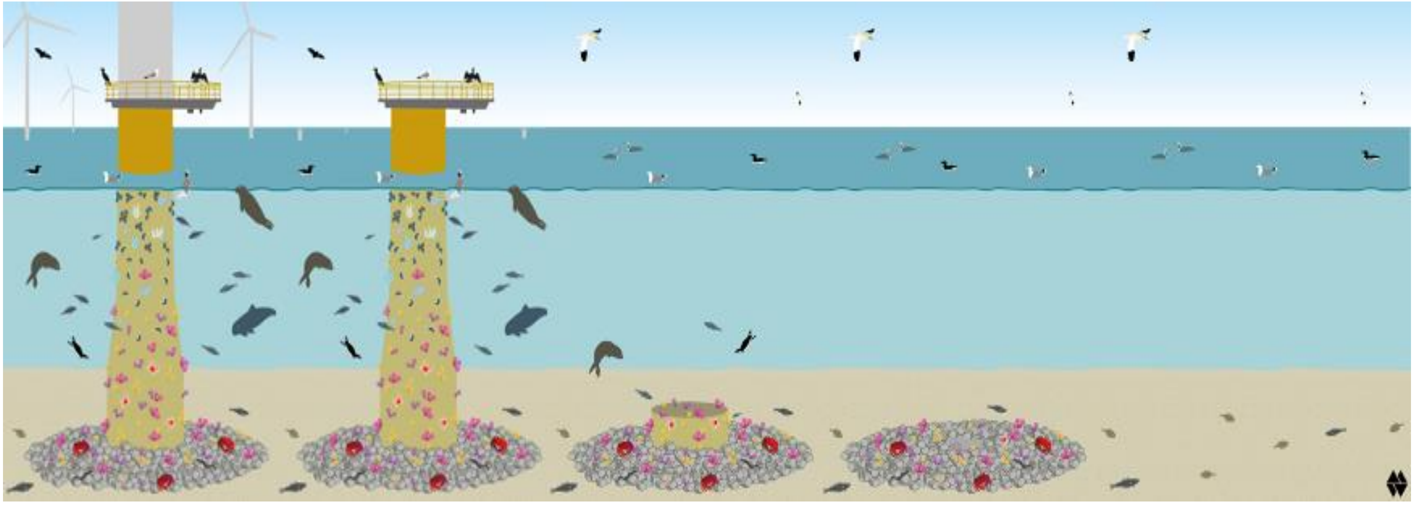
Ecological impact of decommissioning offshore wind farms

Overview of potential impacts and their importance



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Preface

The development of offshore wind farms is occurring on a large scale. Meanwhile, the oldest wind farms within the Dutch offshore areas, but also elsewhere in the North Sea, will reach the end of their estimated lifespan of 20-25 years in the next five to ten years. After operation, wind farms need to be decommissioned in accordance with the 1989 resolution of the International Maritime Organization (IMO) and the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR). The removal or replacement of offshore wind farms can have a number of ecological impacts that have not yet been systematically studied. Due to the lack of detailed knowledge on this subject, it is important to identify, at an early stage, which ecological aspects may play a role and which ones need to be addressed and studied well in advance.

Rijkswaterstaat (RWS) has therefore commissioned Bureau Waardenburg to carry out an exploration of the ecological impacts of the removal, reuse and replacement of wind farms in the North Sea. The project was coordinated by Rob Gerits at Rijkswaterstaat.

The project team from Bureau Waardenburg consisted of Malenthe Teunis, Rebecca Bakker, Wouter Lengkeek and Karin Didderen (all Department of Aquatic Ecology), Mark Collier and Abel Gyimesi (both Department of Bird Ecology) and Job de Jong (Department of GIS and Data Management). Ruben Fijn conducted the quality control of the report. Furthermore, Elisa Bravo Rebolledo, Miriam Schutter and Rob van Bemmelen also provided feedback during internal expert sessions. We thank them all for their contributions.

The authors also thank all staff members of offshore wind energy companies who have responded to our enquiry about decommissioning strategies.

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Summary

The development of offshore wind farms is occurring at an accelerating pace. Meanwhile, the oldest wind farms within the Dutch offshore areas, but also elsewhere in the North Sea, will reach the end of their estimated lifespan of 20-25 years in the next five to ten years. After operation, wind farms need to be decommissioned in accordance with the 1989 resolution of the International Maritime Organization (IMO) and the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR).
So far ecological aspects of decommissioning have not yet been systematically described or defined. The current study focusses on defining the ecological impacts of several decommissioning strategies and the gaps in the knowledge that still exist and hamper future assessments.

Decommissioning strategies

As international regulations do not explicitly define "decommissioning" or "removal" and countries themselves can make exceptions that allow for partial removal, several decommissioning strategies have arisen. Not all of these strategies fully adhere with the international regulations but are still addressed within this study:

- Complete removal. The entire wind farm is being removed and no artificial material is left on site. To fill up holes in the seafloor left by monopiles or other foundations the bottom can be profiled after removal.
- Partial removal. The wind turbine is removed and possibly also (part) of the monopile and scour protection.
- Repower. The wind farm site is repowered, by placing new wind turbines on existing scour sites, or by removal of the entire old wind farm and placing a new wind farm. The old wind farm can also be partially removed and a new wind farm can be placed within the old one.

Ecological aspects marine habitat and species

Impacts of decommissioning activities on marine habitat types and species can be separated in effects during deconstruction and effects after deconstruction.

Decommissioning activities cause noise pollution and vibrations, bottom disturbance and turbidity. Moreover, risks arise of chemical pollution during removal activities and possible spread of non-native species during transportation to shore. All the above aspects can potentially cause an ecological impact on present marine ecosystems. The actual ecological impacts of deconstruction depend largely on the type of foundation present, the decommissioning strategy chosen and the duration of the activity.
Current ecological impact assessments commonly assume that expected disturbance during deconstruction, like noise- and vibration levels, do not exceed levels experienced during the construction of the wind farm, and are of a temporary and local nature. Therefore, ecological impacts during deconstruction are considered to have the same (or less) impact as during construction of the wind farm. Mitigation measures similar to the

ones applied during construction processes can also be applied here to minimize the impact.

After deconstruction several aspects of a wind farm that have an ecological function may (partially) be removed. Aspects discussed in this study are the artificial hard substrate, exclusion zone of bottom disturbing fisheries and disturbance in stratification layers. The most important ecological impacts are described below:

- After deconstruction the artificial hard substrate (scour protection, monopile and other type of foundation) is no longer present, or remains only partially present. Therefore, also the epifauna community, which has colonized the substrate in its 20-25 year life span, will also be (partially) removed. Moreover, also the function of the artificial hard substrate as foraging, hiding or spawning habitat for associated species like certain fish and mobile macrobenthos will be removed.
- The artificial hard substrate not only attracts native epifauna species but can function as a stepping stone for non-native epifauna species. Non-native species mainly reside in the intertidal zone of the monopile. Complete removal of the wind farm and its artificial hard substrate also removes the stepping stone function of the wind farm site for non-native species.
- Besides acting as a stepping stone for non-native species, the artificial hard substrate can also act as a stepping stone for valuable or protected native species, for example flat oysters *Ostrea edulis*. Moreover, the eventual exclusion of bottom trawling fisheries in offshore wind farms leaves the sea floor undisturbed for the lifespan of the wind farm, potentially favouring the development of long-lived species or even biogenic reef systems. The removal of the wind farm can harm these valuable or protected species or reef systems, as hard substrate is removed and bottom trawling fisheries are most likely allowed to return on site.
- Lastly, the complete removal of an offshore wind farm reduces the risk an offshore wind farm poses to the ocean's stratification layers. Namely, large scale offshore wind farm developments can disturb the stratification layers, and thus can affect the biological activity (phytoplankton production). Removal of monopiles directly removes the risk of disturbance in the stratification layers on site.

Ecological aspects birds and bats

Impacts of decommissioning activities on birds and bats can also be separated in effects during deconstruction and effects after deconstruction.

During decommissioning activities, increased shipping activity, aerial structures such as cranes, additional lighting, noise and the disappearance of the actual turbines and related structures can cause an effect on birds and bats. The activities and presence of vessels, lighting and noise during this phase may lead to increased risks of disturbance, barrier effects or collisions for birds and bats. The actual ecological impact of deconstruction is depends largely on the type of decommissioning and the duration of the activity.

Most importantly, after deconstruction wind turbines are not present anymore, and hence also the negative impacts of offshore wind farms pose on birds and bats are removed;

these being collisions, barrier effects and effective habitat loss (or disturbance). Some birds and bats, however, can benefit from turbines as resting opportunities. Removing the above-water components of wind turbines will directly remove such benefits.
When partially removing a wind farm by leaving above-water low-level platforms, birds and bats can still benefit from resting- and potentially even nesting opportunities, particularly if these structures are further optimized. These remaining structures may still result in barrier effects and disturbance, albeit at possibly lower levels since there are no moving parts left, and collision risk is expected to be negligible.

Location dependent impact

One of the most important aspects of determining the actual ecological impact, besides the decommissioning strategy chosen, is the location of the wind farm. The North Sea region does not consist of one uniform habitat but a variety of habitat types across the shelf. Moreover, the habitat types and their associated marine life present in the North Sea region have changed over the years. Knowing the ecological value of the location is therefore crucial in determining the optimal decommissioning strategy in terms of ecological impacts.

Knowledge gaps

As ecological aspects of decommissioning have not yet been systematically studied, knowledge gaps still exist. Noise- and vibration levels of decommissioning activities, for example, are largely unknown. Moreover, the presence of valuable or protected species and habitats within offshore wind farms can only be determined close to the end of a wind farm’s life span and needs monitoring before large scale decommissioning commences.

1 Introduction

1.1 Background

Although the development of many offshore wind farms (OWFs) is ongoing at an accelerating pace, the oldest wind farms within the Dutch coastal area, but also within the exclusive economic zone (EEZ) of other North Sea countries, will start to be decommissioned within the next few years (in the Netherlands, OWEZ and PAWP around 2026 and 2027 respectively). Permits for OWFs in the Netherlands are valid for 30 years, including the time required for construction and decommissioning. In the offshore wind farm developments that are currently being planned until 2050, decommissioning activities will gradually reach a considerable size. The evaluation of ecological (cumulative) impacts of offshore wind farms requires a careful knowledge-driven process. In the future, attention will also have to be given to the ecological impacts of decommissioning and the re-use and replacement of wind farms. So far, ecological aspects of decommissioning have not yet been systematically described or defined. It is important to fill this knowledge gap and define relevant ecological aspects early in the process.

1.2 Decommissioning scenarios

According to current regulations (IMO, OSPAR Decision 98/3 and national regulations), all disused offshore installations should be fully removed and transported to shore for re-use, recycling, or final disposal. Compliance with this legalization is different between North Sea countries, as some see wind turbines separate from offshore installations. Moreover, the full removal of offshore wind turbines is costly and can pose safety risks or have potential impacts on present marine ecosystems within the wind farm. As international regulations do not explicitly state how a wind farm should be (completely) removed and countries themselves can make exceptions that allow for partial removal, several decommissioning strategies have arisen (Topham & McMillan, 2017; Smyth et al, 2015; Fowler et al, 2019; Henriksen et al, 2019). Not all of these strategies fully adhere with the international regulations but are still addressed within this study.

1.3 Study aim and scope

This study aims to give an overview of the available knowledge and gaps in the knowledge on ecological impacts of several decommissioning strategies of offshore wind farms within the North Sea. The focus lies on the ecological effects of decommissioning on birds and bats (above water) and on marine habitats and associated species below the sea surface. Due to the limited amount of case studies related to the ecological effects of decommissioning, this study is meant to give an insight in possible ecological effects of several decommissioning strategies. Important gaps in the knowledge are defined, which should be addressed in the future before large scale decommissioning commences.

Scope of this report
This report describes the impacts of offshore wind farm developments within the North Sea on the ecology of the local area and outlines possible ecological situations at established wind farms close to the end of their life span. An overview of the ecological impacts of several decommissioning strategies is given.

For any decommissioning plan it is necessary to establish an ultimate goal, from restoration of the situation prior to the construction of the wind farm to enhancement of the current condition, in order to guide the decision-making of the decommissioning strategy of the specific wind farm in question. This decision-making itself lies outside the scope of this report.

In short, this study is set-up in three steps:
1. An overview of the wind farms within the North Sea region and their expected decommissioning dates
2. Decommissioning strategies
3. Ecological impacts above and below water

The study only focusses on the ecological aspects. Costs, recycle options, carbon footprint, navigational safety, technical unfeasibility and other aspects of decommissioning are not part of this study, but should be taken into account in future decision-making processes.

Due to time and scope of this study, it was only possible to briefly touch upon the effects of removing (export) cables of offshore wind farms. There are effects to be expected, but these need further and more in-depth research. Especially when it comes to top- end high voltage cables like the export cable outside the OWF.

1.3.1 Readers guide

Below is a short overview of the content of this study:

Chapter 2: An overview of decommissioning in the North Sea
This chapter gives insight into the decommissioning regulations and an overview of the already constructed and planned wind farms in the North Sea. Moreover, we visualize when certain wind farms are expected to be decommissioned (20-25 years after construction).

Chapter 3: Decommissioning strategies
To determine ecological effects, it essential to have a good understanding of the different decommissioning strategies available. In this chapter several decommissioning options are explained.

Chapter 4: Ecological impact decommissioning subtidal
In this chapter the ecological impact on marine habitats and associated species is discussed, related to the decommissioning strategies from chapter 3. Important knowledge gaps that hamper good assessment are given.

Chapter 5: Ecological impact decommissioning birds and bats

In this chapter the ecological impact on birds and bats is discussed, related to the decommissioning strategies from chapter 3. Important knowledge gaps that hamper good assessment are given.

Chapter 6: Conclusion and visualization

Above chapters are combined to formulate a conclusion of the ecological impact of different decommissioning strategies. The different strategies are visualized in infographics.

2 Decommissioning offshore wind in the North Sea region

2.1 Regulations wind farm decommissioning

2.1.1 International level

According to international regulations, offshore wind farms (OWFs) in the North Sea region should be removed when disused or abandoned. International regulations concerning offshore installations are described by the IMO, UNCLOS and OSPAR.

IMO and UNCLOS
Article 60(3) of the United Nations Convention on the Law of the Sea (UNCLOS) states that offshore installations should be "*removed to ensure safety of navigation taking into account any generally accepted international standards established in this regard*" (Smyth *et al*, 2015). This is based on regulations and standards set by the International Maritime Organisation (IMO), stating that "*abandoned or disused offshore installations or structures on any continental shelf or in any exclusive economic zone are required to be removed, except where non-removal or partial removal is consistent with the following guidelines and standards*". Aspects which are discussed when considering a partial removal are; 1) navigation safety, 2) deterioration rate of used materials, 3) effect on marine environment, 4) risk of shifting materials, 5) risk and feasibility of a full removal and 6) reuse or other reasonable justifications to leave part of the OWF (IMO Resolution A.672 (16)).

OSPAR
The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) states that in general offshore installations must be removed. Dumping or leaving (partial) installation in place is prohibited. However, OSPAR also provides exceptions to this policy. National authorities can decide that part of the OWF can stay in place, as long as "*no adverse impact on the environment, the safety of navigation and other uses of the sea*'' are ensured.

2.1.2 National level

The interpretation of the above regulations differs between North Sea countries, as UNCLOS does not require a full removal and for the regulations according to IMO and OSPAR exceptions can be made (Smyth *et al.*, 2015). The applicable exceptions differ between countries and OWF sites.

In the Netherlands, for example, the national law states that a non-operational OWF needs to be fully removed (art. 6.16l). However, permits can be granted to execute only a partial removal, for example leaving the foundation in place for ecosystem services. The minister can also decide to exclude the export cable from the removal regulations, when the removal damages the natural environment (Staatsblad, 2015). It is not decided upon up to which specific depth materials need to be removed, but a depth of 6 meters at which monopiles will be cut off is generally maintained (E-connection, 2007; Dekkers, 2007).

In the UK, a full removal of an offshore installation is the default position, according to IMO standard, although strong arguments for exceptions can be raised, concerning risks to executing personnel, the marine environment, extreme costs and technical unfeasibility (Crown, 2019). In Denmark, the national law does not include specific regulations regarding the decommissioning of OWF’s, and the Danish Energy Agency may allow a partial removal (Bech-Bruun, 2017). In Belgium, currently no specific policy is formulated for the decommissioning (Larsen, 2019).

2.2 An overview of decommissioning in the North Sea region

Decommissioning of wind farms has already taken place in the North Sea region. For example, the first two offshore wind farms of the UK near Blyth were decommissioned in 2019, and the oldest offshore wind farm Vindeby (Denmark) was also completely removed in 2017. In the upcoming decades, decommissioning activities in the North Sea will increase. These activities will be most substantial between 2040-2060 (and onwards), as most wind farms are planned to be constructed between 2020-2040. Building activities beyond 2040 might even accelerate but no planning is available yet.

In figure 2.1 an indicative overview is given of existing wind farms and wind farms planned to be built in the North Sea up until 2039. The red and yellow areas indicate wind farms that have been constructed in the last two decades, whereas green and blue wind farms are yet to be built.

In appendix I an overview is presented of all wind farms constructed or planned to be constructed in the North Sea in the coming decades, including their size.

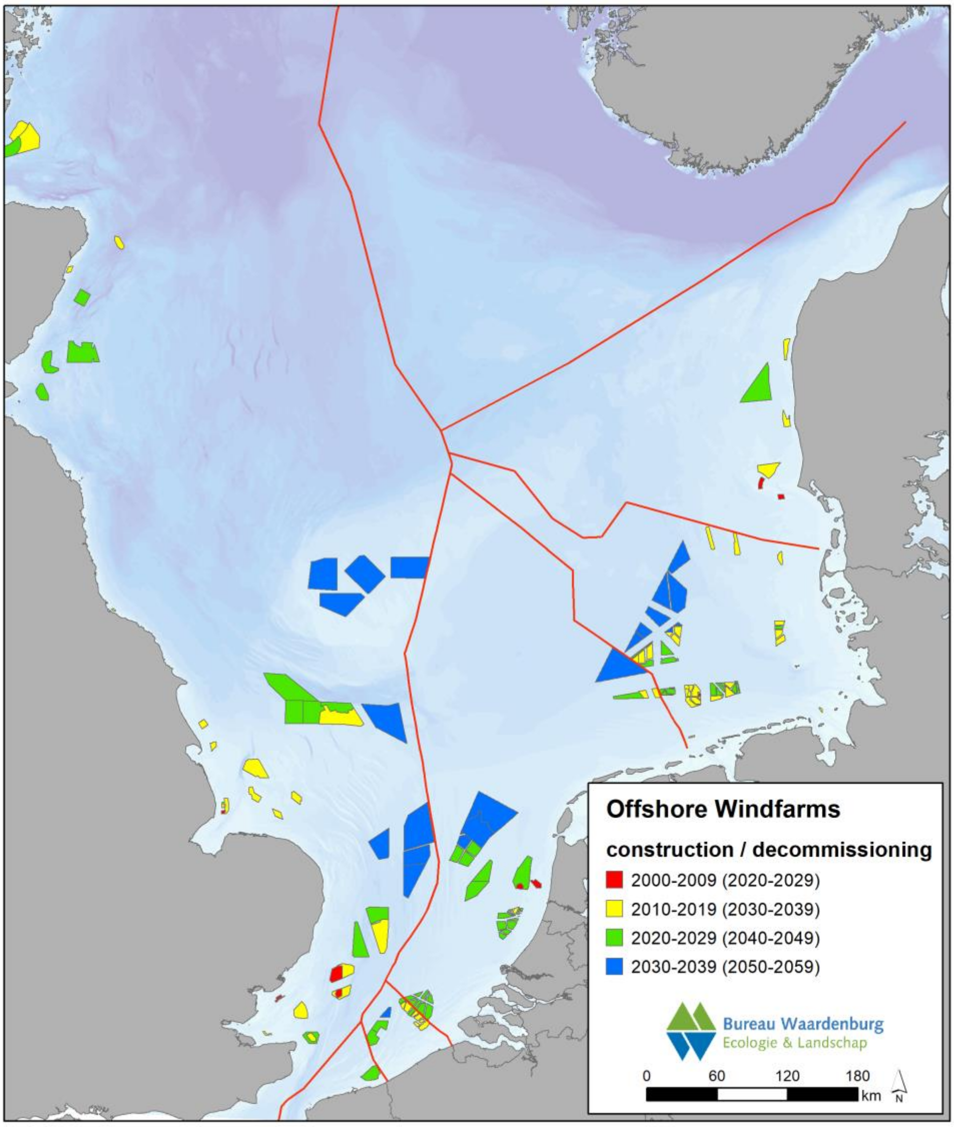


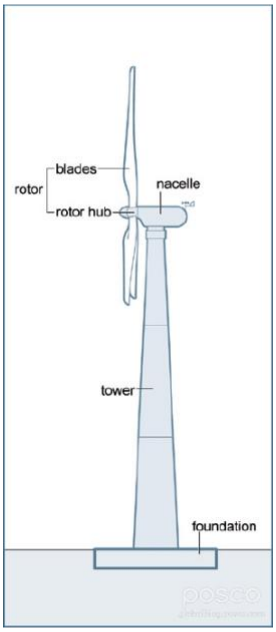
Figure 2.1 *An indicative overview of the present and planned wind farms in the North Sea until 2039. The different colours represent in which decade the wind farm was or will be constructed, and the corresponding (expected) decade of decommissioning.*

3 Decommissioning strategies

3.1 Overview of wind farm components and options for decommissioning

A wind turbine reaches its designated life expectancy (20-30 years) when it cannot function efficiently due to failure or fatigue, or no longer satisfies the expectations or needs of its user (Ortegon *et al*., 2013). At this point there are two main options: to repower or to decommission the wind farm.

When studying the different strategies of decommissioning it is important to first of all have a better understanding of the construction. The components a wind turbine consist of are three rotor blades, being connected to a hub. This is connected to the nacelle which houses the gearbox and the generator, and is placed upon a tower (figure 3.1, 3.2).



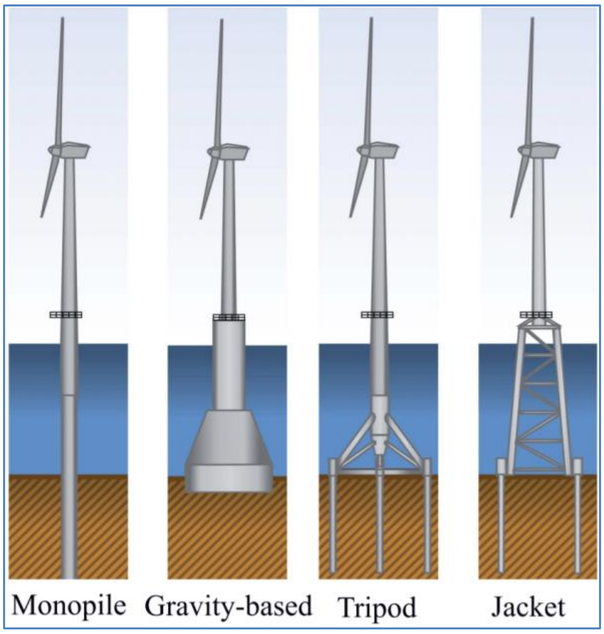


Figure 3.1 (left illustration) Wind turbine components

Figure 3.2 (right illustration) Bottom fixed types of foundations (Wiser et al., 2011, Posco, 2016).

The entire wind turbine construction is placed upon a foundation. The types of foundation used for wind turbines in offshore waters can be divided in two main groups, floating foundations and bottom fixed foundations (Wittingen, 2018). So far, floating turbines are still in the experimental phase and only one wind farm, Hywind, with five floating turbines, is operational in the North Sea to this date. In 2021 and 2022, two other floating wind farms in the North Sea will be commissioned by the UK and Norway, with a total capacity of 138 MW (Ramírez *et al.*, 2020).

Bottom fixed foundations are currently the standard in OWFs with the monopile, gravity-based, tripod and jacket being the most common foundation types (figure 3.2). Monopiles are drilled/hammered into the sediment to a depth of about 30 m, depending on sediment conditions (Linley *et al.*, 2007). Gravity-based foundations consist of a concrete or steel platform with an approximate weight of 1,000 tonnes, partly embedded in the seafloor. A jacket foundation, used in deeper waters, consists of a lattice framework which has three or four anchor points, attached to the seabed with piles (Iberdrola, 2020). Being more light-weighted than the jacket, the tripod attaches the central cylinder of the turbine with three legs to the seafloor, also being secured in the seabed with piles (Plodpradit *et al.,* 2019). Until the end of 2019, the monopile is the most popular foundation in Europe, being used in 81% of the European wind farms (Ramírez *et al.,* 2020). As displayed in figure 3.3 the monopile is followed up by the jacket and gravity-based foundations.

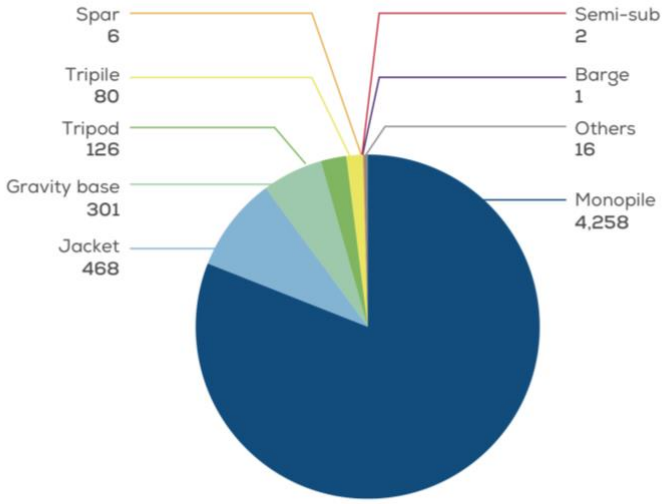


Figure 3.3 Number of foundations grid-connected by substructure type in Europe (Ramírez et al., 2020).

Around the foundation of offshore wind turbines, scour protection is placed, preventing scour to occur around the monopile or other foundations. Scour is the phenomenon of erosion of sediment around a structure and is commonly observed at constructions in the marine environment, including wind turbines (Van Eijk, 2016). Around the gravity-based foundation and monopile-, jacket- and tripod foundations, loose rock dumps act most commonly as scour protection (Asgarpour, 2016; Ruiz de Temiño Alonso, 2013). The scour protection covers in general an area of four to six times the pile diameter around the (mono-) pile, where the diameter of a monopile can vary from four to ten metres (Lengkeek *et al.,* 2017). Other types of scour protections used by the offshore wind energy sector are rock bags, collars and frond mats (Raaijmakers, 2011). An eco-friendly design of scour protection, which optimises habitat suitability for specific species, is also in development (Lengkeek *et al.,* 2017).

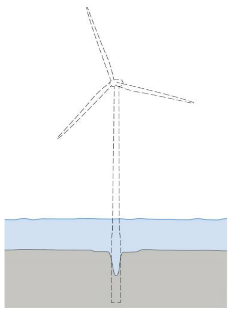
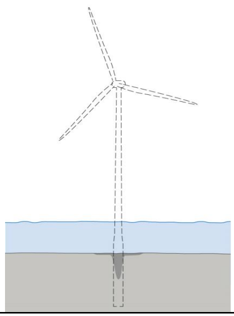
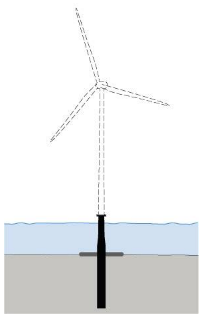
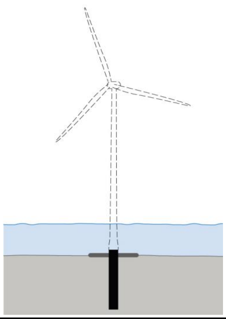
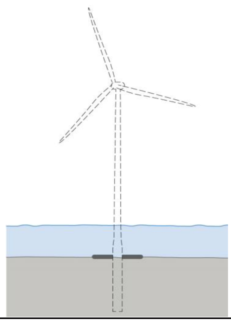
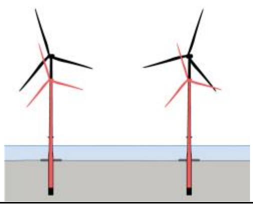
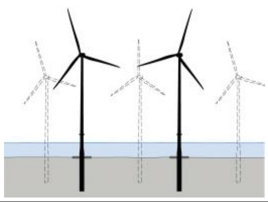
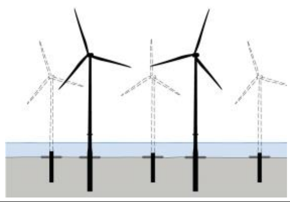
3.1.1 Decommissioning strategies

As international regulations do not explicitly state how a wind farm should be completely removed and countries themselves can make exceptions for the allowance of partial removal, several decommissioning strategies have been proposed in literature (Topham & McMillan, 2017; Smyth et al, 2015; Fowler et al, 2019; Henriksen et al, 2019).

The strategies can be divided in three main options, with each option having several sub-options (table 3.1).:

1. Complete removal of the wind farm (§3.2);
2. Partial removal (§3.3);
3. Repowering (§3.4).

Table 3.1 Decommissioning strategies for offshore wind farms.

Complete removal			
	Leave it be	*Bottom profiling*	
Partial removal			
	Removal of wind turbine only	*Removal of wind turbine and monopile above seafloor*	*Removal of wind turbine and monopile below seafloor, scour protection remains in place*
Repower			
	Replace wind turbine and monopile	*Complete removal old OWF and placement of new OWF in different configuration*	*Partial removal old OWF and placement of new OWF in same area.*

3.2 Complete removal

In this paragraph the sub-options are discussed for a complete removal of a wind farm, involving the removal of all components of the wind turbines, including its foundation and scour protection.

3.2.1 Complete removal and leave it be

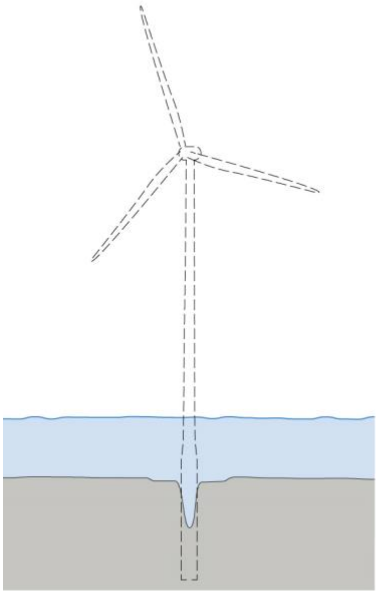


Figure 3.4 Decommissioning by complete removal of all used material

By removing the entire construction of a wind turbine, including its monopile or gravity-based foundations (GBF) and the scour protection, a hole in the seafloor will remain (figure 3.4). With the 'leave it be' strategy no further actions are taken to restore the site to its original state. The time it takes for these holes to disappear is estimated to range widely from several months to years, highly depending on the areas' dynamics (Volckaert *et al.,* 2011).

In already executed decommissioning activities, this option has already been implemented. The four wind turbines of wind farm Lely in Lake IJssel were completely removed in 2016, including their scour protection and the retraction of the monopiles (Henriksen *et al.,* 2019). The oldest offshore wind farm Vindeby (Denmark) was also completely removed, having the gravitational foundations cut in pieces on site and transported to land (PowerTechnology, 2017). The first two offshore wind turbines of the UK near Blyth, built in 2000, were decommissioned in 2019. These turbines with gravity-based foundations were completely removed from the hard seabed (Baminfra, 2018). The ballast sand was initially removed from the foundation, whereafter it could be removed as a whole. Nothing has been published about restoration actions of the natural environment taken after the removal. Therefore, it is assumed that no further actions were taken to fill the holes or restore the site to the original situation.

3.2.2 Complete removal and bottom profiling

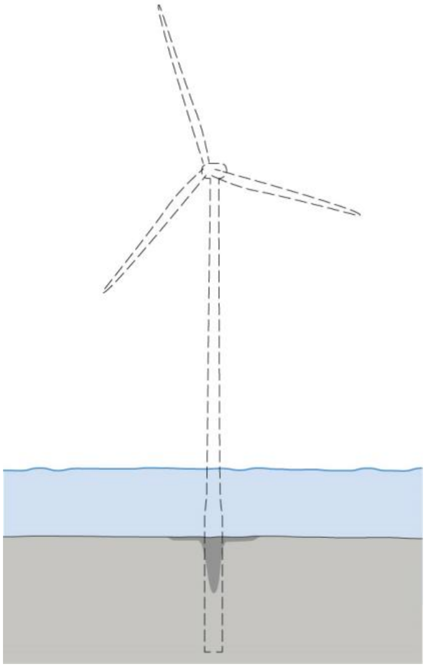


Figure 3.5 Complete removal and bottom profiling

After the complete removal of a wind turbine (including its foundation and scour protection) there is also the option to take action in filling up the holes left on the wind farm site, and hence restoring the bottom profile to the original state before the wind farm was constructed. This could be achieved by filling these holes with sediment present on site (Volckaert *et al.,* 2011, figure 3.5). While (mono)piles leave deep holes with a small diameter, gravity-based foundations leave much shallower holes but with a larger diameter. As monopiles are the most commonly used foundation in the North Sea, the upcoming decommissioning of wind farms in the North Sea will leave many deep but narrow holes within the North Sea seabed. Unclear is how deep these holes will be after the removal of the monopiles but it is likely to differ between sites.

3.3 Partial removal

When the wind turbines have reached the end of their lifespan and need to be removed, the other option is to leave parts of the construction (partly) in place below the surface of the sea. In this paragraph several options for this partial removal are described.

Important to note is that these strategies do not fully adhere with international regulations of complete removal. However, as exceptions can be made at a national level, all partial removal strategies stated in literature are reviewed.

3.3.1 Removal of wind turbines only

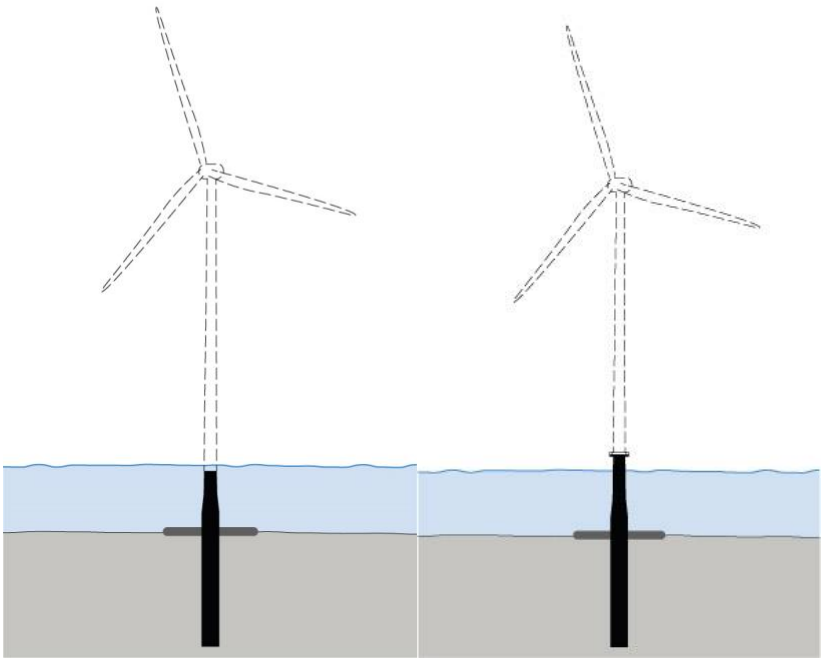


Figure 3.6a,b (Below sea surface) wind turbine removal.

In this case only the wind turbine will be removed, whereas the monopile (or other foundation) and the scour protection stay in place. The monopile can stay in place just below the sea surface (figure 3.6a), leaving behind a large surface of hard substrate, or even just above the sea surface by leaving the platform in place (figure 3.6b). Important to note is that for both of these options maritime safety needs to be taken into account, and additional measures need to be taken to prevent offshore safety hazards. The strategy closely relates to the ‘Rigs to Reefs’ programme that is already applied to the offshore mining industry in the Gulf of Mexico (Smyth *et al.,* 2015).

3.3.2 Removal wind turbine and monopile foundation above seafloor

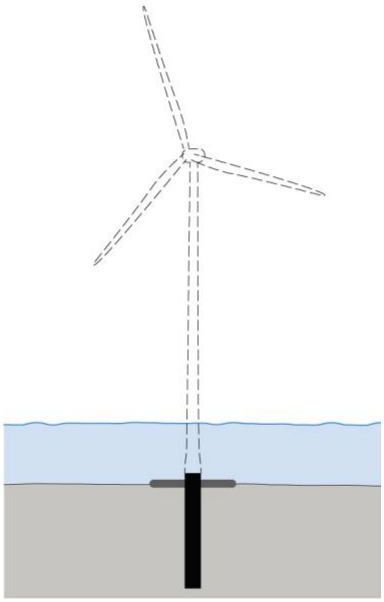


Figure 3.7 Above seafloor wind turbine removal.

Another option is to also remove part of the foundation at seafloor level or a few metres above (figure 3.7). The lower part of the foundation, which stands *in* the seabed, can stay in place, just as the scour protection on the seabed. This strategy has already been applied during the decommissioning of the five turbines of Yttre Stengrund wind farm in Sweden where the concrete gravity-based foundations were cut off at seabed level (Russell, 2016).

3.3.3 Removal wind turbine and monopile foundation below seafloor

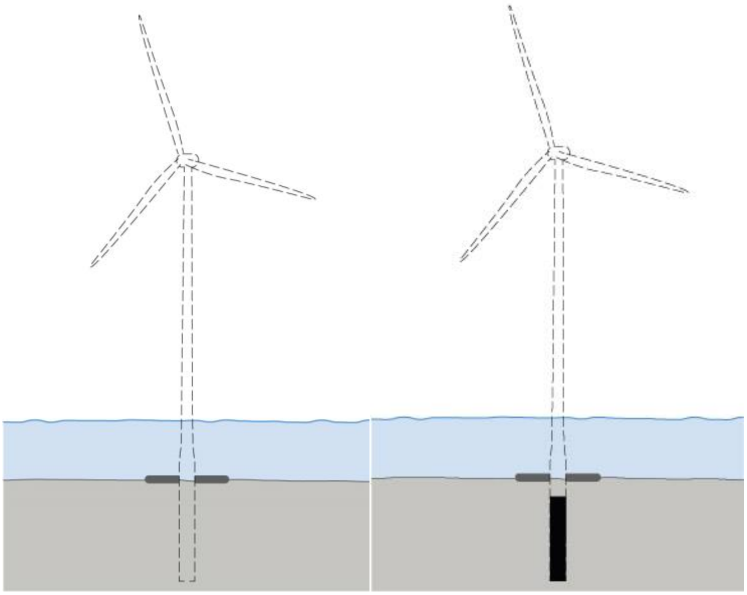


Figure 3.8a,b below seafloor (monopile) foundation removal

Besides leaving part of the monopile behind as described earlier, it is also an option to remove the foundation entirely (below sea floor), leaving only the scour protection behind (figure 3.8a,b).

In other cases, the foundation can been cut off below seafloor level. In addition, in some cases the scour protection can also be removed. During the decommissioning of wind farm Utgrunden, for example, built in 2000 and decommissioned in 2018, the scour protections of the seven turbines were removed and the monopiles were cut off 1 m below the seabed (Henriksen *et al.,* 2019), leaving only part of the foundation behind. The same strategy is planned for the decommissioning of two wind turbines with jacket foundations in Scotland, built in 2007. The decommissioning is planned to take place in 2024-2027, when the turbines and jackets will be fully removed and the piles will be cut off 3 m below the seafloor (O'Sullivan, 2018). As mentioned before in §2.1.2, in the Netherlands no specific depth is defined up to which materials need to be removed, but a depth of 6 meters is generally maintained for cutting activities. For example, this cutting depth was already mentioned in the decommissioning plan of the cancelled Dutch wind farm Rijnveld Noord/Oost (E-connection, 2007).

3.4 Repower strategies

In this chapter the options for repowering are discussed in case a wind farm reaches the end of its lifespan and the location will still be used for generating offshore wind energy.

3.4.1 Removal of wind turbine and monopile and placement of new turbines and monopiles: same location

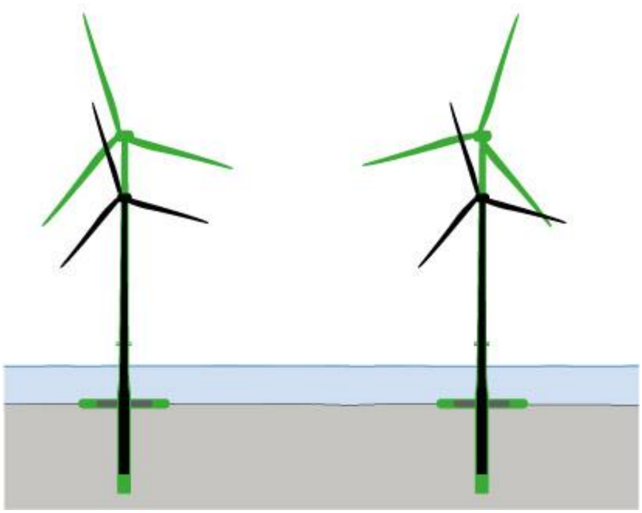


Figure 3.9 Replacement of wind turbine and monopile.

When there is a possibility to combine the new wind turbines with the old constructions, parts of these turbines can remain on site (figure 3.9). This may apply to the scour protection and in some cases to its foundation, depending on the type which is used. In this case, wind turbines are placed at the exact locations of the previous wind turbines. Gravity-based foundations are designed to last for 100 years, although currently no foundation has reached this age (Topham *et al.,* 2019[1]). This provides an opportunity for re-using these foundations.

3.4.2 Removal of entire wind farm and placement of new wind farm

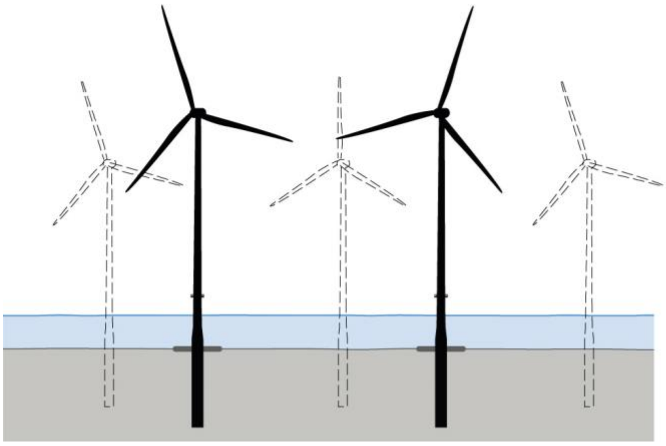


Figure 3.10 Removal of entire wind turbines and replacement on the same site.

When a wind farm has reached its designated lifespan, but the location is still considered to be feasible for generating wind energy, also an entire new wind farm can be constructed at the same site. Since technologies in the offshore wind energy sector are rapidly evolving, there is a chance that new turbines cannot be placed on the former foundations and/or monopiles, for example due to differences in size or design or with regards to the guaranteed remaining life cycle of the (monopile) foundation. In this scenario all parts of the old wind farm are removed before the new wind farm is built (figure 3.10). So far none of the decommissioned offshore wind farms have been replaced by a new wind farm.
Due to the rapid upscaling of turbine sizes, developments in technologies, and the lack of spare parts, removal of the turbine is often the preferred option. Nearly 95% of the weight of current wind turbines consists of steel, cast iron and copper, and could potentially be recycled onshore (Topham, 2020). The five percent of the wind turbines that cannot be recycled, consists of electronics, lubricant, cooling substances and polymers, which are mainly used in the blades (Topham *et al.,* 2019; Jensen, 2018).

3.4.3 Partial removal of old wind farm and placement of new wind turbines on new sites.

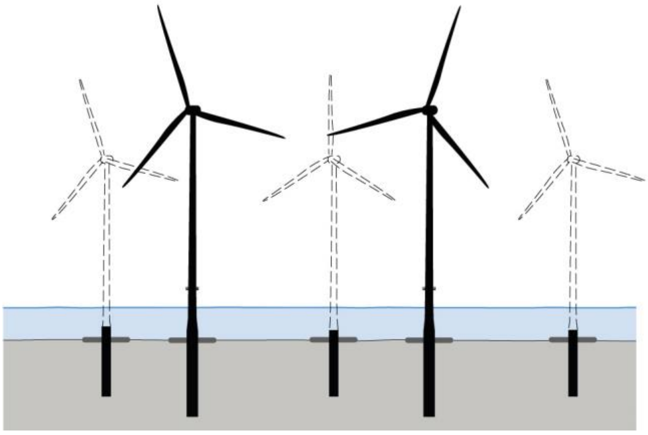


Figure 3.11 Partial removal of wind turbines and replacement on the same site.

At last, there is the possibility to build new wind turbines at the same site, while leaving part of the old construction in place (figure 3.11). So far none of the decommissioned offshore wind farms have been repowered, and therefore this method has not yet been implemented.

3.5 Removal of infield cables

Within an offshore wind farm, a network of cables is present for the transportation of the generated electricity to shore. The types of cables can be divided into two main groups: the infield (inter-array) cables that connect wind turbines with each other and with the central sub-station of the wind farm, and the export cable connecting the sub-station with the land (Ramírez *et al.,* 2020). The cables are most often placed more than one metre below the seabed (Topham & McMillan, 2017). Where the lifespan of turbines is expected to be 20 to 25 years, cables could last from 30 (Witteveen & Bos, 2017) up to 50 years (Topham *et al.,* 2019). During the decommissioning of a wind farm, the infield (inter-array) cables can be partially removed, being cut off close to the foundation of the turbine and reburied in the seabed (Topham & McMillan, 2017). By a complete removal the cables can be removed by pulling and excavating measures.

4 Ecological impact decommissioning strategies below water

4.1 Overview of effects

The ecological effects that are taken into account in this study for marine species and habitats are divided into effects during deconstruction and after deconstruction (tabel 4.1). No prioritisation is made.

Tabel 4.1 Overview of discussed activities, risks or other aspects that can potentially cause an ecological effect on present marine ecosystems within the wind farm.

Process	activity / risk / aspect
Deconstruction	Noise pollution and vibrations
	Bottom disturbance
	Risk of spreading non-native species
	Risk of chemical pollution
Post-deconstruction	Removed artificial hard substrate
	Removed stepping stone function for non-native hard-substrate species
	Exclusion from bottom-disturbing fisheries removed
	Removed disturbance of stratification layers

As this is an exploratory study, effects are only discussed and not evaluated. Important knowledge gaps that may hamper proper assessment and future decision-making are defined.

4.2 During deconstruction process

The deconstruction process of an offshore wind farm involves activities that may influence species or habitats. There are no known studies on the effects of the deconstruction of offshore wind farms on species and habitats, so information provided here is based on current educated expert knowledge of the potential effects of the construction and operation of existing offshore wind farms.

4.2.1 Noise pollution and vibrations

The removal of the wind turbine, monopile (or other foundation), scour protection and/or infield power cables causes noise pollution and vibrations, which can have an impact on aquatic species, like fish, benthos and marine mammals. Methods of removal vary widely and are dependent on which decommissioning strategy is chosen and what kind of foundation is present. The main scope is to transport structures as complete as possible, simplifying the operations offshore and reducing the time and economic expenditure. Namely, offshore lifting is risky and dependant on wind speed, so the preference is often to maximise onshore disassembly (Tophman, 2017).

Noise and vibrations are produced from the deconstruction ship itself, but also from the decommissioning activities, such as:

- Removing the wind turbine by removing the bolts with normal methods, or with angle grinders and plasma cutters if the first option is not possible;
- Cutting of a monopile, jacket or tripod below or above the sea floor;
- Removing the entire gravity-based foundation, monopile, jacket or tripod;
- Removing the scour protection.

As sound levels of above activities have not been published or studied yet, it is not known to which extend these can harm the marine environment. Current assessments commonly assume that noise and vibrations during the decommissioning phase are of a similar temporary and local nature and size to the ones produced during the construction phase. Therefore, ecological effects during deconstruction are considered to have the same (or less) impact on the marine environment as during construction and mitigation measures similar to the ones applied in the construction process can be applied to minimize the effect.

4.2.2 Bottom disturbance

The disturbance of the top layer of sediment at an offshore wind farm site due to the removal of monopiles, scour protection and/or infield power cables causes benthic species to be displaced or damaged. Whether this affects the present species composition long term, is largely dependent on the location of the offshore wind farm. In highly dynamic areas, species are often adapted to being buried or displaced by sand waves, while in low dynamic areas species are adapted to a stable environment and do not often survive burial or displacement (Daan *et al.,* 2009; Leewis & Klink 2017; Leewis *et al.,* 2018). The effect of bottom disturbance therefore is location dependent and will have a larger impact in areas where species are adapted to low disturbance and low dynamic conditions.

Turbidity

Besides disturbance from displacement of sediment and associated species, bottom disturbance can also cause a temporary higher turbidity (loss of transparency) in the water column. As fish and marine mammals may rely on eyesight to locate prey, this can have an effect on their feeding abilities. Moreover, increased turbidity within the water column can also hamper primary production by phytoplankton, particularly when occurring during potential blooming periods of the year.

Similar to noise and vibrations, the increase in turbidity is a short term- and local effect, most likely not impacting North Sea level populations of fish or marine mammals. However, when large scale decommissioning activities are taking place on multiple sites within the North Sea region, this might generate a negative cumulative impact.

4.2.3 Spread of non-native species

By transporting monopiles and scour protection to shore a risk arises that non-native species, which have settled on the artificial substrate, can spread to new locations in the process of transportation. The risk of this happening might increase when it concerns decommissioning at far offshore locations, and thus distant from the coastal region where the actual recycling takes place. This risk can be restrained by carefully removing non-native species from the monopile before transportation (labour intensive), or safely transporting the materials to minimize the risk of spread.

4.2.4 Chemical pollution

When a wind farm is decommissioned there is a risk of chemical pollution, which mainly involves the risk of spilled oil or resin that is present within the wind turbine (Topham *et al.,* 2019; Jensen, 2018). Chemical pollution can harm the entire food chain of the North Sea, from phytoplankton to birds and mammals, and should be well considered. To prevent or reduce the potential risk of spillage during decommissioning, the turbines can be emptied. Another option when decommissioning is to safely conceal the turbine and parts that contain chemicals.

4.3 Post-decommissioning

The post deconstruction effects of an offshore wind farm may involve impacts on species or habitats, as the habitat composition of a wind farm site changes due to decommissioning activities. There are no known studies on the effects of the deconstruction of offshore wind farms on species and habitats, so information provided here is based on the best currently available expert knowledge of the potential effects of the construction and operation of existing offshore wind farms.

4.3.1 Removal artificial hard substrate

By decommissioning of an offshore wind farm becomes the artificial hard substrate (foundation and scour protection) (partially) removed. This process is accompanied by the removal of associated species on these substrates. Namely, the monopile (or other foundation type) and scour protection is during its 20 -25 year life span commonly colonised by epifauna communities. These communities were not locally present before the construction of the wind farm, because OWF sites in the North Sea are most often built on soft sediment substrate (sand/muddy sand). As the monopiles (or other types of foundations) and the scour protection offer artificial hard substrates in an otherwise soft sediment dominated ecosystem, they increase habitat diversity and thereby local biodiversity and species biomass (Coates *et al.,* 2014; Coolen *et al.,* 2015; Dannheim *et al.,* 2020).

Species that can profit from the artificial substrate provided in offshore wind farms, are species that require settlement substrate (epifauna), shelter in crevices, foraging habitat (mobile macrobenthos, fish and cetaceans) or even spawning habitat (fish) on and around the substrate (appendix 2). On the other hand, also non-native species associated with hard substrate can profit from the artificial substrate, which they can use as a stepping stone to further colonize the North Sea region.

As differences between decommissioning strategies mainly differ in the amount of artificial substrate that is (partially) removed it is important to have an understanding of the species present on and around the monopile and scour protection and will be affected. A more elaborate description of marine species that benefit from the artificial hard substrate is presented in Appendix 2.

4.3.2 Removal of exclusion from bottom disturbing activities

Currently, in most OWFs bottom-disturbing activities such as fish trawlers are not allowed, partly to protect infield cables but also for the prevention of safety hazards. As the North Sea is an intensively fished and bottom-disturbed region, OWFs are one of the few areas where the seafloor is not disturbed by bottom-trawling fishing gear. As shown in figure 4.4, most parts of the North Sea are trawled at least once a year.

This no-fishing zone between the monopiles results in an undisturbed seafloor. The direct effects of excluding bottom-disturbing fisheries on benthic organisms are reduced mortality, change in the availability of food and change in habitat conditions. Species that benefit from the current conditions with regular soil disturbance (such as worms) are likely to decline and the productivity of the soil community may change (van Denderen *et al.*, 2013).

Positive effects that can occur are development opportunities for bivalves, burrowing sea urchins, epifauna, long-lived species in the soil and biogenic reefs (Jongbloed *et al.*, 2013), lobsters (Roach *et al.*, 2018) as well as an increase in species biomass and biodiversity (van Denderen *et al.*, 2014; Reiss *et al.*, 2009, Eigaard *et al.*, 2016, Roach *et al.*, 2018). A decrease in soil disturbance can also lead to an increase in organic material in the soil. As a result, for example, more white furrow shell *Abra alba* can grow (de Jong *et al.*, 2015).

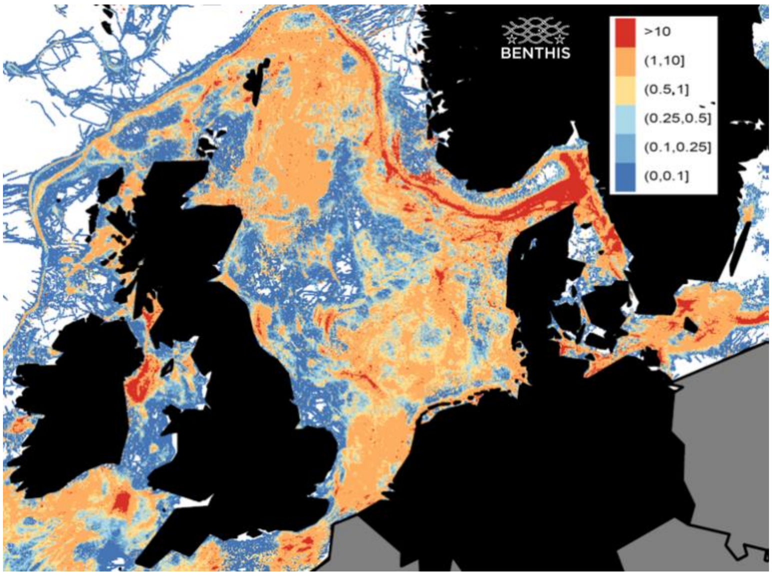


Figure 4.4 Bottom trawling activity in the North Sea. Colour indicates average number of times per year a unit area (1.9 km^2) is trawled (BENTHIS).

However, these positive ecological effects are location dependent. Areas that are naturally low-dynamic will benefit more from the absence of bottom-disturbing fisheries than high dynamic areas that are adjusted to an increase in bottom disturbance from natural processes (Rijnsdorp *et al.*, 2017).

Decommissioning of an offshore wind farm will likely allow bottom disturbing fisheries to return in the area. As regulations that establish an exclusion zone are related to the operational activity of a wind farm, once the wind farm is removed these regulations will likely not apply anymore.

4.3.3 Disturbance in stratification layers

Stratification is the formation of different density layers within the water column, caused by differences in temperature and/or salinity, wherein water with the lowest temperature and highest salinity occurs at the bottom of the water column. The stratification pattern in the North Sea is dependent on the location and time of year (figure 4.5).
Stratification affects light transmission in the water column and nutrient availability, which in its turn determines the biological activity in the area. Whereas stratification can limit nutrient access, mixed waters can increase the level of suspended matter in the water and thereby decrease light intensities (Van Leeuwen *et al.,* 2015).

Large scale offshore wind farm developemnts can affect stratification levels in the water column (Boon *et al.*, 2018). As the tidal currents move past the turbines, they generate a “wake”, which decreases stratification of the water column. At small scale this effect is negligible, but when large areas of the North Sea region are occupied by wind farms it can cause a significant impact (Boon *et al.*, 2018; Carpenter *et al.,* 2016). Floeter *et al.* (2016) proposed comparable findings, providing results on the increased vertical mixing in the water column within offshore wind farms, which lead to a reduced thermocline and more transportation of nutrients to the sea surface. The complete removal of an offshore wind farm nullifies the disturbance of stratifications layers.

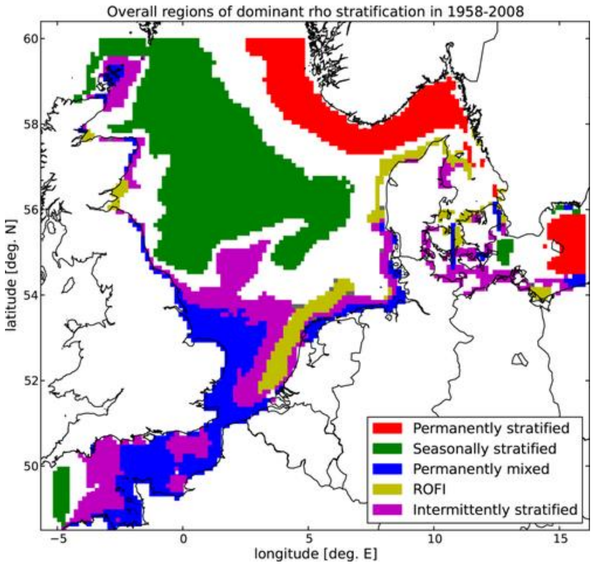


Figure 4.5 Water stratification modelled for the North Sea (Van Leeuwen et al., 2015).

4.4 Ecological impact per strategy

To determine the ecological impact of different decommissioning strategies, the above-described ecological impacts are assessed per strategy. This assessment is based on available literature and expert judgement. As decommissioning of wind farms is a relatively new development, its possible impacts and differences between strategies can only be roughly estimated. Gaps in the knowledge are defined, which can aid in improving the quality of future assessments.

The 'spread of non-native species during transport' and 'chemical pollution' as risks of deconstruction of are not further discussed as they apply to all strategies and do not significantly differ among strategies.

4.4.1 Complete removal

'Leave it be' strategy (figure 4.5)

During deconstruction

When completely removing a wind farm, the effect of noise pollution and vibrations can have a negative impact on benthos, fish and marine mammals. As sound levels during deconstruction are still unclear it is not known to what extend species can be impacted. Expected is that the noise and vibration levels do not exceed the noise and vibration during construction and with similar mitigation measures negative impacts can be minimized.

Bottom disturbance during deconstruction, by removing scour protection and foundation, can also have a negative impact on marine life. The species present can be directly affected by burial or dislodgement during the removal activities. On the long-term, complete removal with a 'leave it be' strategy can leave holes within the sea floor up to several metres deep (figure 4.5). The effect of these holes on local biodiversity and biomass has not yet been studied but it is known that it can take years (<10 m) to decades (>10 m) for these holes to fill up with sediment.

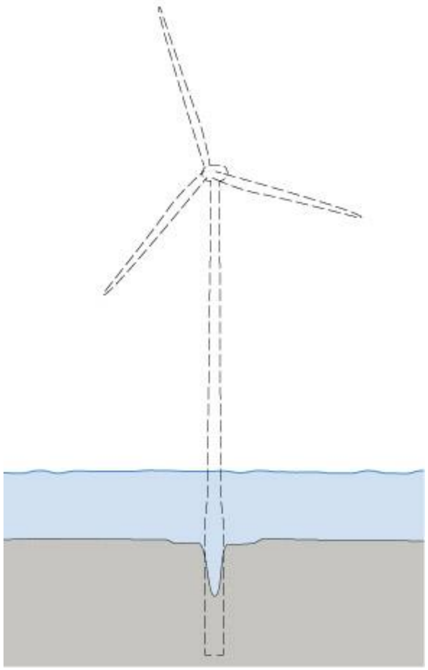


Figure 4.5 Complete removal 'leave it be'

Studies on the biodiversity within sand extraction holes has been and shows life returning to the extraction site within a year, but full recovery of the site can take up to decades, depending on the extraction depth and location (de Jong *et al.,* 2016).

Post deconstruction

Complete removal of a wind farm ensures no artificial material is left on site and the site is returned to its original state. In most cases this means an ecosystem dominated by soft sediment. The complete removal of the artificial substrate (foundation and scour protection) goes coupled with the complete removal of epifauna / macrofauna species living on the monopile and scour protection and also reduces the foraging function of the location for certain fish and cetacean species. Most of these epifauna species are not present in the area before construction of the wind farm but can colonize the artificial substrate in its 20-25 years lifespan. In addition to the removal of native epifaunal and macrofauna species associated with hard substrate, non-native species are also removed. This in turn directly reduces the risk of an OWF to act as a stepping stone for non-native species.

Due to the exclusion of bottom-trawling fisheries, the sea floor between the monopiles is undisturbed for 20-25 years lifespan of the wind farm, favouring long-lived benthic species and creating possibilities for biogenic reef systems to develop. When completely removing a wind farm also entails that bottom trawling fisheries can return, leading to damaging or removing potentially protected habitats (biogenic reefs H1170). The likelihood of these protected habitat types and species to be present within a wind farm site is strongly dependent on the abiotic conditions and presence of natural reef systems in the area. On locations in the North Sea where natural reef systems are not (and have not been) present due to local conditions (hydrodynamics, sediment type, location) the chances of these species and habitats to successfully colonize an offshore wind site are minimal, as these are not adapted to these habitat zones and most likely will not thrive in these areas.

The possible destratification effect of large-scale offshore wind farms is nullified by completely removing wind farms after their operational period.

Active bottom profiling (figure 4.6)
During the wind farm decommissioning process, the foundation and monopiles can leave holes within the sediment up to several metres deep. Depending on location (hydrodynamics, sediment particle size and intensity of activities), these holes can remain present for multiple years. By active profiling these holes are filled up with sediment present on the site (figure 4.6). Thereby the OWF site returns to its state prior to the wind farm construction. During the filling up of the holes, the nearby bottom is disturbed, and benthic organisms present may be buried or crushed. After filling up the holes the biodiversity and biomass will restore to the T0 state within years to decades, depending on the dynamics of the area.

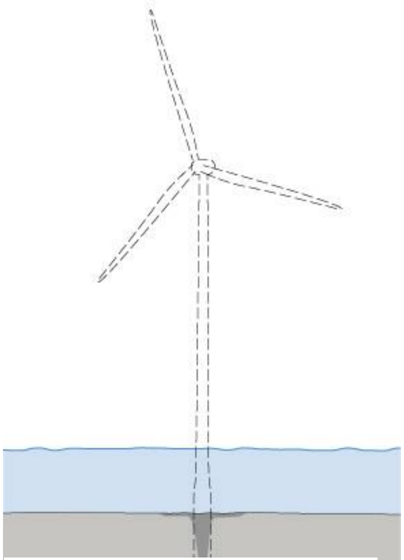


Figure 4.6 Complete removal 'bottom profiling'

4.4.2 Partial removal

Removal of wind turbine (figure 4.7)

During deconstruction

When partially removing a wind farm and only removing the wind turbine, noise pollution and vibration have a lower impact on marine life than during complete removal of a wind farm. As only the wind turbine needs to be removed, and the monopile and scour protection can stay in place (figure 4.7), bottom disturbance is low to none, as all decommissioning activities take place above the sea floor.

Post deconstruction

By only removing the wind turbine, artificial hard substrate from the monopile (or other type of foundation) and scour protection stays intact. Epifaunal species on the monopile and scour protection remain present and specific fish and cetacean species can still benefit from the habitat functions the monopile and scour protection offer. On the other hand, the artificial substrate still acts as a stepping stone for non-native macrofauna species and the area is not reclaimed to its original state as artificial materials remain on the sea floor.

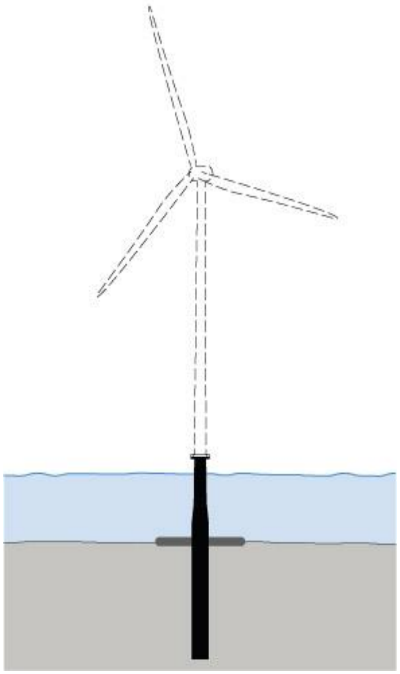


Figure 4.7 Partial removal only wind turbine

Protected species and habitats, like flat oysters or *Sabellaria* reefs (if present), can remain present on the scour protection and monopiles or surrounding soft substrate.

Exclusion from bottom trawling fisheries has a beneficial effect on the biodiversity and biomass within a wind farm. When partially removing a wind farm, most likely bottom trawling fisheries will return, if the area is favourable for bottom trawling activities and no formal exclusion remains in place. The monopile and scour protection however remain in the area and therefore bottom disturbing fisheries are partially prevented by the remaining structures. The monopile and scour protection can thus form a refugee for fish and benthic species, in a similar way as the functioning of shipwrecks in the North Sea.

When only removing the wind turbine, the disturbance in stratification layers will remain apparent. The effects on the stratification layers can impact the biological activity of the whole North Sea if a large number of monopiles remain in place (Boon *et al.*, 2018).

Removal of wind turbine and monopile aboveground (figure 4.8)

During deconstruction

When not only removing the wind turbine but also cutting off part of the monopile, noise pollution and vibrations will be higher compared with only removing the wind turbine. Namely, not only the wind turbine needs to be removed but also the monopile (or other foundation) needs to be cut off. When removing only the wind turbine and top part of the monopile, bottom disturbance will be low to none, as decommissioning activities take place above the sea floor.

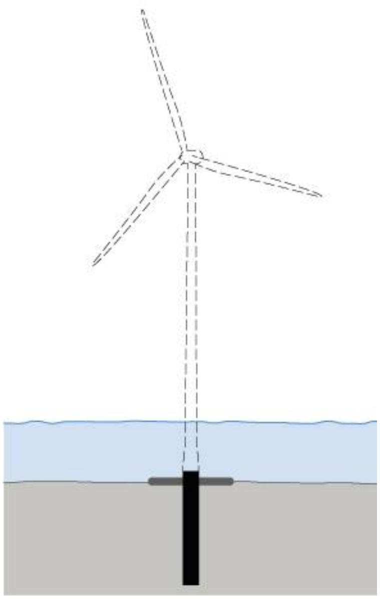


Figure 4.8 Partial removal wind turbine and monopile (above sea floor)

Post deconstruction

The difference between only removing the wind turbine and removing the wind turbine and part of the monopile mainly lies in the fauna present on the monopile. As the top part is cut off, part of the colonizing fauna is removed. A direct benefit from removing the top part of the monopile is reducing the hazard of the spread of non-native species, as most of these species reside in the intertidal zone of the monopile. The scour protection and bottom part of the monopile, which harbour most divers epifaunal species composition, will stay in place.

Removal of wind turbine and monopile belowground (figure 4.9)

When not only removing the wind turbine but the entire monopile as well (or at least below the seafloor), bottom disturbance increases and the epifauna community on the monopile is lost. It is unclear how the scour protection will stay in place after removing the monopile. If part of the sour protection is buried during removal activities, this will affect the organism growing on and between the scour protection and reduce the biodiversity and biomass of epifaunal species. In addition, also the refugee function of the artificial substrate will be reduced, as physical obstacles (*i.e.* the monopile) for bottom disturbing fisheries are removed.

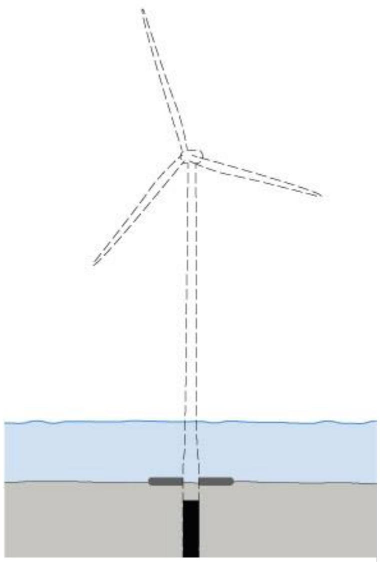


Figure 4.9 Partial removal wind turbine and monopile (blow sea floor)

A benefit of removing the entire monopile is the reduction of the hazard of the spreading non-native species, as most of these species reside in the intertidal zone of the monopile. Moreover, removal of the monopiles nullifies the disturbance in the stratification layers in the North Sea.

4.4.3 Repower

Complete removal old wind farm, new turbines in same area (figure 4.10)

During deconstruction and construction

When repowering a site, the effects during deconstruction are similar to those during complete or partial decommissioning. As the wind farm is not merely removed but also rebuilt, both removal activities and construction activities take place, and hence the impact period will be longer.
Due to both activities taking place (removal and repower), also bottom disturbance takes place over a longer time period and thus have a larger impact on marine life.

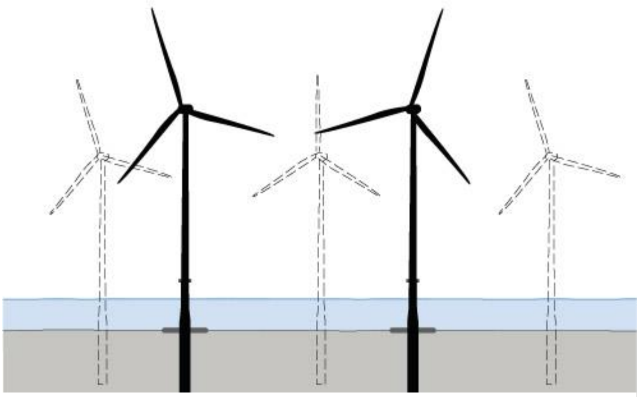


Figure 4.10 Complete removal and repower

Post deconstruction and construction

When completely removing the old wind farm from site, species that have settled on the scour protection and monopile will be lost. Establishing a new wind farm creates new settlement opportunities and epifaunal species will have the opportunity to recolonize the site. The risk of the site acting as a stepping stone for spreading non-native species remains present, as new turbines are placed that can facilitate non-native species.

During complete removal of the old wind farm, protected species and habitats that were formed on the artificial hard substrate will be lost. Protected species and habitats present between the monopiles can also be impacted if the new wind farm is placed in a different configuration, affecting the undisturbed habitat between the old monopiles.

If bottom trawling fisheries remain excluded from the wind farm site, the bottom will stay undisturbed after construction of the new wind farm.

Partial removal old wind farm, new wind farm in same area (figure 4.11)

The main difference between partial and complete removal of the old wind farm and repowering is the amount of artificial substrate in the area. When partially removing the old wind farm and repowering a new wind farm on site, the amount of artificial material within the area increases. The epifaunal communities in the old wind farm remain present and the newly placed monopiles and scour protection create additional habitat to be colonized. Protected species and habitats (when present) on the

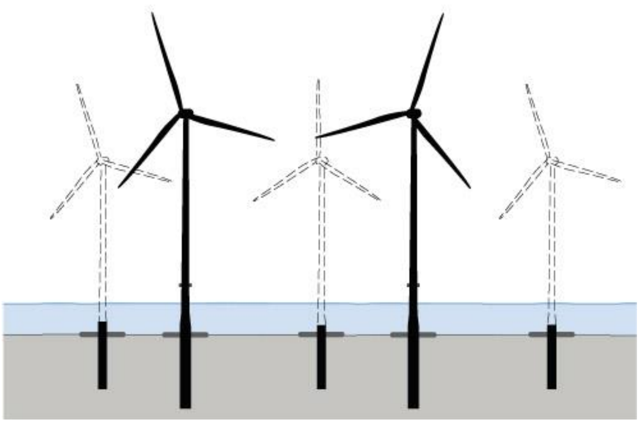


Figure 4.11 Partial removal and repower

monopiles and scour protection of the old wind farm can remain present and can colonize the new substrates easily. However, the favourability of the site for non-native species also enhances, as more artificial substrate will be present.

4.4.4 Removal Infield cables

Besides complete or partial removal of the wind farm the infield cables between the wind turbines can also be removed or (partially) left in the sea floor, depending on the permit.

Complete removal inter-array cable network

When completely removing the infield cables bottom disturbance will increase, as the cables have to be pulled or excavated out of the seabed. Local infauna and biogenic reefs (if present) located above the cables can get damaged during these activities.

Cut off cable at foundation and leave behind.

When the cable is cut off at the foundation, the bottom disturbance will be of lesser impact, as the cable does only need to be excavated close to the foundation. The drawback of this strategy is that despite the low impact during the decommissioning phase, large amounts of non-natural materials (plastics/metals) stay in the environment, buried in the sand.

5 Ecological impact decommissioning strategies above water

5.1 During deconstruction process

The deconstruction process of an offshore wind farm involves activities that may influence species of birds and bats in the area. There are no known studies on the effects of the deconstruction of offshore wind farms on birds or bats, so the information provided here is based on current knowledge of the potential effects of the construction and operation of existing offshore wind farms.

The main factors potentially affecting birds and bats during the deconstruction phase include increased shipping activity, aerial structures such as cranes, additional lighting and noise and the disappearance of the actual turbines and related structures. The activities and presence of vessels, lighting and noise during this phase may lead to increased risks of disturbance, barrier effects or collisions for birds and bats (Rebke *et al.,* 2019). Furthermore, there is the potential for pollution or chemical spills from increased shipping activity and deconstruction processes. This potential for pollution, however, unless particularly severe, or in an area with large numbers of sensitive species, is unlikely to be a key concern so is not discussed further here.

The temporary and localized nature of the deconstruction process is unlikely to result in higher levels of collisions or barrier effects than during the operational phase, except under certain circumstances with high concentrations of flight activity in the area or where this increases due to attraction to lighting or under certain conditions (Wiese *et al.,* 2001). Disturbance of some species may be higher during the deconstruction phase, although again for most species this is likely to be temporary and at the local level (Kahlert *et al.,* 2004).

Effects may be higher at certain times of year or under specific weather conditions when higher concentrations of birds or bats can occur, such as during the breeding season or during favourable conditions for migration (Kahlert *et al.,* 2004; Lagerveld *et al.,* 2017), although any effects could be expected to be minimal. Mitigation for the negative effects of the deconstruction phase largely lie in the timing of deconstruction for periods when densities of sensitive species are at their lowest. Furthermore, reduction of noise, lighting and shipping activity will also help to reduce potential effects on birds and bats. The use of certain types of lighting on board vessels and the reduction in the intensity of lighting at night can also help to reduce the attraction of birds (OSPAR, 2012, Poot *et al.,* 2008).

5.2 Post-decommissioning

For birds and bats, the complete removal of the above-water components of offshore wind farms will nullify the effects of the presence of a wind farm; these being negative effects such as collision risk, barrier effects and effective habitat loss (or disturbance) (Drewitt &

Langston, 2006). Nevertheless, to some degree also positive effects will be removed as well. Namely, structures may act as resting places for some species of both birds and bats and the removal of these may therefore reduce the use of the area by some species (Vanermen *et al.*, 2013, Vanermen *et al.*, 2014), e.g., cormorants in areas further than ca. 15km from the coast. This will result in a situation more akin to the one before the wind farm was built with birds using wind farms as resting place present in lower numbers.

Following deconstruction, changes in the underwater ecology of the area is also likely to have an effect on some bird species, particularly those that feed on fish and other marine organisms. This is unlikely to influence bats and terrestrial species of birds. Potential influences on underwater organisms are discussed in §4.2. Currently, little is known about the role of changes in prey availability on the presence of birds within wind farms.

The species affected and the type and level of effects will depend on the level of deconstruction and any subsequent reconstruction. The complete removal of above-water structures will result in different effects in comparison with partial deconstruction, while active restoration and repowering scenarios bring additional effects, as well as their own opportunities to mitigate those.

5.3 Ecological impact per strategy

To determine the ecological impact of different decommissioning strategies the above-described ecological impacts are assessed per strategy. This assessment is based on available literature and expert judgement. As decommissioning is a relatively new field of knowledge, the assessment only gives a rough estimate of effects. Knowledge gaps are defined, which can aid in improving the quality of futures assessments.

5.3.1 Complete removal

Collisions have long been considered one of the most important negative impacts of wind turbines on birds. The same holds true for bats (Arnett *et al.,* 2016; Thaxter *et al.,* 2017). More recently the impacts of disturbance, effective habitat loss and barrier effects have also received more attention. The species that are impacted by each of these differ (Garthe & Hüppop 2004; Bradbury *et al.,* 2014; Diershcke *et al.*, 2016).

The complete removal of above-water structures will eliminate the risk of collisions for flying birds. This will benefit both marine species as well as migrant land-based species. Bats will no doubt also benefit from the lack of collision-risk but are thought to benefit from prey that are found close to the rotors with turbines appearing to attract them (Cryan *et al.,* 2014).

Offshore wind turbines have the potential to act as temporary roost places areas for bats. Removal of above-water parts of turbines will result in a loss of these functions. Any effects may be most evident in species that use offshore wind farms during migration, particularly where they are speculated as having a ‘stepping stone’ function. Whether these effects are desirable depends on the species concerned and in the case of exotic species may be unwelcome.

Similarly, offshore wind farms may extend the available habitat of coastal species of birds, such as cormorants, gulls and terns, that use the structures for resting. Cormorants (*Phalacrocorax* spp.) in particular rely of such haul-outs between foraging bouts. The presence of offshore structures can increase the number of coastal species in areas where they otherwise would not regularly occur.

Disturbance effects resulting from the presence of offshore wind farms can influence different species greatly (Garthe & Hüppop 2004; Bradbury *et al.,* 2014; Dierschke *et al.*, 2016; Leopold 2018). This can translate into lower densities of birds in and around the active wind farm resulting in effective habitat loss (Peschko *et al.,* 2020). The removal of above-water structures will remove this source of disturbance, opening up the habitat for species that would otherwise have been absent or present in lower numbers.

Conversely, some species may be attracted to the wind farm, particularly due to perching opportunities or possibly due to increased prey availability. For the latter, underwater factors are likely to be more important than the presence of above-water structures and numbers are likely to be unaffected by the removal of above-water structures. On this subject, the most important effect of the removal of above-water structures is likely to be the loss of structures used as perching opportunities.

Barrier effects to both local (particularly breeding birds) and migrating birds can occur. This results in additional energy expenditure as birds change their flight routes to avoid offshore wind farms and in extreme cases may result in the areas behind the wind farm becoming too energetically costly to utilise. Although there are relatively few studies quantifying barrier effects, and those available mostly consider these effects as marginal, the absence of such effects will likely benefit species that breed close to the wind farm area and make regular trips to the area (Kahlert *et al.,* 2004; Masden *et al.,* 2009; Fox & Petersen 2019).

5.3.2 Partial removal

Partial removal here, in relation to birds and bats, assumes certain above-water structures remain after the removal of the rotors and turbine. Removal of the moving parts of the turbine would result in far fewer collisions, which are considered to be negligible with supporting structures. Remaining structures would provide opportunities for perching, resting or maybe even nesting, although in an area that lack similar structures in a natural sitaution. The benefits of the remaining structures to birds and bats following partial removal could be enhanced further through the inclusion of additional structures to provide perching, nesting and roosting sites.

Based on incidental observations, static posts and small, low-level platforms could be expected to result in less disturbance than moving wind turbines. How birds may react to large numbers of these is difficult to judge but, as with active wind farms, it is likely to differ depending on the species, location and possibly time of year. Furthermore, lighting and human movement due to maintenance of these structures has the potential to cause further disturbance.

5.3.3 Repower

Based on current trends, repowering of wind farm areas could be expected to result in fewer, but larger turbines. This situation would have an effect on birds and bats in relation to collisions, disturbance (effective habitat loss) and barrier effects. The level to which these effects will change is dependent on a range of factors such as the number and size of turbines, location and layout, turbine design, colour and lighting, and operating protocols.

In general, the number of collisions increases with increasing numbers of turbines, although collision risks and rates vary depending on turbine size, height and operating characteristics. Assuming fewer turbines, the number of collisions could also be expected to be lower. Disturbance and barrier effects may also be lower in situations where the footprint of the repowering scenario is smaller than the existing situation. In case the footprint remains comparable to the original wind farm, the spacing between turbines could be expected to be larger. This could result in different levels of disturbance, both around and within the wind farm, and although it could be expected that larger turbines could result in disturbance effects at greater distances, particularly if lit (Heinänen *et al.,* 2020), currently few data exist to back up notions of differences from layouts within wind farms (Leopold 2018).

To properly assess the potential effects of repowering, scenarios should be assessed at the time based on the latest knowledge and methods available at the time.

6 Discussion and conclusion

6.1 Decommissioning offshore wind farms North Sea region

After operation (20-25 year lifespan), wind farms need to be decommissioned in accordance with the 1989 resolution of the International Maritime Organization (IMO/ OSPAR Decision 98/3 and national regulations). Decommissioning of offshore wind farms is already taking place and decommissioning activities will increase in the upcoming decades. Most offshore wind farms are planned to be decommissioned between 2040-2060 (and onwards), as most wind farms are planned to be constructed between 2020-2040.

Several decommissioning strategies for offshore wind farms exist:

- Complete removal. The entire wind farm is being removed and no artificial material is left on site. To fill up holes in the seafloor left by monopiles or other foundations the bottom can be profiled after removal.
- Partial removal. The wind turbine is removed and possibly also (part) of the monopile.
- Repower. The wind farm site is repowered, by placing new wind turbines on existing scour sites, or by removal of entire old wind farm and placing a new wind farm. At last, the old wind farm can also be partially removed, and the new wind farm can be established within the old site.

6.2 Ecological impact

Ecological impact of different decommissioning strategies can be divided into effects of the deconstruction itself and effects of post deconstruction.

During decommissioning activities, increased shipping activity, aerial structures such as cranes, additional lighting, noise and the disappearance of the actual turbines and related structures can cause an effect on birds and bats. The activities and presence of vessels, lighting and noise during this phase may lead to increased risks of disturbance, barrier effects or collisions for birds and bats. Below water, noise pollution, vibrations and bottom disturbance during decommissioning activities and ship movement may cause an impact on marine species and habitats.

The ecological impact post-construction of the different removal strategies is summarized in table 6.1a (below water) and 6.1b (above water). Moreover, visualisations are made based on literature search and expert knowledge, and the species expected on site in different removal strategies are indicated (§6.3).

Table 6.1a Overview of most important effects of different decommissioning strategies below water.

Activity / effect		**Complete removal**	**Partial removal**	**Repower**
Below water	Removal of artificial hard substrate	No artificial material left behind, reclamation of the area to its original state	Artificial material left behind. Epifauna community and associated species remain present.	Artificial material left behind. Epifauna community and associated species remain present.
	Spread non-native hard substrate species	Removal of stepping stone / risk for spread non-native species	Stepping stone for non-native species (partly) maintained	Stepping stone for non-native species maintained
	Removal of protected/ valuable species or habitat (when present)	Valuable habitat and species affected by removal of artificial substrate and bottom disturbance (fisheries)	Valuable species and habitat maintained around scour protection and monopile	Valuable species and habitat possibly maintained around scour protection and monopile
	Exclusion of bottom trawling fisheries	Bottom disturbing fisheries re-introduced	Bottom disturbing fisheries re-introduced, artificial material can possibly act as refugee	Bottom disturbing fisheries excluded (in most OWF)
	Disturbance of stratification layers	Effect removed, by removing monopiles	Effect still apparent when monopiles are not removed	Effect still apparent

Table 6.1b Overview of most important effects of different decommissioning strategies above water.

Activity / effect		**Complete removal**	**Partial removal**	**Repower**
Above water	Collision risk	No collision risk	Negligible collision risk	Risk of collisions remains, level varying dependent on turbine characteristics
	Barrier effect	No barrier effects	Less barrier effects	Barrier effects
	Habitat loss / artificial resting places	No disturbance and effective habitat loss, but loss of artificial resting places	Negligible disturbance and effective habitat loss. Functionality as resting place remains (depending on whether above-water structures remain)	Disturbance and effective habitat loss. Artificial resting places remain

6.2.1 Ecological impact dependent on location

The impact on marine life and birds and bats caused by many of the activities and effects described above depend on the location of the offshore wind farm site. Namely, the North Sea does not consist of one uniform habitat but varies in habitat types across the shelf region. Moreover, the habitat types present in the North Sea region and their associated marine life have changed over the years (Box 1).

The impact of the decommissioning activities is therefore dependent on the location of the OWF. For example, in some areas of the North Sea an OWF may be built in a favourable site for oyster reef development. Even though this habitat was not present in the area before placement of the wind farm, it can be formed in the 20-25 year life span of the wind farm. When decommissioning such wind farm, protected marine life in the form of these oyster reefs could be damaged. Not only by the decommissioning activities themselves, but also by re-opening up the area for fisheries.

The impact of different decommissioning strategies on birds and bats is also influenced by the location of a wind farm. Wind farms further offshore may provide resting places for species that typically only occur closer to shore. Besides, in wind farms in areas of high bird flight intensity, such as close to colonies, collision and barrier effects could be expected to be higher.

Box 1 The North Sea once harboured different reef habitats at different locations
While stony reefs, oyster reefs and moor logs[1] once covered a significant part of the North Sea shelf (figure 6.1) at various locations, nowadays most of the North Sea region consists of soft sediment dominated habitats, such as coarse sand, fine sand, sandy mud or mud (EUNIS-habitat-classification). Stony reefs (H1170) are still present in some areas, but often degraded due to bottom trawling fishing activities. Oyster reefs and moor logs completely disappeared over the past 50-100 years due to human activity.

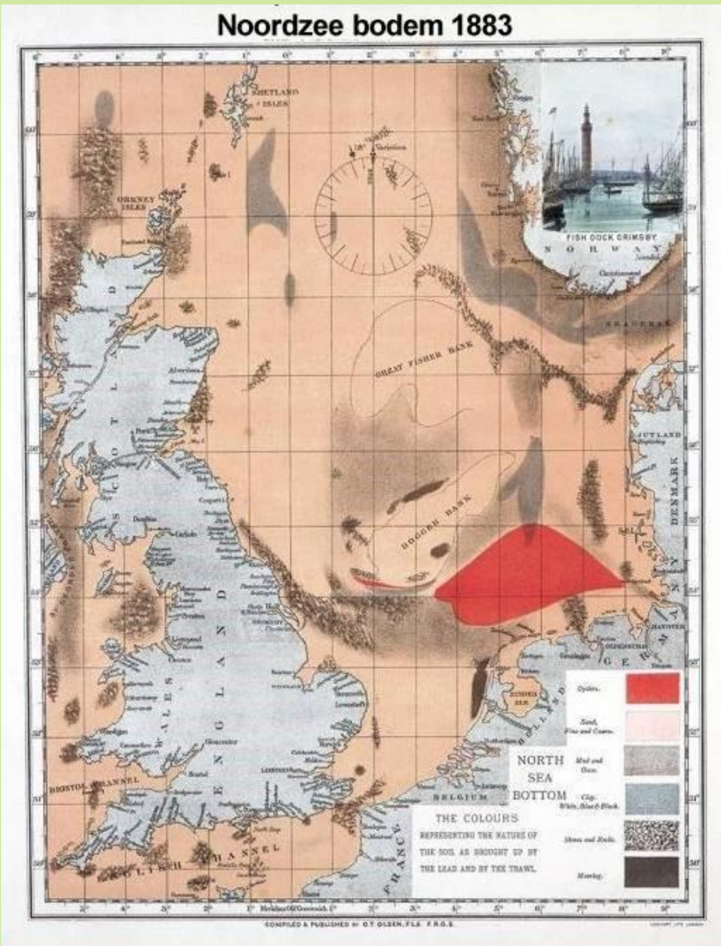


Figure 6.1. Habitat map of the North Sea (Olsen, 1883).

6.3 Knowledge gaps

During the exploratory study, knowledge gaps arose, which hamper proper assessment. Table 6.2 summarizes these knowledge gaps and prioritizes them based on the following levels:

[1] Course peat, such as ancient tree remnants, generally considered as hard substrate

1 – High priority, answers are vital for proper assessment and decision making, research is needed.
2 - Medium priority, answers are important but rough assessment is possible without additional research.
3 – Low priority, answers are supplementary and are not essential for proper assessment and decision making.

Table 6.2 Knowledge gaps

Process	Activity	Knowledge gap	Impact on	Priority
During deconstruction	Noise and vibration	Noise and vibration levels during decommissioning activities remain unclear	Benthos, fish, marine mammals and birds and bats	1
During deconstruction	Bottom disturbance	Size of the hole left during deconstruction of a wind farm and time needed for the holes to naturally fill up	Benthos present and recolonization possibilities of benthos and associated species	2
During / post deconstruction	Lighting and shipping activity	Level of disturbance unknown, dependent on activity and species	Local species (disturbance) and migrants (lighting)	2
Post deconstruction	Stratification	Tipping point, when monopiles significantly affect stratification layers and thereby biological activity at the ecosystem level	Marine ecosystem functioning	1
Post deconstruction	Removal of valuable / protected habitat types and species	Presence of valuable/ protected species and habitat within OWF, and changes of development	Valuable / protected species and habitat types	1
Post deconstruction	Resting place	Presence and value of resting places for coastal and land birds and bats.	Coastal and migrant bird species and bats, as well as underwater fauna (i.e. prey species)	2

Post deconstruction	Loss of foraging area	Implications of (partial) removal on foraging fish and seals and species composition within the area	Fish and seal species	3
Post deconstruction	Removal foundation	Amount of scour protection and associated organisms that may become buried when foundation is removed	Benthic species	2

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Appendix I: (Planned) wind farms in the North Sea

Country	Wind farm	Start construction	Planned decommissioning	Capacity (MW)	Piles (#)
Belgium	Belwind / Nobelwind	2013	2033	171	56
Belgium	Fairy Bank 1	2025	2045	700	70
Belgium	Fairy Bank 2	2027	2047	700	58
Belgium	Fairy Bank 3	2030	2050	700	47
Belgium	Mermaid (part of Seamade)	2020	2040	246	28
Belgium	Norther	2019	2039	370	44
Belgium	Northwester 2	2019	2039	219	23
Belgium	Northwind	2015	2035	216	72
Belgium	Rentel	2018	2038	209	44
Belgium	Seastar (part of Seamade)	2020	2040	246	30
Belgium	Thorton Bank / C-power	2013	2033	324	54
Denmark	Horns Rev 1	2002	2022	160	80
Denmark	Horns Rev 2	2008	2033	338	91
Denmark	Horns Rev 3	2018	2043	393	49
Denmark	Tender / Thor	2025	2045	800	80
Denmark	Vesterhavet Nord/Syd	2019	2043	344	43
France	Dunkerque	2025	2045	750	63
Germany	N-0.1 Riffgat	2012	2032	108	30

Germany	N-0.2 Nordergründe	2016	2036	111	18
Germany	N-1.1 OWP West	2024	2044	240	24
Germany	N-1.2 Borkum Riffgrund West II	2024	2044	240	24
Germany	N-1.3 Borkum Riffgrund West I	2024	2044	420	42
Germany	N-2.1 alpha ventus	2009	2029	60	12
Germany	N-2.2 Trianel windpark	2013	2033	200	40
Germany	N-2.3 Trianel Windpark Borkum Bauphase 2	2018	2038	200	32
Germany	N-2.4 Borkum Riffgrund I	2014	2034	312	78
Germany	N-2.5 Borkum Riffgrund II	2018	2043	448	56
Germany	N-2.6 Merkur Offshore	2017	2037	396	66
Germany	N-3.1 Gode Wind 01	2015	2035	330	55
Germany	N-3.2 Gode Wind 02	2015	2035	252	42
Germany	N-3.3 Nordsee One	2016	2036	332	54
Germany	N-3.4 Gode Wind 03	2022	2042	110	11
Germany	N-3.5 DE-tender 2025	2028	2048	420	35
Germany	N-3.6 DE-tender 2024	2028	2048	480	40
Germany	N-3.7 DE-tender 2026	2026	2046	225	19
Germany	N-3.7 Gode Wind 04	2022	2042	132	13

Germany	N-3.8 DE-tender 2022	2026	2046	375	31
Germany	N-4.1 Meerwind Süd/Ost	2013	2033	288	80
Germany	N-4.2 Nordsee Ost	2012	2032	295	48
Germany	N-4.3 Amrumbank West	2014	2034	288	80
Germany	N-4.4 KASKASI II	2021	2041	325	33
Germany	N-5.1 Dan Tysk	2013	2033	288	80
Germany	N-5.2 Butendiek	2014	2034	288	80
Germany	N-5.3 Sandbank	2015	2035	288	72
Germany	N-6.1 BARD Offshore	2010	2030	400	80
Germany	N-6.2 Veja Mate	2016	2036	402	67
Germany	N-6.3 Deutsche Bucht	2018	2038	260	31
Germany	N-6.6 DE-tender 2026	2029	2049	630	52
Germany	N-6.7 DE-tender 2029	2029	2049	270	23
Germany	N-7.1 EnBW He dreiht	2024	2044	900	90
Germany	N-7.2 DE-tender 2027	2026	2046	900	75
Germany	N-8.1 Global Tech I	2012	2032	400	80
Germany	N-8.2 EnBW Hohe See	2018	2038	497	71
Germany	N-8.3 Albatros	2018	2038	112	16

Germany	N-8.4	2031	2051	300	20
Germany	N-9.1	2030	2050	1000	67
Germany	N-9.2	2032	2052	1000	67
Germany	N-10	2033	2053	1700	113
Germany	N-11	2034	2054	3550	237
Germany	N-12	2036	2056	2000	134
Germany	N-13	2038	2058	2000	134
Norway	Utsira Nord			1500	
Norway	Sørlige Nordsjø II			3000	
The Netherlands	Borssele I and II	2020	2040	752	94
The Netherlands	Borssele III and IV	2020	2040	752	79
The Netherlands	Borssele V	2020	2040	19	2
The Netherlands	Gemini East	2016	2036	600	150
The Netherlands	Gemini West	2016	2036	600	150
The Netherlands	Hollandse Kust North I and II	2024	2044	760	95
The Netherlands	Hollandse Kust South I and II	2025	2045	752	94
The Netherlands	Hollandse Kust South III and IV	2023	2043	752	94
The Netherlands	Hollandse Kust West I (Noord)	2021	2041	760	76
The Netherlands	Hollandse Kust West II (Zuid)	2021	2041	760	76
The Netherlands	IJmuiden Ver I	2027	2047	1000	100

The Netherlands	IJmuiden Ver II	2028	2048	1000	100
The Netherlands	IJmuiden Ver III	2029	2049	1450	100
The Netherlands	IJmuiden Ver IV	2030	2050	1450	100
The Netherlands	IJmuiden Ver Noord	2031	2051	2000	200
The Netherlands	Luchterduin	2013	2033	129	43
The Netherlands	North East IJmuiden (6A)	2032	2052	2000	133
The Netherlands	North North Wadden (6C)	2033	2053	2000	133
The Netherlands	OWEZ	2005	2025	108	36
The Netherlands	Prinses Amaliawindpark	2006	2026	120	60
The Netherlands	Ten Noorden van de Waddeneilanden (TNW)	2026	2046	760	76
United Kingdom	Aberdeen / European Offshore Wind Deployment Centre	92	112	92	11
United Kingdom	Beatrice BOWL	2017	2037	588	336
United Kingdom	Dogger Bank Creyke Beck A	2030	2050	1200	80
United Kingdom	Dogger Bank Creyke Beck B	2030	2050	1200	80
United Kingdom	Dogger Bank Sofia	2030	2050	1200	80

United Kingdom	Dogger Bank Teesside A	2030	2050	1200	120
United Kingdom	Dudgeon	2016	2036	402	67
United Kingdom	East Anglia 1	2018	2038	714	102
United Kingdom	East Anglia 1 North	2025	2045	800	80
United Kingdom	East Anglia 2	2024	2044	800	80
United Kingdom	East Anglia 3	2030	2050	1200	150
United Kingdom	Galloper	2010	2030	353	56
United Kingdom	Greater Gabbard	2008	2028	504	140
United Kingdom	Gunfleet Sands 1	2008	2028	108	30
United Kingdom	Gunfleet Sands 2	2008	2028	64	18
United Kingdom	Hornsea Project Four	2023	2043	1000	180
United Kingdom	Hornsea Project One	2018	2038	1218	174
United Kingdom	Hornsea Project Three	2030	2050	2400	300
United Kingdom	Hornsea Project Two	2022	2042	1386	173
United Kingdom	Humber Gateway	2014	2034	219	73
United Kingdom	Hywind Scotland Pilot Farm	2017	2037	30	5
United Kingdom	Inch Cape	2020	2040	700	288
United Kingdom	Inch cape (Repsol)	2023	2043	784	78

United Kingdom	Inner D. Racebank, Linc S Shoal	2010	2030	1256	349
United Kingdom	Kentish flats 1	2004	2024	90	30
United Kingdom	Kentish flats 2 (extension)	2015	2035	50	15
United Kingdom	Kincardine	2020	2040	50	0
United Kingdom	Lincs	2010	2030	270	75
United Kingdom	London array	2010	2030	630	175
United Kingdom	Lynn	2008	2028	97	27
United Kingdom	Moray Firth Eastern Development Area	2023	2043	1116	100
United Kingdom	Moray Firth Western Development Area	2019	2039	850	340
United Kingdom	Neart na Gaoithe	2020	2040	450	324
United Kingdom	Norfolk Boreas	2030	2050	1800	180
United Kingdom	Norfolk Vanguard	2030	2050	1800	180
United Kingdom	Race Bank	2016	2036	573	91
United Kingdom	Scroby Sands	2003	2023	60	30
United Kingdom	Seagreen - Alpha and Bravo	2020	2040	1050	600
United Kingdom	Sheringham Shoal	2010	2030	317	88
United Kingdom	Teesside	2014	2034	62	27

United Kingdom	Thanet	2017	2037	300	100
United Kingdom	Thanet extension	2023	2043	340	34
United Kingdom	Triton Knoll	2010	2030	860	143
United Kingdom	Westermost Rough	2014	2034	210	35

Appendix II: Species associated with artificial hard substrate OWF

Below, a short description of each species group is given and its presence on and around artificial hard substrates of OWF. The description is a general indication based on monitoring studies within offshore wind farms across the North Sea. Important to note is that specific species compositions on monopiles (or other types of foundation) and scour protection within wind farms differ per site, as the abiotic conditions differ.

Macrobenthos/ epifauna species

Colonisation of epifaunal species happens almost instantly after an offshore wind farm has been constructed. In the intertidal zone of the monopile, mussels *Mytilus edulis* are often the most dominant species. When moving down the monopile, in the subtidal zone, *Jassa herdmani* can be the dominant species. Close to the seafloor and scour protection anemones like *Metridium senile* are most dominant (Whomersley & Picken, 2003; Lindeboom *et al.*, 2011; Krone *et al.*, 2013; De Mesel *et al.*, 2015; Mavraki *et al.,* 2020).

The total amount of epifaunal species and biomass differs based on location, substrate and over lifetime of the OWF (table 4.1, figure 4.1). Most species are found on rocky substrates (scour protection), as this substrate is more complex than the straight steel surfaces of the monopile and hence create a diverse habitat for a wide range of species (Kostylev *et al.*, 2005).

In addition to the increase in habitat complexity around the scour protection, the scour protection area also profits from the biodeposition processes of fouling organisms on the monopile. These fouling organisms create organic rich soft sediments near the base of offshore wind foundations, which in turn increase the abundance and species richness of the macrofaunal communities (Coates *et al.*, 2014; Mavraki *et al.,* 2020). Krone *et al.* (2017) showed in the German Bight of the North Sea that monopiles with scour protection harbour twice as many North Sea crabs *Cancer pagarus* than monopiles without this protection.

Non - native macrofauna

Apart from being a substrate for native species, artificial substrate can also enhance the spread of non-native hard substrate species (Adams *et al.*, 2014; Macreadie *et al*, 2011). In a monitoring study of an OWF in the Netherlands, it was found that 64% of the macrofauna samples taken held one or more non-native species (Coolen *et al*., 2020a). In total, 11 non-native species were found (9 on monopiles and 4 on scour protection). The most observed non-native species was the tunicate *Diplosoma listerianum*. In contrast, on a natural reef area in the North Sea, the Borkum Reef Ground, only two non-native species were found. Most non-native species in an OWF are found in the intertidal zone and decrease in amount with increasing depth (De Mesel *et al.*, 2015; Coolen *et al.*, 2020a).

Figure 4.1 Epifauna community on scour protection within OWEZ (Bouma & Lengkeek 2012)

Table 4.1 Number of species in offshore wind farms.

Location	Total *n* species found	*n* species found scour protection
OWEZ (2008 & 2011)	55	34
PAWP (2011 & 2013)	110	49

Fish

The high density of epifaunal species on the monopile and scour protection attracts certain fish species due to the increased prey abundance (Reubens *et al.*, 2011, 2013). On and around the monopile the species Atlantic cod *Gadus morhua*, pouting *Trisopterus luscus*, bullrout *Myoxocephalus scorpius*, common dragonet *Callionymus lyra* and sea scorpion *Taurulus bubalis* occur in significantly higher numbers on the scour protection than in the surrounding soft seabed (Van Hal *et al.*, 2017).

Krone *et al.*, (2017), sampled using scientific divers four wind turbine foundations with a substrate surface area of 1050 m^2 each. Around one monopile on average 17 individuals of Atlantic cod were observed. Rock gunnel *Pholis gunnellus* and pouting were most common around the monopiles, with on average respectively 1032 and 625 individuals (Krone *et al.*, 2017).

When looking into the feeding ecology of fish species attracted to the epifaunal community on monopiles and scour protection it is found that the benthic species bullrout and benthopelagic species Atlantic cod and pouting feed primarily on colonizing species like the amphipod *Jassa herdmani* and the long-clawed porcelain crab *Pisidia longicornis,* which live on the monopiles and scour protection *(*Mavraki *et al.,* 2020*)*. These species thus utilize artificial reefs, such as OWFs, as feeding grounds for a prolonged period.

All above mentioned species are known to be associated with hard substrates within the North Sea region and are attracted by it, as hard substrate and its associated fauna creates a suitable foraging and possible spawning habitat.

Pelagic species like mackerel and Atlantic horse mackerel *Trachurus trachurus* only occasionally use the colonizing fauna on the artificial hard substrate, like *Jassa herdmani* as a food source*.* Their main diet consists of zooplankton (Mavraki *et al.,* 2020).

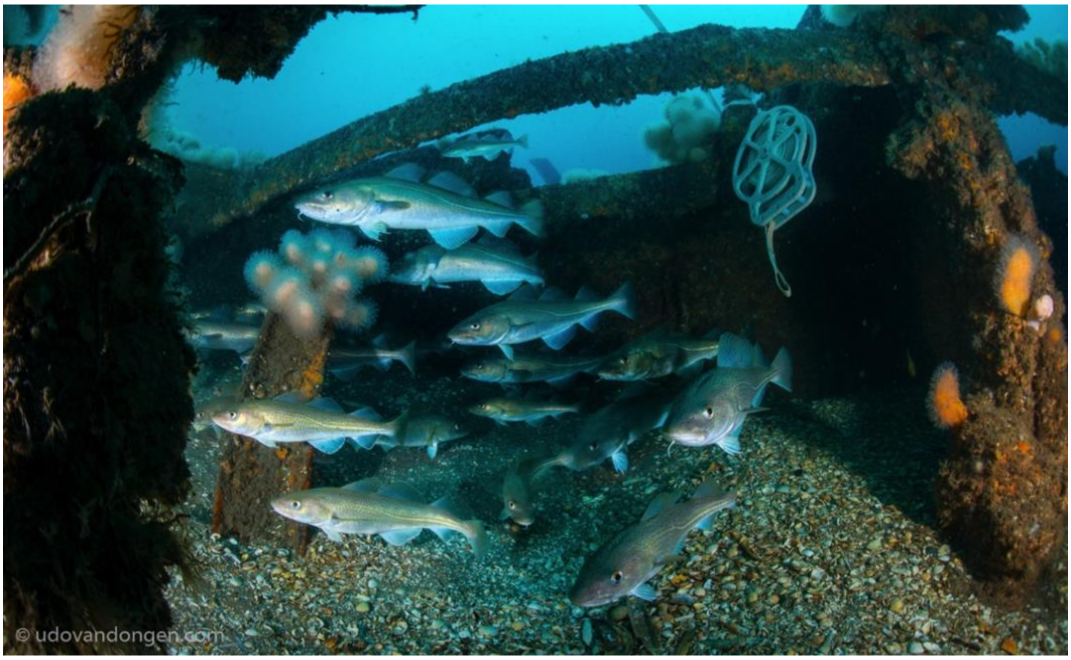


Figure 4.2 Atlantic cod (Gadus morhua) within a shipwreck in the North Sea

Marine mammals

Marine mammals are regularly sighted within offshore wind farms (*e.g.* Lindeboom *et al.,* 2011; Fijn *et al.,* 2012; Russel *et al.,* 2014) and have been seen actively foraging around the monopiles (*e.g.* Scheidat *et al.,* 2011; Russel *et al.,*2014; Bureau Waardenburg unpubl. data from OWEZ and Eneco LUD).

In the study of Russel *et al.* (2014), several seals were tagged with a GPS tracker. The data revealed that some seal individuals (both harbour and grey*)* move from monopile to monopile within an offshore wind farm and use these wind farms as foraging grounds (figure 4.3).

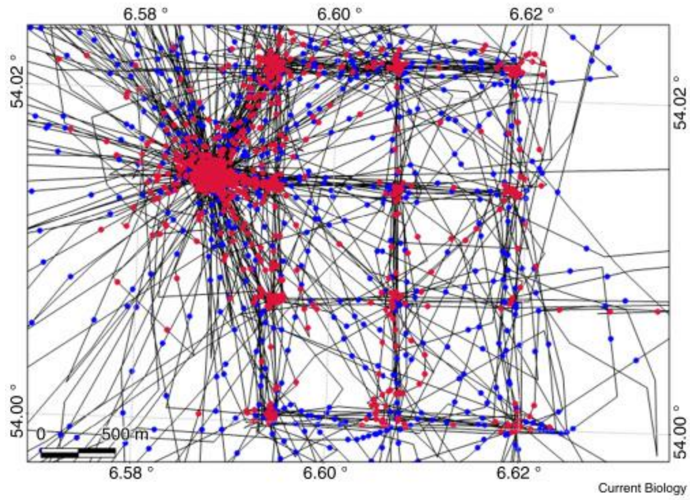


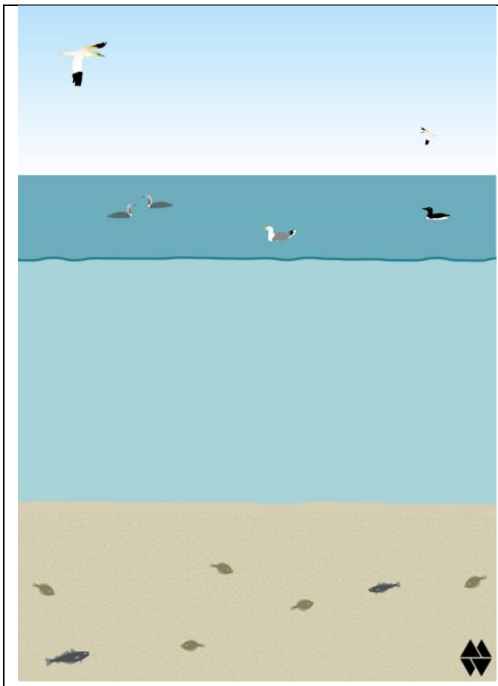
Figure 4.3 The tracks of a harbour seal in and around Alpha Ventus wind farm. Red points indicate foraging locations and blue travelling points. The individual appears to forage at altogether 12 turbines and the meteorological mast (constructed in 2003) to the west of the wind farm (Russel et al., 2014).

A study in the Dutch wind farm Egmond aan Zee investigated the acoustic activity of harbour porpoises before construction and during the operational phase of the wind farm, as well as at reference sites. Their results showed an increase in acoustic activity in the area during the operational phase, with the activity being significantly higher within the wind farm than in the reference areas (Scheidat *et al.,* 2011). Suggested reasons for the increase of harbour porpoises within the wind farm are the increased food availability and the lack of marine traffic (Scheidat *et al.,* 2011). Another comparable study in Denmark indicated that harbour porpoises gradually return to a wind farm when it is operational (Tougaard *et al.,* 2006). In the same region in a later constructed wind farm no significant difference in harbour porpoise acoustic activity between the baseline study and the operational phase of the wind farm was found (Teilmann *et al.,* 2012). In Scotland, the results from boat-based surveys also indicated that after a wind farm was operational, it had no significant effect on the distribution of harbour porpoises in the area. No other cetaceans were observed during surveys taking place in the Irish sea (Walls *et al.,* 2013).

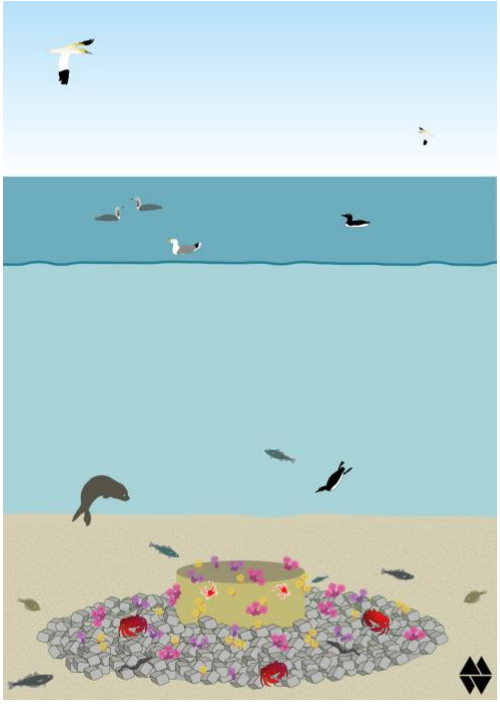
Appendix III: Visualisation post decommissioning

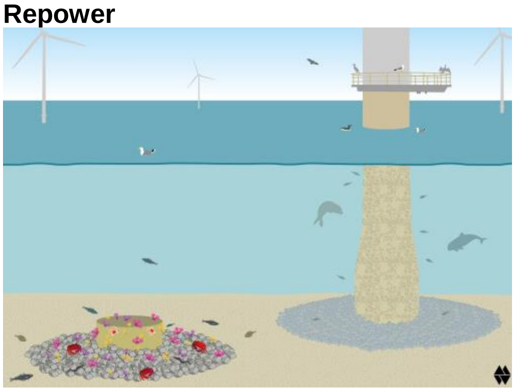
*Table III.1 Ecological impacts of different decommissioning strategies. *indicates impacts that are partly uncertain / habitat specific and need further research.*

Decommissioning strategy	Ecological impact
Wind farm present (T0) 	**Above water** - Resting function of turbine for specific species - Possible foraging function of monopile / scour protection - Collision risk and barrier effects for (migrating) birds and bats - Habitat loss due to disturbance **Below water** - Artificial material, with colonizing epifauna that attracts certain fish and seal species. - Possible habitat for endangered species and habitat (biogenic reefs) on and near scour protection * - Exclusion zone for bottom disturbing activities - Stepping stone for non-native species (mainly in intertidal zone) * - Disturbance in the ocean's stratifications layers*
Complete removal	**Above water** - Collision risk and barrier effects for (migrating birds) and bats removed - Habitat loss due to operational disturbance removed - Possible foraging function of monopile / scour protection removed - Resting function of platforms removed **Below water** - Wind farm site brought back to original state, no artificial material left behind

	- Possible holes left behind after removal monopile/foundation - Stepping stone for non-native species removed - Disturbance in stratification layers removed - Disturbance due to operational activity removed - Epifaunal community and associated species (partly) removed - Possible habitat for endangered species and habitat (biogenic reefs) on and near scour protection removed*

Decommissioning strategy	**Ecological impact**
Partial removal 	**Above water** - Collision risk and barrier effect for migrating birds largely removed - Resting function of turbine for specific species maintained - Possible foraging function of monopile / scour protection maintained* - Habitat loss due to operational disturbance reduced but possibly some remains due to remaining structures. **Below water** - Artificial material maintained, with colonizing epifauna that attracts certain fish and seal species. - Possible habitat for endangered species and habitat (biogenic reefs) on and near scour protection * - Refugee function of hard substrate (protection against bottom trawling fisheries)

	- Stepping stone for non-native hard substrate species (mainly in intertidal zone) * - Disturbance in the ocean's stratifications layers*
Partial removal 	**Above water** - Collision risk and barrier effects for (migrating birds) and bats removed - Habitat loss due to operational disturbance removed - Possible foraging function of monopile / scour protection removed - Resting function of platforms removed **Below water** - Artificial material partly maintained, with colonizing epifauna that attracts certain fish and seal species. - Possible habitat for endangered species and habitat (biogenic reefs) on and near scour protection * - Refugee function of hard substrate - Disturbance in the ocean's stratifications layers largely removed - Stepping stone for non-native hard substrate species (mainly in intertidal zone) *

Decommissioning strategy	**Ecological impact**
Repower 	**Above water** - Resting function of turbine for specific species - Possible foraging function of monopile / scour protection - Collision risk and barrier effects for (migrating) birds and bats - Habitat loss due to disturbance

	Below water - Artificial material, with colonizing epifauna that attracts certain fish and seal species. - Possible habitat for endangered species and habitat (biogenic reefs) on and near scour protection * - Exclusion zone for bottom disturbing activities - Stepping stone for non-native species (mainly in intertidal zone) * - Disturbance in the ocean's stratifications layers* - Disturbance due to operational activities (ship movement and noise / vibration operational wind turbine)