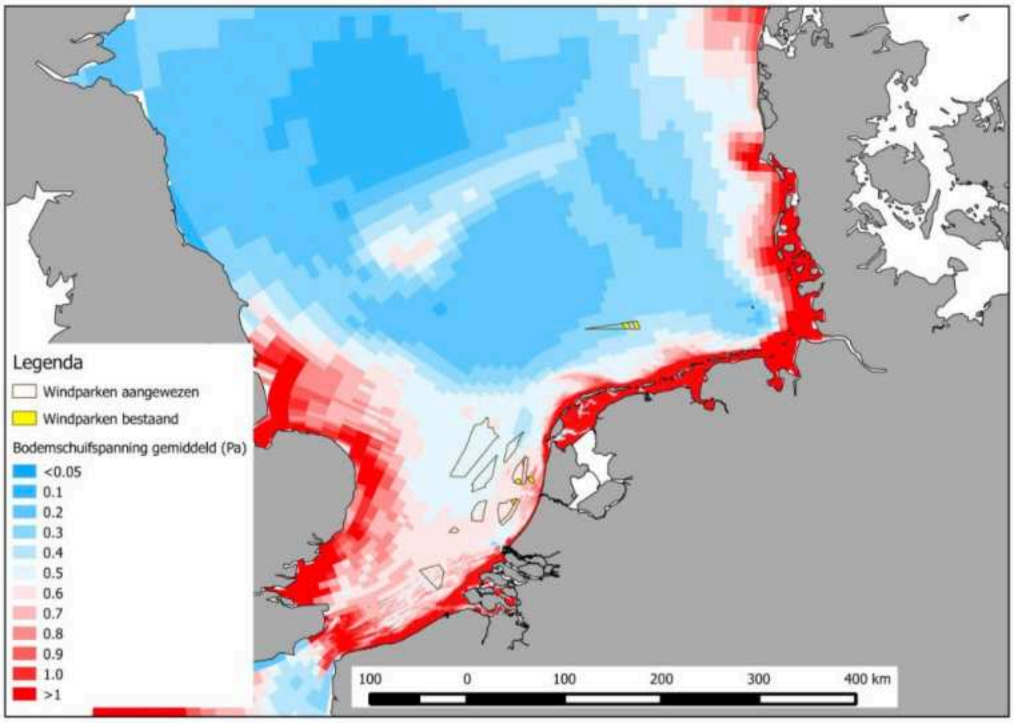


Figure A.13 Average seabed shear stress (in Pascal) in the North Sea. The locations of the OWFs are depicted. (From Smaal et al. 2017).

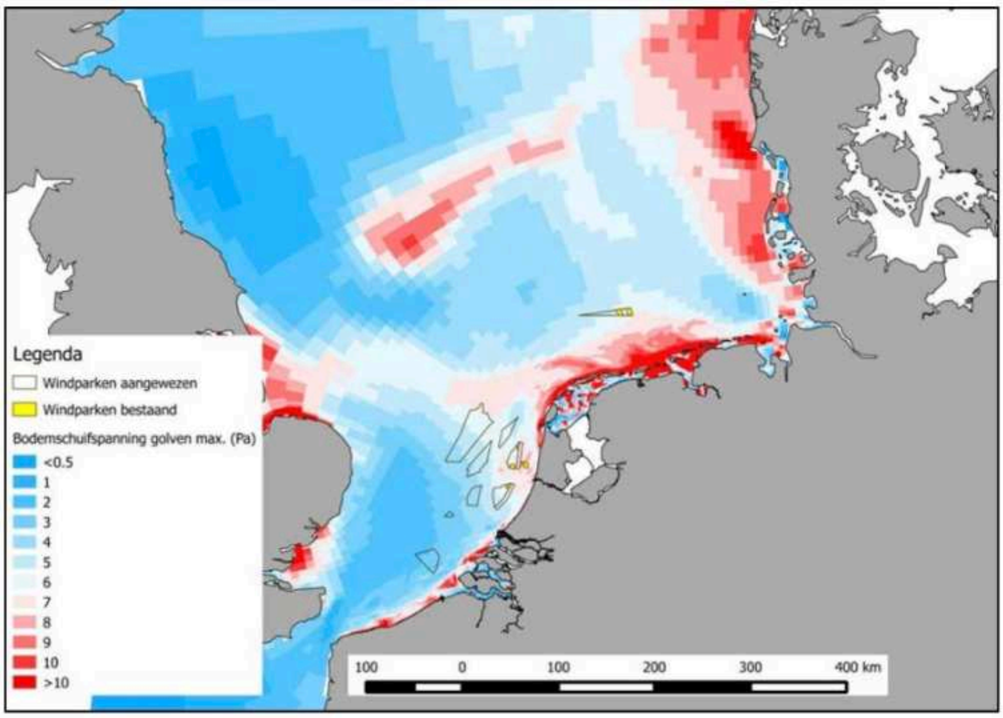


Figure A.14 Maximum seabed shear stress (in Pascal) in the North Sea. In addition, the locations of the OWFs are depicted. Note the 10-fold difference in colour scale with previous map. (From Smaal et al. 2017).

Seabed motion

Erosion and deposition of sediment takes place at the seabed. Bed motion describes the bed dynamics on a larger scale: the geomorphology of the seabed. A distinction can be made between sand banks, sand waves and mega ripples (Figure A.15), which range respectively from stable, large (> 5km) and high (> 10m) to unstable, small (0.6-30m) and low (0.06-1.5m). Sand waves move with a speed of 0-20m/yr and mega ripples move with speeds of 30-40m/yr (Kamermans *et al.* 2018). However, this is usually not a gradual process, but occurs mainly during brief episodes of stormy weather.

These processes of sediment transport can influence the suitability for reef building species especially the highly dynamic areas are unsuitable for reef establishment. In general, the sand waves are most important to take into consideration for the creation of biogenic reefs, although the mobility of mega ripples can probably affect biogenic species as well (Kamermans *et al.* 2018). *Sabellaria* reefs were recently found in valleys of sand waves in the Brown Bank area (Van der Reijden *et al.* 2019).

Mobile sand waves occur among others in the southern and western part of the Dutch Continental Shelf (DCS) (Figure A.15). It is thought that Borssele is the most dynamic site of the OWFs studied here (Smaal *et al.* 2017). At this site, the wavelength varies from 114 to 513 m, wave height varies from 1.4 to 7m and propagation speed varies from 0.6 to 3.2m per year (Smaal *et al.* 2017).

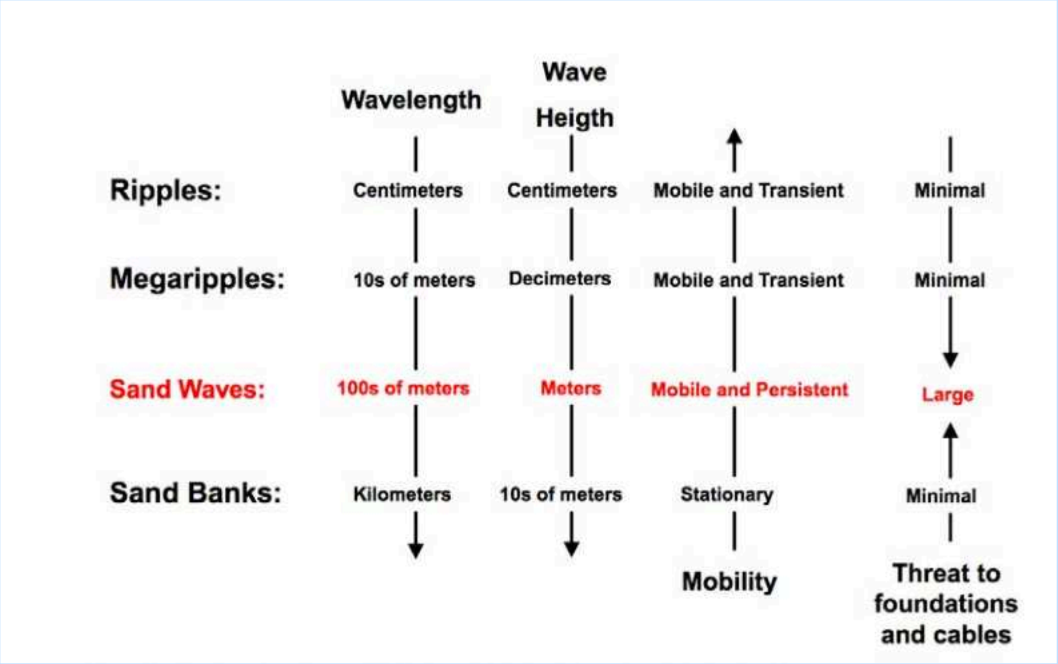


Figure A.15 Characteristics of morpho-dynamical seabed features. (From Hasselaar et al. 2015)

Suspended Particulate Matter (SPM)

All reef building species in this study are filter feeders and the concentration of suspended particles is an important factor for their growth. High levels of suspended, inorganic matter inhabit growth, as inorganic matter cannot be used for their metabolism. Yet, bivalves can close their shell and are therefore able to withstand short periods of high SPM (Suspended Particulate Matter) concentrations, for instance during stormy weather (Kamermans *et al.* 2018).

Model calculations are performed of the SPM in the bottom layer (Figure A.16). These maps show highest SPM concentrations in the shallow coastal waters. Furthermore, high maximum SPM concentrations can be found further off the coast as well. The average SPM is high along the coast and in the Wadden Sea, but low further offshore (Figure A.16).

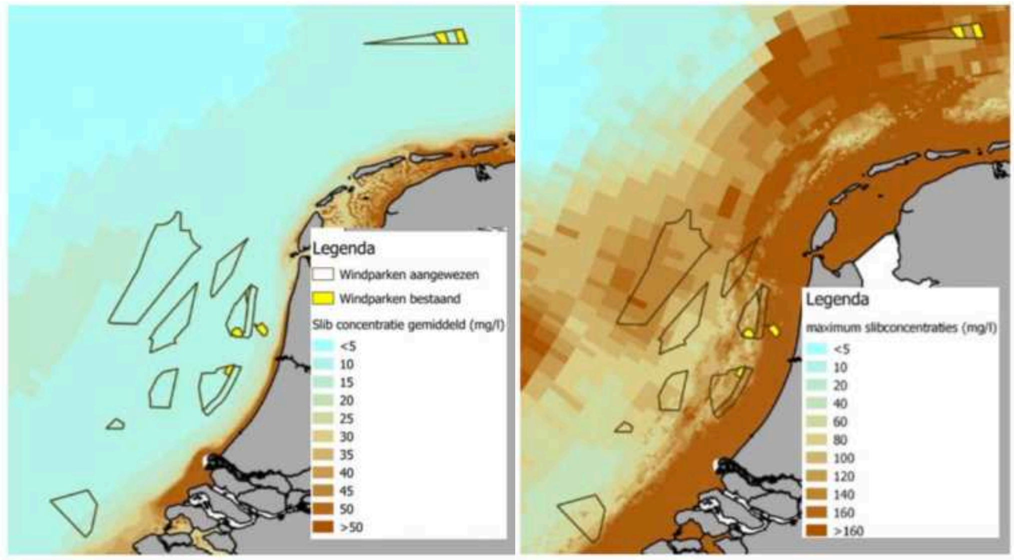


Figure A.16 Modelled average (left) and maximum (right) suspended particulate matter at the bottom layer in the Dutch coastal zone. (From Smaal et al. 2017).

Salinity

The salinity level in the DCS is about 35 psu and shows a low variability over the year (Maar *et al.* 2011). Close to the coast the salinity level is lower because of freshwater input from rivers (Figure A.17).

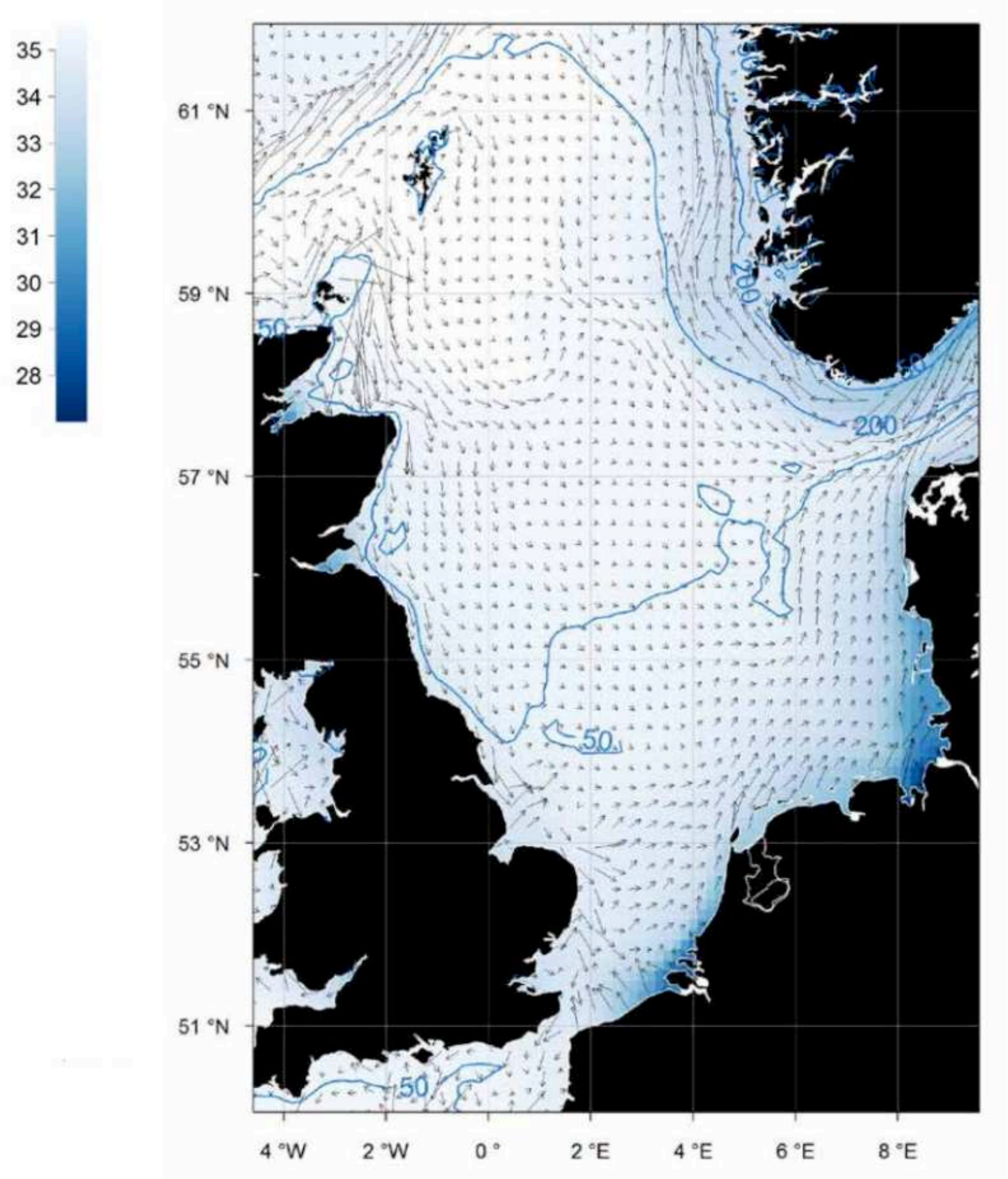


Figure A.17 Mean surface salinity (psu) in the North Sea, arrows indicate water current direction. (From Herman et al. 2014).

Oxygen content

Oxygen is an important factor for survival, although most reef building species can survive without oxygen for a short period of time. In general, oxygen supply is probably not limited at the wind farm locations considered in this study since there is no prolonged stratification here (Smaal *et al.* 2017; Kamermans *et al.* 2018). However, at the central part of the North Sea oxygen depletion occurs occasionally in areas with seasonally or permanent temperature stratification (Figure 5.15), especially in the Oyster grounds and north of the Dogger Bank (Figure A.18). Furthermore, following the GETM-ERSEM data (Figure A.18 right) Gemini and Borssele might also experience lower oxygen saturation during summer.

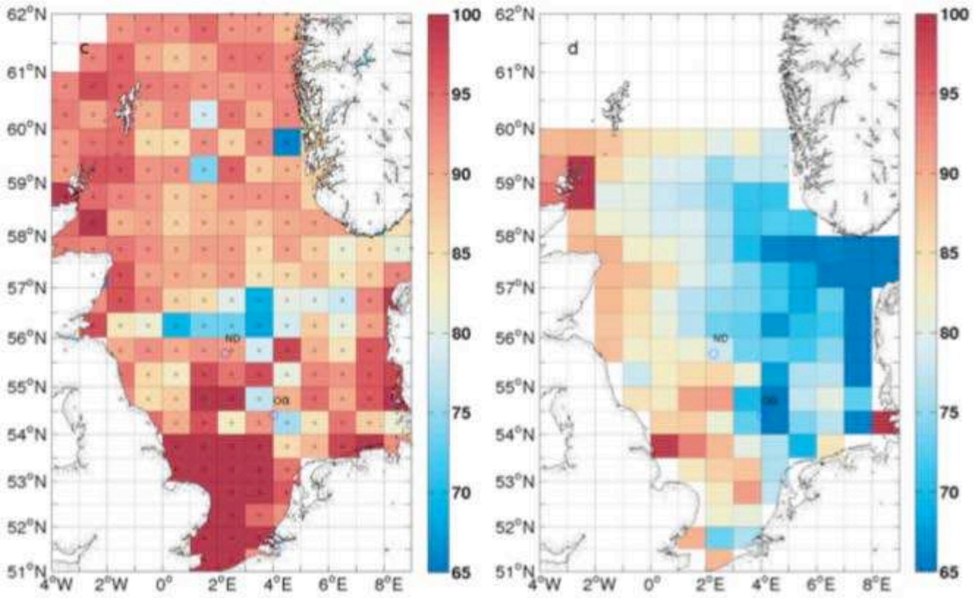


Figure 5.18 Mean summer oxygen saturation at the bottom (%) of the North Sea. Left: data form 1900-2000 from the ICES database and right: data from 1958-2008 from the GETM-ERSEM. OG = oyster grounds and ND = north of the Dogger bank. From Queste et al. 2015.

Biotic factors

Food concentrations, related to stratification regime

The availability of phytoplankton is an important factor for growth, reproduction and survival. For flat oysters, especially the spring and summer plankton concentrations are important for gonad development and larval development respectively (Smaal *et al.* 2017). The chlorophyll-a concentrations are influenced by seasonality (Table A.4, Figure A.20), in particular by temperature stratification. This is when water masses do not mix and from layers, which occurs mostly in spring and summer. This results in lower chlorophyll-a concentrations near the seabed, and possibly limiting conditions for benthic life (Kamermans et al 2018). The North Sea can be divided into areas with different stratification regimes (Figure A.19). The southern part is permanently mixed or intermittently stratified (<40 days), close to the coast is a region of freshwater influence (ROFI), and other regions are seasonally stratified (in summer) or are highly variable and therefore not classifiable (van Leeuwen *et al.* 2015). Since biological activity is mainly driven by light and nutrient availability, these regimes influence phytoplankton dynamics.

In areas with short term or no stratification the colonial algae *Phaeocystis* dominates, and prolonged stratification results in diatom-based food webs (van Leeuwen *et al.* 2015).

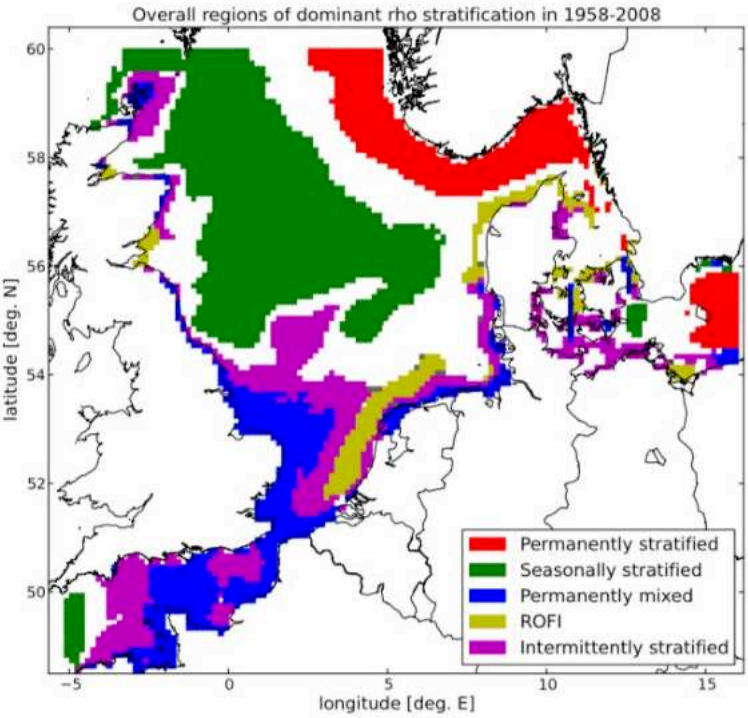


Figure A.19. Different stratification regimes in the North Sea: transparent areas indicate that the dominant regime occurs less than 50% of the time. ROFI: 'region of freshwater influence'. (Source: van Leeuwen et al. 2015.)

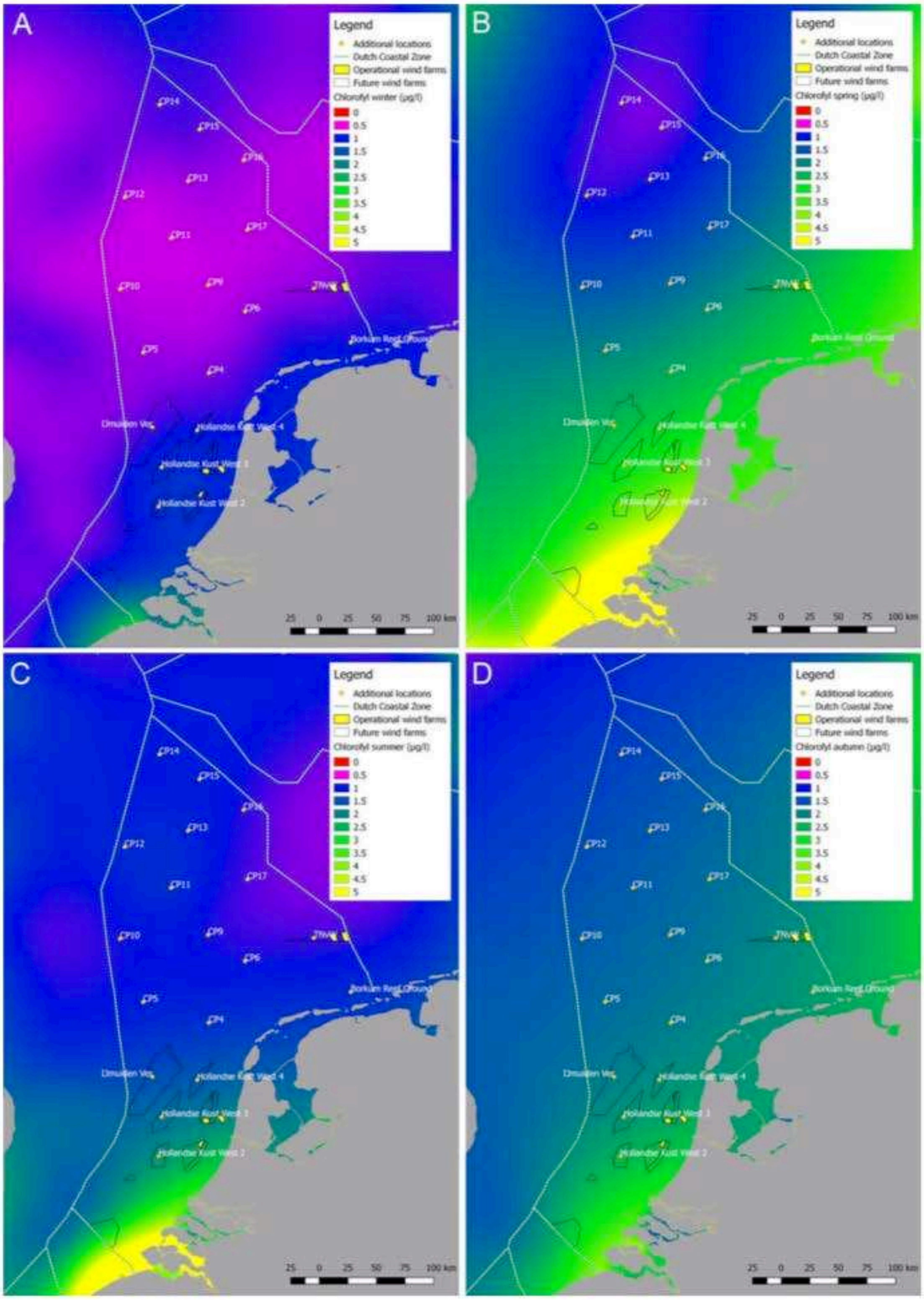


Figure A.20 10-year average chlorophyll-a concentrations from the upper water layer in the North Sea in four different seasons: a) winter b) spring c) summer d) autumn. From Kamermans et al. 2018

Larval retention

Larvae produced by reef building species should either settle close to the adult population or should be able to colonise close-by suitable habitats. A model study mapped passive larval dispersion at the different OWFs in the DCS. The model was based on passive, neutrally buoyant larvae that stay in the water column for ten days before they settle (Smaal *et al.* 2017). This is representative for flat oyster larvae, which have a relatively short larval phase. Based on these characteristics and the net current per site, Borssele, Buitengaats and Zee-energie show higher larval retention that the other sites (Figure A.21). Other sites are subjected to the outward flow of the Rhine and the northward current. It is possible for the larvae at the wind farms along the coast of Zuid- and Noord-Holland to reach the other wind farms.

The other biogenic reef building species discussed in this report have a longer larval phases, for instance 1-1.5 month for blue mussels to 6 months for horse mussels. Therefore, it is very likely that the dispersal of larvae of these species cover a larger area than the models presented in Figure A.21. Additionally, these species release their egg and sperm cells in the water column, where the eggs are fertilized. For successful fertilization the current should however not continuously be strong.

Historical abundance of flat oysters

The historic distribution of flat oyster is relatively well known because of its commercial importance and is reviewed by Smaal *et al.* (2015) and Kamermans *et al.* (2019). Similar information is lacking for other target species of this study.

Figure eft top to right bottom: a) Borssele, b) Hollandse kust Zuid, c) Luchterduinen, d) Hollandse kust Noord, e) Egmond aan Zee, f) Prinses Amalia, g) Buitengaats and h) Zee-energie. Based on a short larval phase (10 days) typical for flat oysters. Most other reef building species have a longer larval phase of about 6-8 weeks (Sabellaria), up to 9 weeks (Lanice), 4-6 weeks (Mytilus) up to 24 weeks (Modiolus).

Spatial variation within OWFs

In previous sections of this chapter OWF locations were described in general, varying from site to site on a North Sea scale, but also within he wind farm areas factors are not homogenous.

One of the factors that can be spatial variable is seabed morphology. For instance, in the OWF Borssele it is shown that there is variation in depth because of mobile sand waves (Figure A.22). In addition to differences in wave height, there is difference in migration direction and wave stability. Since the conditions of the sand waves are depending on wind speed, more dynamic conditions are expected in winter than in summer (Hasselaar *et al.* 2015).

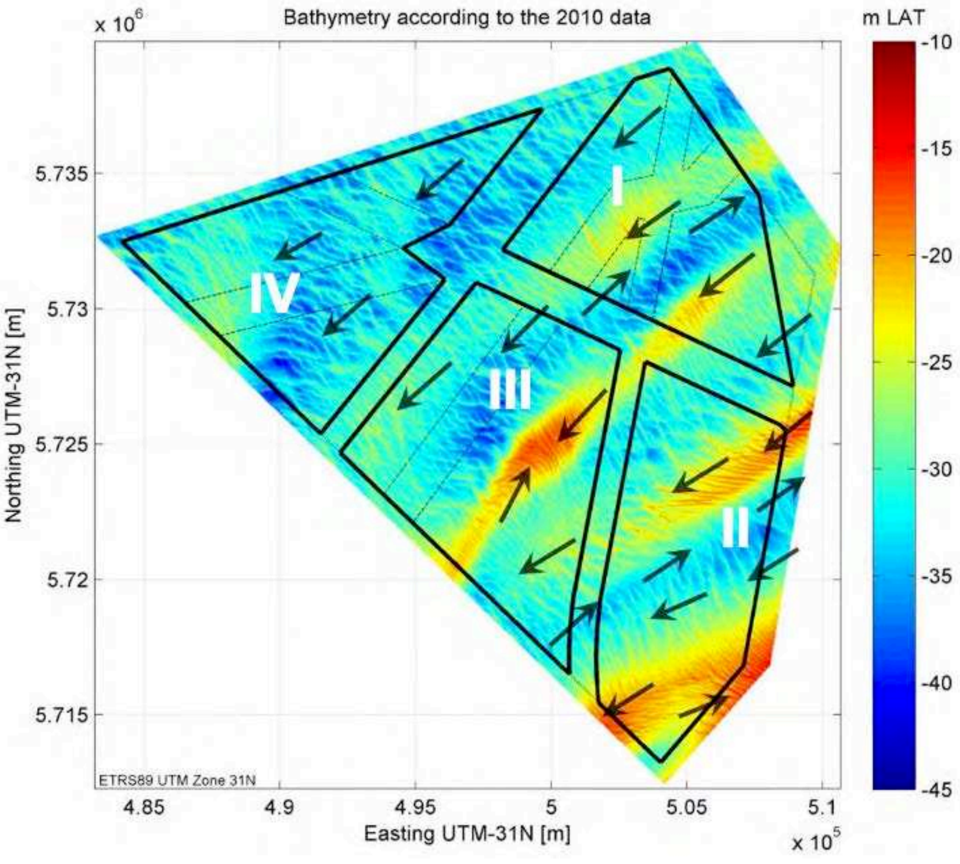


Figure A.22 Map plot of water depth and the sand wave migration directions in the four areas of Borssele windpark. (Source: Hasselaar et al. 2015).

Table A.1 General information of the wind farms (from north to south) constructed till 2023 within the Dutch Continental shelf. (Source: www.rijksoverheid.nl and Lengkeek et al. 2017).

Name OWF	**Operational since / in**	**Surface area (km^2)**	**#turbines**	**Distance to shore (km)**	**Owner**	**Capacity (MW)**	**Type scour protection**
Gemini (= Buitengaats and Zee-energie combined)	2016	68	150	55	Northland Power, Siemens, van Oord HVC	600	Armour layer: small stones (diameter ~ 0.15m) Filter layer: 1-3” Edge scour: 1-2m
Egmond aan zee (OWEZ)	2007	26	36	11	Shell, NUON	108	Armour layer: course stones (60-300 kg) Filter layer: 1-3”
Prinses Amalia	2008	14	60	23	Eneco	120	Armour layer: medium course stones (10-200 kg) Filter layer: 2-8”; Edge scour: ~1m
Luchterduinen	2015	16	43	23	Eneco, Mitsubishi Corporation	129	Armour layer: medium course; Filter layer: 1-3” Edge scour: 2-2.5m
Hollandse Kust Zuid	2023	225	pm	22-19	Vattenfall	700 700	pm
Hollandse Kust Noord	2023	174	61-73	18,5	unkown	700	pm
IJmuiden Ver							
Hollandse Kust West - 2							
Hollandse Kust West - 3							
Hollandse Kust West - 4							
Borssele I&II and III&IV V (innovation area))	2020 2021	138 94	171 2	22	Orsted + Blauwwind + Van Oord, Investri Offshore, Green Giraffe	752,732 19	I and II: For III and IV are 2 designs proposed: Fine = Armour layer: 5-40 kg;Filter layer: 22/125mm Coarse = Armour layer: 10-60 kg Filter layer: 63/200mm

Table A.2 Abiotic factors part 1: substrate type, concentration of suspended particles (SPM), seabed shear stress and seabed motility.

Name OWF	**Substrate type**	**SPM avg**	**SPM max**	**Shear stress avg**	**Shear stress max**	**Sea bed motion**
Gemini 1(= Buitengaats)	Fine sand	10	40	0,3	6,8	Relatively stable
Gemini 2 (= Zee-energie)	Fine sand	10	40	0,3	5,6	Relatively stable
Egmond aan zee (OWEZ)	Fine sand	20	50	0,8	8,7	No sandwaves
Prinses Amalia	Coarse to fine sand	10	35	0,6	7,1	Two areas with sand waves, rest is stable
Luchterduinen	Coarse to fine sand	10	35	0,6	6,7	Covered with low and stable sand waves
Hollandse Kust Zuid	Coarse to fine sand	10	35	0,5	5,9	Low sandwaves 1-3 m
Hollandse Kust Noord	Fine sand	10	35	0,6	6,8	No sandwaves in most parts, small area with low sandwaves 1-3 m
IJmuiden Ver	Coarse to fine sand	5-10		0,5	5,2	Northern part without sandwaves, southern part with low sandwaves 1-3 m
Hollandse Kust West – 2	Fine sand	5-10		0,5	4,2	Intermediate sandwaves 4-6 m
Hollandse Kust West – 3	Coarse sand	5-10		0,5	4,7	Low sandwaves 1-3 m
Hollandse Kust West – 4	Coarse sand	5-10		0,5	6,2	No sandwaves in most parts, small area with low sandwaves 1-3 m
Borssele	Coarse to fine sand	10	25	0,6	3,4	High sandwaves, low motility
Source	Smaal *et al.* 2017	Smaal *et al.* 2017		Kamermans *et al.* 2018		Lengkeek *et al.* 2017

Table A.3 Abiotic factors part 2: water depth, water temperature and stratification regime.

Name OWF	**Water depth (m)**	**Temperature °C min**	**Temperature °C max**	**Stratification regime**
Gemini 1 (= Buitengaats)	28-36	3	18	Irregular stratification
Gemini 2 (= Zee-energie)	33-40	3	18	Irregular stratifiation
Egmond aan zee (OWEZ)	15-21	3	20	Semi-permanently mixed (ROFI)
Prinses Amalia	20-27	3	18	Semi-permanently mixed (ROFI)
Luchterduinen	20-27	3	20	Semi-permanently mixed (ROFI)
Hollandse Kust Zuid	20-27	4	18	Semi-permanently mixed (ROFI)
Hollandse Kust Noord	20-27	4	18	Semi-permanently mixed (ROFI)
IJmuiden Ver		4	18	Intermittent stratificaton
Hollandse Kust West - 2		4	18	Semi-permanently mixed (ROFI)
Hollandse Kust West - 3		4	18	Semi-permanently mixed (ROFI)
Hollandse Kust West - 4		4	18	Semi-permanently mixed (ROFI)
Borssele	20-40	4	20	Intermittent stratificaton
Source	Smaal *et al.* 2017	Smaal *et al.* 2017		Van Leeuwen *et al.* 2015

Table A.4 Chlorophyll-a concentrations in the upper water layer at the different OWF locations during all seasons. Data from Kamermans et al. 2018.

Name OWF	Chlorophyll-a				
	winter	**spring**	**summer**	**autumn**	**annual average**
Gemini 1(= Buitengaats)	0,78	2,57	0,90	2,14	1,60
Gemini 2 (= Zee-energie)	0,76	2,49	0,89	2,10	1,56
Egmond aan zee (OWEZ)	1,11	3,53	2,02	2,41	2,27
Prinses Amalia	1,14	3,43	1,98	2,37	2,23
Luchterduinen	1,17	3,81	2,26	2,56	2,45
Hollandse Kust Zuid	1,21	3,91	2,34	2,62	2,52
Hollandse Kust Noord	1,12	3,26	1,86	2,29	2,13
IJmuiden Ver	0,88	2,57	1,45	1,95	1,71
Hollandse Kust West - 2	1,17	3,56	2,13	2,48	2,33
Hollandse Kust West - 3	1,11	3,01	1,78	2,18	2,02
Hollandse Kust West - 4	0,99	2,84	1,56	2,09	1,87
Borssele (I&II and III&IV)	1,22	4,43	2,89	2,70	2,81

Appendix III Success parameters

Table A.5. The success parameters of the enhancement options are specified, which are related to the general aims and questions of the Rich North Sea project and apply to all focal species (Chapter 1).

Enhancement option	**Research questions**	Parameter
1. Baseline biodiversity	What is the baseline biodiversity within OWF?	#species
2. Hotspots	Are there biodiversity hotspots within OWF?	#species
3. Natural substrate	What is the best location and substrate for biodiversity and settlement of reef building species?	# recruits
4. Biogenic reefs	What is the distribution and size within OWF?	density
4. Biogenic reefs	Is the population increasing?	population change
4. Biogenic reefs	What is the survival rate?	survival rate
4. Biogenic reefs	What is the growth rate?	growth rate
4. Biogenic reefs	What is the condition? Is the condition sufficient for reproduction?	condition index
4. Biogenic reefs	Does the enhanced/introduced population produce larvae?	gonad index
4. Biogenic reefs	Are the larvae detected in the water column?	# larvae
4. Biogenic reefs	What is the settlement rate?	# recruits
4. Biogenic reefs	What is the settlement substrate?	substrate type
4. Biogenic reefs	Do the larvae settle on artificical substrate	settlement rate
4. Biogenic reefs	What is the disease status?	Bonamia prevalence
3. Natural substrate	What is the best location and substrate for biodiversity and settlement of reef building species?	# recruits
5. Artificial substrate	What are the effects of artificial substrates deployed on the sediment?	biodiversity
6. Artificial substrate	What are the effects of artificial substrates deployed on scour protection?	biodiversity
All options	Evaluation: what are the success and failure factors of enhancement options?	all parameters

Table A.6. Detailed overview of success parameters is given in relation to the general questions of the Rich North Sea Programme. Population change of biogenic reef species include survival, growth, reproduction, sex ratio, #larvae, #recruits.

General questions	Monitoring parameters											
	biotic							abiotic factors				
	population change	disease	predators	biodiversity	alien species	phytoplankton	zooplankton	temperature	current	shear stress	sediment	SPM
What are the possibilities of recovery or restoration in time and space (spatial and temporal potential)?	1	1	1			1	1	1	1	1	1	1
What are the environmental conditions for biogenic reefs? abiotic, biotic conditions, human use (disturbance)		1	1			1	1	1	1	1	1	1
What are the most important knowledge gaps on the short term?	1	1	1	1	1							
Which measures and methods are practical and feasible?	1											
Are these measures feasible and which factors are relevant for the success?	1											
Which ecosystem services do developed or reintroduced biogenic reefs generate?				1		1	1					1
What are the ecological risks of biogenic reef restoration: introduction of live specimens, introduction of substrates		1	1	1	1							
Which conditions within OWFs are relevant for the development of biogenic reefs?	1	1	1	1	1	1	1	1	1	1	1	1
Which conditions and characters should be developed for biogenic reef enhancement?			1	1	1							
Monitoring: which parameters should be measured from T_0 to (1) evaluate the success of restoration	1	1	1			1	1	1	1	1	1	1
Which parameters should be measured from T_0 to evaluate (2) the output of ecosystem services				1		1	1					1
North Sea outside OWFs: what measures should be taken outside OWFs for biodiversity enhancement and biogenic reef restoration?	1											

Table A.7. Additional questions are presented, which are important to take into account when establishing a plan to measure the success of enhancement options.

Topic	General questions
Measuring success	Monitoring: which parameters should be measured from T0 to (1) evaluate the success of enhancement options?
Measuring success	Which parameters should be measured from T0 to evaluate (2) the output of ecosystem services
Measuring success	Which measures and methods are practical and feasible?
Measuring success	Are these measures feasible and which factors are relevant for the success?
Biogenic reefs	What are the possibilities of recovery or restoration in time and space (spatial and temporal potential)?
Biogenic reefs	What are the environmental conditions for biogenic reefs?: abiotic, biotic conditions, human use (disturbance)
Biogenic reefs	What are the most important knowledge gaps on the short term?
Biogenic reefs	Which conditions within OWFs are relevant for the development of biogenic reefs?
Biogenic reefs	Which conditions and characters should be developed for biogenic reef enhancement?
Ecosystem services	Which ecosystem services do enhancement options generate?
Ecological risks	What are the ecological risks of biogenic reef restoration: introduction of live specimens, introduction of substrates
Wider North Sea	North Sea outside OWFs: what measures should be taken outside OWFs for biodiversity enhancement and biogenic reef restoration?

Appendix IV Expert interviews

In June 2019 three marine ecology experts were interviewed about their experience, ideas and knowledge considering biodiversity enhancement options in the North Sea and offshore wind farms in particular.

- Prof. dr. Peter Herman (Deltares, TU Delft)
- Prof. dr. Han Lindeboom (Wageningen Universiteit)
- Prof. dr. Tinka Murk (Marine Animal Ecology, Wageningen Universiteit)

A short summary of their interesting and inspiring ideas:

For choosing the most promising project locations, keep in mind the historic records of species occurrence and the distance to a rich source of biodiversity (e.g. wracks). Furthermore, consider the sand dynamics, the food concentrations and the predation pressure. Another requirement of the location is that bottom disturbance such as bottom trawling is excluded. Besides, do not start with introducing monocultures, but do facilitate other (mobile) species, preferably allies (i.e. predators of the predators).

There are still large knowledge gaps, that is, even some basic information on the ecology of several desired species is scarce, therefore work on this. Furthermore, interesting and important questions are amongst others: how large must the starting population be to create a self-sustaining population? Will the OWFs destabilize the seafloor and alter the temperature stratification regime and thereby possibly disturb the reefs? What will the effect be of cables and electromagnetic fields on marine life? How will the food web develop and what impact will the addition of filter feeders have on the carrying capacity of the North Sea ecosystem?

Some questions could be addressed by monitoring the projects itself and the influence of the projects in the surrounding area. Ideas for monitoring are amongst others: automatic equipment for environmental measurements, video and ROV surveys, eDNA analysis, isotope analysis, shell valve monitoring and placing receivers for tagged animals.

Keep in mind that creating biogenic reefs is complex and that several projects will probably gain disappointing results. This is no problem but communicate on forehand that not everything will work, that is, work on realistic expectation management. To reduce the risk of failure, prevent seafloor disturbance (e.g. bottom trawling fisheries) and work experimentally in diverse and spatial different habitats and monitor what works. Another risk is the introduction or facilitation of invasive species, but by creating a highly biodiverse ecosystem the risk of fast spreading will be reduced.

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