Macrobenthos in offshore wind farms

A review of research, results and relevance for future developments

Authors: Robbert Jak and Sander Glorius

Wageningen University &
Research Report C043/17

Macrobenthos in offshore wind farms

A review of research, results and relevance for future developments

Author(s): Robbert Jak and Sander Glorius

Publication date: 11th May 2017

Wageningen Marine Research
Den Helder, May 2017

Wageningen Marine Research report C043/17

R. Jak & S.T. Glorius, 2017. Marcobenthos in offshore wind farms; A review of research, results, and relevance for future developments. Wageningen, Wageningen Marine Research (University & Research centre), Wageningen Marine Research report C043/17. 477 pp.

Keywords: macrobenthos, benthos, offshore wind farms, hard substrate.

Client: Dr. I. van Splunder
Rijkswaterstaat Water, Verkeer & Leefomgeving
Postbus 2232
3500 GE Utrecht

Wageningen Marine Research is ISO 9001:2008 certified.

Dit rapport is gratis te downloaden van https://doi.org/10.18174/415357
Wageningen Marine Research verstrekt geen gedrukte exemplaren van rapporten.

Wageningen Marine Research
institute of Stichting Wageningen
Research is registered in the Dutch
traderecord nr. 09098104,
BTW nr. NL 806511618

A_4_3_2 V25

Contents

Summary **4**

1 Introduction **6**

2 Assignment **7**

2.1 Benthic research in wind farms 7
2.2 Aim 7

3 Methods **8**

3.1 Information 8
3.1.1 Wind farms and ecological research 8
3.1.2 Literature review 9
3.2 Workshop 10

4 Wind farms in the North Sea **11**

4.1 Location and stage of development 11
4.2 Foundation and environmental properties 12

5 Methods and results per country **15**

5.1 Belgium 15
5.1.1 The Belwind wind farm 16
5.1.2 The Thornton Bank wind farm 17
5.2 Denmark 19
5.2.1 Horns Rev I wind farm 20
5.2.2 Horns Rev II wind farm 22
5.3 The United Kingdom 24
5.3.1 Scroby Sands wind farm 24
5.3.2 Kentish Flats wind farm 26
5.3.3 Lynn and Inner Dowsing 28
5.3.4 Gunfleets Sands I + II. 29
5.4 Germany 30
5.4.1 Alpha Ventus 30
5.5 The Netherlands 32
5.5.1 Prinses Amalia 32
5.5.2 Egmond aan Zee 34
5.6 Summary of effects on hard- and soft-substrate benthos communities 36
5.6.1 Soft sediment 37
5.6.2 Hard-substrate (fouling) community 37

6 Conclusions and recommendations **39**

7 Quality Assurance **41**

References **42**

Justification **46**

Summary

Offshore wind farms potentially have an effect on the benthic ecosystem. Given the plans for large-scale development of offshore wind farms on the Dutch Continental Shelf (DCS), understanding these effects is relevant for policy and regulations regarding these developments.

Because studying the effects of offshore wind farms on the benthic ecosystem is expensive and time-consuming, it is important to use all knowledge which is already available before deciding if and what additional research is necessary. To facilitate the uptake of all available knowledge in Dutch policy and management decisions, we reviewed the research conducted to study benthic effects of offshore wind farms in the North Sea (and Kattegat). We focus on the research conducted, results obtained, methods used, technical parameters of the offshore wind farms and prevailing abiotic conditions. Using the results of this review, we assess the relevance of this research for the Dutch offshore wind development and its effects on the benthic ecosystem of the DCS, and derive lessons for possible future studies.

This work is part of WoZep (Wind Op Zee Ecologisch Programma), the Dutch Wind at Sea Programme.

We have compared methods and results of studies targeting the effects of offshore wind farm development on the benthic communities (both hard substrate and soft sediment) in Denmark, Belgium, Germany, The United Kingdom and The Netherlands.

We found that both operational wind farms and those in development in most cases use monopile foundations. We expect that this will remain the dominant foundation type in the Dutch Continental Shelf, where water depth is generally within the range suitable for monopiles.

An increasing trend in height of the turbines and span width of the rotor blades was found, and this trend will most likely result in fewer turbines per unit area in the future. This means more area closed to trawling per unit hard substrate, providing of course that the remaining policy will be continued to forbid trawl fishing within wind farms, so that the former mechanism of altering the benthic ecosystem will become increasingly more important. On the other hand, less hard substrate will be introduced at reduced turbine density.

Wind farms in development are generally planned further offshore and at greater water depths compared to those currently operational. If this trend continues, the relevance of research results so far will be increasingly smaller, as both diversity and functional composition of the benthic community on the DCS depend strongly on distance to the coast and water depth (Van Denderen et al. 2014, 2016).

We furthermore conclude that the existing Dutch wind farms OWEZ and PAWP are among the best studied (in terms of benthos effect studies) in the wider North Sea area.

Hard substrate
The results for hard substrate data reveal a clear pattern in the developing community, with consistent zones dominated by one or a few species along a depth gradient. This pattern appears to be largely independent of environmental conditions and technical specifications. Despite the consistence in this pattern of dominant species, it is expected that biodiversity of the fouling community will vary between sites. Following construction, rapid colonisation of a fouling community was found on the turbine-related hard substrate (the turbine itself and scour protection), which generally showed an increasing number of species, density and biomass over time.

Future hard-substrate research is recommended and should focus on obtaining longer time series from existing locations (rather than more time series from new locations), to understand the long-term

dynamics and the potential appearance of invasive species. The location of these studies is of lesser importance as results so far appear very similar throughout the North Sea.

The few studies which considered the soft sediment community in the near vicinity (tens of meters) of the turbine foundation showed that species richness, abundance and sediment organic matter content gradually increased towards the turbine. It is not known if the area in which this occurs expands over time, and we recommend this effect be further studied.

Soft sediment
For soft sediment benthos the results are less clear. Despite substantial monitoring effort, the picture which emerges from the review is that effects, if any are found at all, are subtle, scattered, often temporary and sometimes counter to *a priori* expectations. This may be due to that (1) the effect is small, but is just as likely the result of (2) a flawed or inappropriate monitoring design. A third, equally plausible option (3) is that recovery is slow (as suggested in for example Bergman et al. 2015) and effects have not yet taken place. Further research will be necessary to distinguish between these options (but note that they are not mutually exclusive). It is also important to consider that effects of (removal of) bottom trawling on the benthic community depend strongly on local environmental conditions (Van Denderen et al. 2014, 2016).

Options 1 and 2 could be further studied by a *post-hoc* assessment of statistical power. This would allow for policy-relevant conclusions phrased as '*the effect was with 95% certainty smaller than XX*'. Unfortunately, the conducted studies generally do not report post-hoc statistical power, so that for this a reanalysis of the original data is needed. Such a reanalysis is beyond the scope of this study, but is recommended for those wind farms for which the data can be obtained. This will be possible for some, but most likely not for all wind farms, due to data ownership issues in some countries.

Option 3 can be studied by continuing monitoring in existing wind farms. The Dutch wind farms OWEZ and PAWP are good candidates given that a relatively comprehensive sampling program (in comparison with many other wind farms in the area) has already been carried out.

Since no clear effects of wind farms were found in the soft sediment benthos, these could also not be linked with environmental and technical specifications of the wind farms considered.

We recommend that monitoring of soft substrate in existing wind farms is continued periodically (for example, once every 5 years) to test for long-term effects. OWEZ and PAWP are among the best choices given the monitoring effort so far. However, the relevance of this data should be reconsidered if future wind farms continue to shift to deeper locations further offshore.

Given the difficulty in showing effects using a BACI study design (and the costs involved in carrying out such studies), soft-sediment benthos studies in wind farms should focus instead on uncovering specific potential mechanisms of change to the benthic ecosystem in response to the placement of offshore wind turbines.

1 Introduction

Offshore wind farms potentially have an effect on the benthic ecosystem. This potential effect comes about through two mechanisms, the cessation of bottom fishing and the introduction of hard substrate. The benthic ecosystem is an important element in the functioning of the larger marine ecosystem, including the various kinds of fisheries operating in it. In the development of offshore wind farms it is hence important to take stock of and understand the effects on the benthic ecosystem, so that the potential consequences can be assessed.

In the Netherlands, large-scale development of offshore wind farms is planned for the foreseeable future. The Dutch Continental Shelf (DCS) consists mostly of relatively shallow (up to ~40m) seas with sandy bottoms, and a high degree of natural disturbance from tidal currents and waves. Natural hard sediment is present in the form of gravel and boulders, but is relatively rare. Artificial hard substrate is present in the form of scattered shipwrecks and other large debris, buoys (navigational and otherwise), oil & gas installations and (currently) 4 offshore wind farms. The planned offshore wind farms would significantly increase the presence of hard substrate in Dutch waters. The DCS is fished intensively by a large fleet using various bottom trawl gears. Hence, both potential mechanisms (Introduction of hard substrate and cessation of bottom trawling) play a potentially important role in altering the benthic ecosystem.

Because studying the effects of offshore wind farms on the benthic ecosystem is expensive and time-consuming, it is important to use all knowledge which is already available, before deciding if and what additional research is necessary. To facilitate the uptake of this knowledge in Dutch policy and management decisions, we review the research conducted to study benthic effects of offshore wind farms in the North Sea (and Kattegat). We focus on the research conducted, results obtained, methods used, technical parameters of the offshore wind farms and prevailing abiotic conditions. Using the results of this review, we assess the relevance of this research for the Dutch offshore wind development and its effects on the benthic ecosystem of the DCS, and derive lessons for possible future studies.

This work is part of Wozep (Wind Op Zee Ecologisch Programma), the Dutch Wind at Sea Programme.

2 Assignment

2.1 Benthic research in wind farms

Benthic research in offshore wind farms is carried out to obtain insight into the long term effects that the presence of a wind farm may have on the benthic community of the soft substrate (by excluding bottom disturbing fishery and other factors) and the development of the community that has settled on the newly introduced hard substrate. It is imperative to obtain insight into the effects of operational wind farms in the long turn (decennia) on the benthic community (and indirectly on fish, marine mammals and birds), and what this means when scaling up the area designated for offshore wind farms.

2.2 Aim

The aim of this study is to:

1. Provide an overview of research, methods and obtained results regarding the effects of offshore wind farms on the benthic ecosystem, carried out in the North Sea and Kattegat,
2. Review the location, technical specifications and local abiotic conditions of these wind farms, plus those in various stages of planning.
3. Assess the relevance of the results of 1 for the planned wind farms on the Dutch Continental Shelf, on the basis of the characteristics compiled in 2, including temporal trends which may affect relevance of current research for future offshore wind developments.
4. Derive ‘lessons learned’, both in terms of research results and in terms of methods used, from those studies qualified as relevant.

These aims reflect the assignment and changes to the assignment which are the result of email correspondence and telephone calls between Wageningen Marine Research (S. Glorius and/or Tobias van Kooten) and Rijkswaterstaat (Paul Westerbeek).

3 Methods

3.1 Information

3.1.1 Wind farms and ecological research

A list of both operational wind farms and wind farms that are in development was compiled. Wind farms were included that are currently in operation or planned in the Exclusive Economic Zones of the Netherlands, Belgium, Germany, the United Kingdom and Denmark. For these wind farms, technical- and environmental aspects that were considered of relevance for an ecological interpretation were collected (Table 1). Technical and environmental properties of wind farms that are currently in development were included in this survey. These are important to assess the relevance of current research outcomes for future wind farms. If it is found for example that the sediment type is an important factor determining the responses of the benthic community, the sediment type of future wind farm areas is relevant to obtain a proper estimate of the benthic response.

Table 1. *Information fields in GIS offshore wind farm database.*

General	Turbine	Environment
Location and shape farm (shape file)	Height turbine	Water depth
Status	Diameter rotor blade	Distance to the coast
Date operational	Foundation type	Sediment type
	Number of turbines	
	MW per turbine	

The following categories within 'status' were defined:

- Proposed — *Early idea*
- Development — *Development of idea*
- Application — *Application permit*
- Authorised — *Permit granted*
- Construction — *Building of park*
- Operational — *Activation of park*
- Cancelled — *Deactivation of park*
- Dismantled — *Removed*

The sediment characteristics are based on the seabed habitat map that is available at EMODnet ('European Marine Observation and Data network'). The following categories were defined:

- Mud
- Sand
- Muddy sand
- Mixed sediment — *Heterogenic mix of muddy sand with pebbles, and/or mosaic of large pebbles/boulders in sand or mud*
- Coarse sediment — *Coarse sand or pebbles*

The following foundation types were defined:

- Gravity — *Concrete based structure filled with sand, iron ore or rocks to anchor the foundation*
- Monopile — *One hollow cylindrical pile made of steel*
- Jacket — *Four-legged tube construction made of steel*
- Tripod — *Three- legged steel tube construction, similar to three legged stative*

- Suction bucket — *Construction of steel, with the shape of an upturned bucket. Due to its own weight and by pumping out water from inside the 'bucket' it lowers itself into the sediment*
- Floating — *In development, many different forms possible*
- Other types — *Generally, these are parks in early development and foundation type is not yet known.*

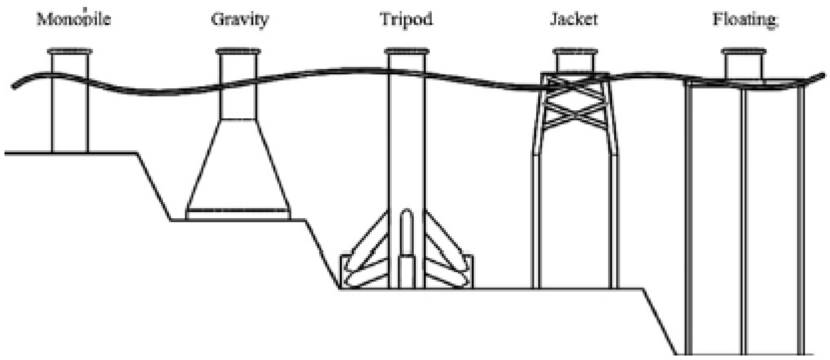

Figure 3-1. *Some of the offshore wind turbine foundation types. Taken from Higgins & Foley, 2014.*

Information made available by different national organisations was used such as 'The Crown Estate' for the UK, 'The Management Unit of the North Sea Mathematical Models and the Scheldt estuary' (MUMM) for Belgium, the 'Bundesamt für Seeschifffahrt und Hydrographie' (BSH) for Germany, the Ministry of Economic Affairs (EZ), the Rijkswaterstaat and the Netherlands Enterprise Agency, all for the Netherlands. Finally, two publicly available databases were used: (1) '4C Global Offshore Wind farm Database' available at www.4coffshore.com/offshorewind/ and OSPAR database of offshore wind farms available at http://odims.ospar.org/odim_data_files/.
The collected environmental and technical information of the wind farms is visualized in this report by several bar- and boxplots (Figs 4-2 to 4-5).

3.1.2 Literature review

In this literature review, papers and reports were collected that describe the results of monitoring programmes conducted in wind farms in the Exclusive Economic Zones of the Netherlands, Belgium, Germany, the United Kingdom and Denmark and which had a focus on hard- and/or soft substrate benthic fauna. For this purpose, 'Web of Science' and 'Scopus' (the two most-used online catalogues of scientific literature in our field) were consulted to obtain 'peer reviewed' publications. In addition, Google was used to obtain relevant reports from the grey literature. In order to further limit the review effort, wind farms with >5 turbines and that are operational since the year 2011 were selected first, as it is believed that changes in benthic species compositions in this kind of farms are more likely than in small farms that also tend to be operational for a shorter period of time.

Information about the following aspects was collected from the selected publications:
- Properties of the wind farm, such as water depth, sediment composition, turbine foundation type and, when possible, type of scour protection, number and density of the turbines.
- Applied experimental setup, for instance 'BACI'*, years and moment of the year sampling took place, applied sampling gear, sampled area and sampled matrix.
- The variables studied in the analyses and the outcome of these analyses.

*In a 'BACI-design' (Before-After-Control-Impact) the impact site (the area where the wind farm will be built), and reference area(s) are sampled both before and after construction of the wind farm (Green, 1979 and Underwood, 1991). In this way deviations from a 'normal' or 'natural' development, that is observed in the reference site(s), can be disentangled from the development caused by the impact (wind farm) site. In order to capture the (yearly) fluctuations that occur naturally it is important to have multiple (yearly) sampling events, both before as well as after the construction of the wind farm.

3.2 Workshop

On the 22nd of September 2016 a workshop was held, in order to discuss the findings of this study the perspective of the current and future Dutch offshore wind farm plans. This workshop was attended by a number of experts on North Sea benthos (all WMR personnel). The outcome of the workshop is incorporated in the conclusions of this report.

4 Wind farms in the North Sea

4.1 Location and stage of development

Figure 4-1 the locations and spatial configuration of wind farms in the EEZ's of the Netherlands, Belgium, the United Kingdom, Germany and Denmark is shown. With the solid dark green areas the operational wind farms at the time of writing this report are depicted. With the other colours farms that are in (a certain stage of) development are shown.

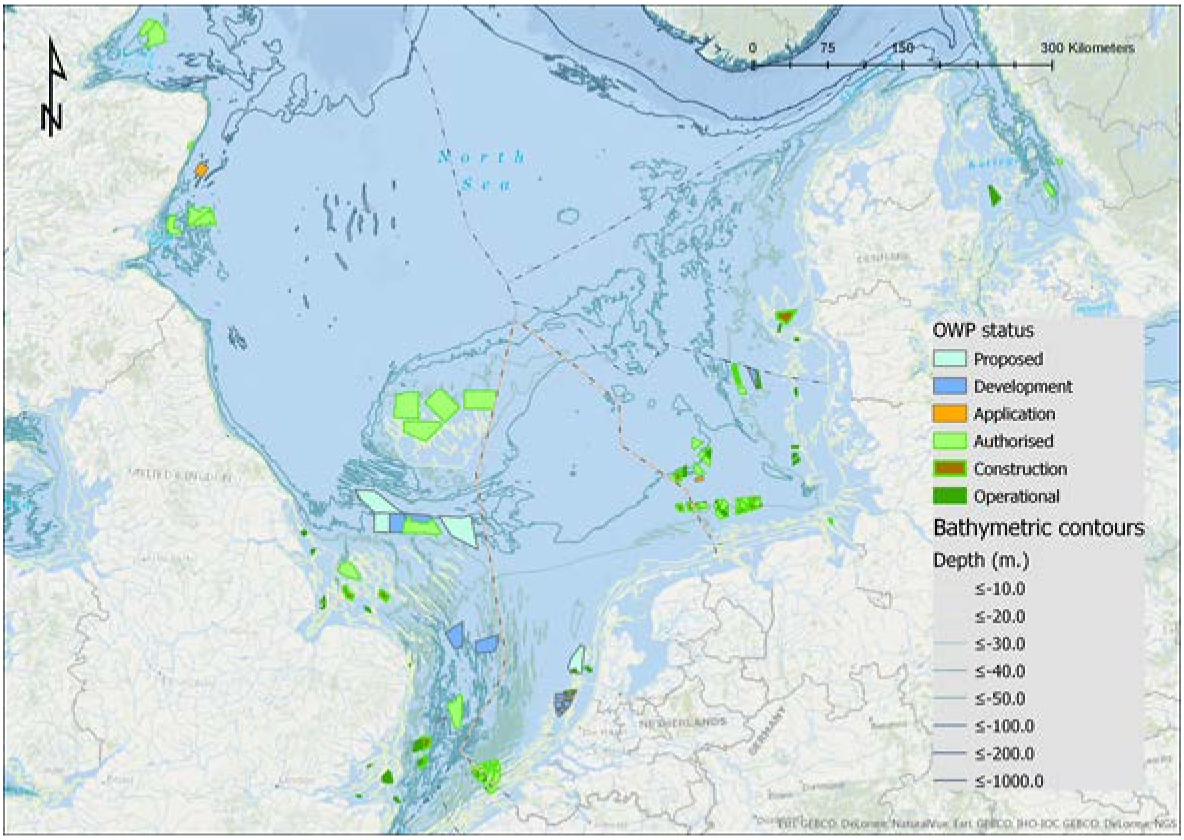

Figure 4-1. *Location and shapes of both operational wind farms and wind farms in development that are present in the EEZ of the Netherlands, Belgium, the United Kingdom, Germany and Denmark. Wind farms that were cancelled or dismantled were excluded.*

4.2 Foundation and environmental properties

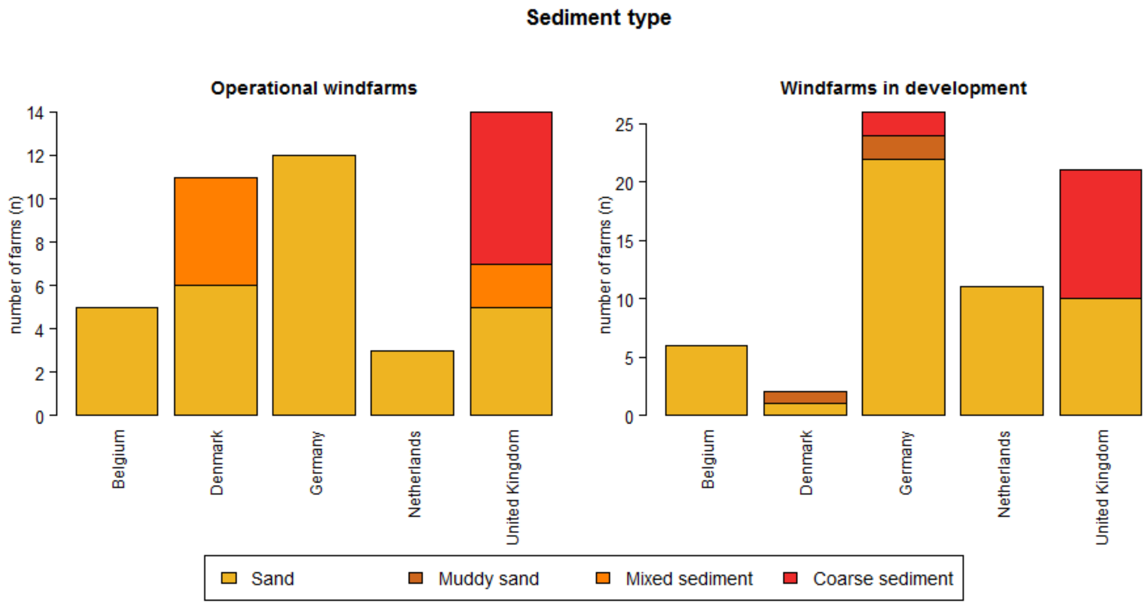

Figure 4-2. *Graph on the left; seabed sediment type of operational wind farms at the time of writing of this report. Graph on the right; seabed sediment types of wind farms that are currently in development.*

Currently most wind farms are located in areas with a sandy seabed type, see left graph in Figure 4-2. It is not to be expected that this will change in the future as can be seen in the right graph in Figure 4-2. There are, however, differences between countries. In the United Kingdom for example almost half of the wind farms that are currently fully operational are situated in areas with a more course sediment type. It is not expected that this will change in the future as wind farms are planned for both sandy areas and areas with a more coarse sediment type. Germany is going to develop some farms on coarse sediment and muddy sediment type, while most new farms will be built in areas with a sandy sediment type. In Belgium and The Netherlands, all wind farms are located in sandy areas, now as well as in the future.

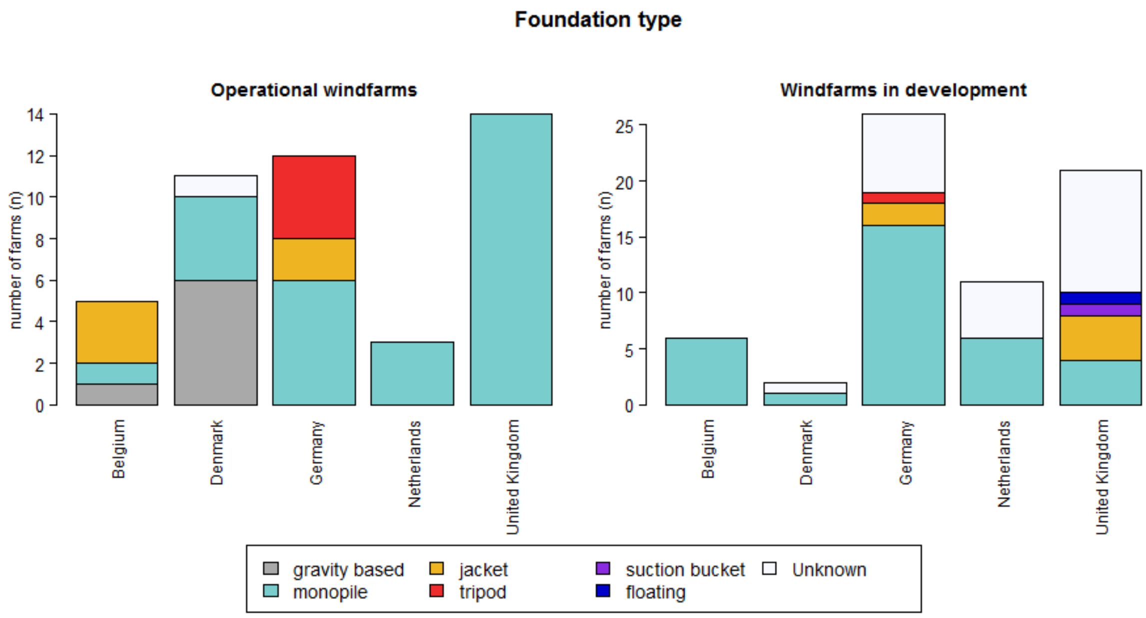

Figure 4-3. *Graph on the left; foundation types of fully operational wind farms at the time of writing of this report. Graph on the right; foundation types of wind farms that are currently in development.*

The monopile is the most commonly applied foundation type at this moment. While gravity based structures were used in both Belgium and Denmark, all future farms will rely on alternative foundation structures with the monopile as the most popular structure. A disadvantage of gravity based structures is the enormous weight required to anchor the structure making the construction complex and time consuming. This structure type is less suitable in deeper waters. Tripods, only applied in Germany, become less popular. Only in the United Kingdom the suction bucket and floating structures are expected to be used. In the Netherlands, only monopiles are applied. For a large proportion of wind farms, in especially the United Kingdom, the foundation type is currently not specified and/or known, but it is likely that monopiles will continue to be the dominant foundation type for the foreseeable future.

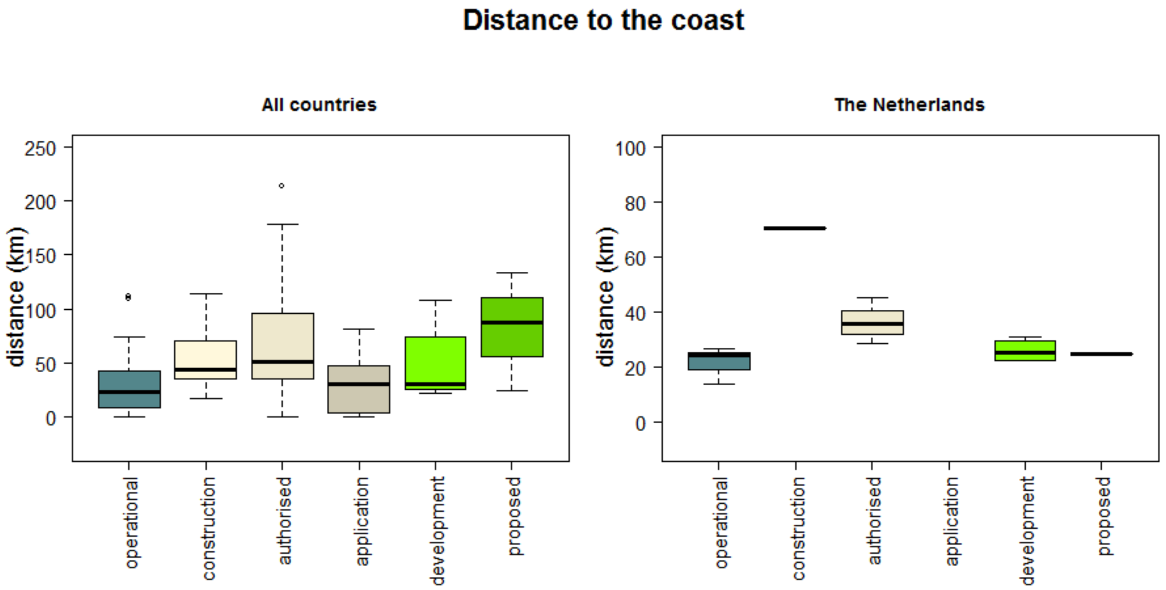

Figure 4-4. *Left panel: boxplots of the distance to the coast for wind farms in various stages of development in the Netherlands, Belgium, the United Kingdom, Germany and Denmark. Right panel: boxplots of the distance to the coast for wind farms in various stages of development in the Netherlands. Note the difference in scale of the y-axis between both graphs. The horizontal lines in the right graph are the result of the limited number of wind farms that is constructed (two, both at a distance of around 70 km) or proposed (one). The box in the boxplot shows the interquartile range (IQR), starting by the 25 percentile (floor of the box) and stopping by the 75 percentile (ceiling of the box). Percentiles give values that contain a certain percentage of the data, so the 75 percentile gives the value below which 75% of the data is contained. Therefore, inside the box 50% of the data is contained. The bold horizontal line printed inside the box shows the median, which is the value that separates the higher half of the dataset from the lower half. The distance of the whiskers (vertical dotted lines) shows the last observed value that falls inside 1.5 times the IQR going up starting from the 75 percentile and going down starting from the 25 percentile. Outliers are shown by circles and are situated above or below the whiskers.*

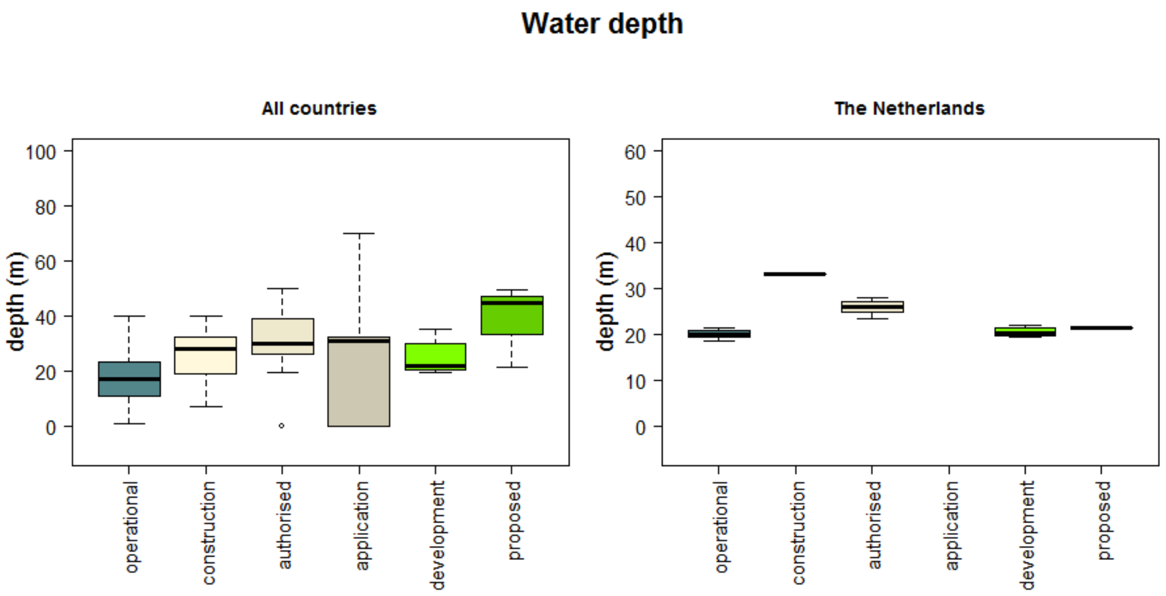

Figure 4-5 . *Graph on the left; boxplots of water depth at wind farms in the Netherlands, Belgium, the United Kingdom, Germany and Denmark for both operational wind farms and wind farms Figure 4-4n development. Graph on the right; boxplots of the water depth at wind farms in the Netherlands for both operational wind farms and wind farms in development. Note the difference in scale of the y-axis between both graphs. The horizontal lines in the right graph are the result of the limited number of wind farms that is constructed (two, both at a water depth of around 33 meter) or proposed (just one wind farm). See Fig. 4-4 for details on interpretation of symbols and boxes.*

Compared to the operational wind farms, those currently planned and under construction, are located farther away from the coastline, see Figure 4-4. Dutch wind farms (except Gemini) are generally (to be) located relatively close to shore.

Future wind farm areas are on average located in deeper waters than those already operational. This trend is also observed in the Netherlands, but Dutch wind farms are generally (to be) placed in relatively shallow areas. There is also an increasing trend in turbine height, blade diameter and energy production per turbine (not shown here). Given the general rule of thumb that the optimum distance between individual turbines is seven times the rotor diameter (Wizelius, 2015), it is expected that the turbine density will decrease in future farms due to an increase in rotor diameter.

5 Methods and results per country

This chapter describes the experimental setup and results of the monitoring programmes which took place in and around wind farms in Belgium, Denmark, Germany and the UK, targeting benthic communities of the soft and hard substrate. This includes the research conducted in the Dutch wind farms, 'Egmond aan zee' and 'Prinses Amalia'. These studies were the result of the search effort described in 3.1.2.

5.1 Belgium

An area of 238 km^2 is designated for offshore wind energy production in the EEZ of Belgium (ICES, 2015). Five licences were granted for the harvest of wind energy namely: Norther, C-Power/Thornton Bank, Rentel, Northwind and Belwind. The applied research methods and results of the environmental monitoring that took place in and around the Belwind and Thornton Bank are described in this chapter.

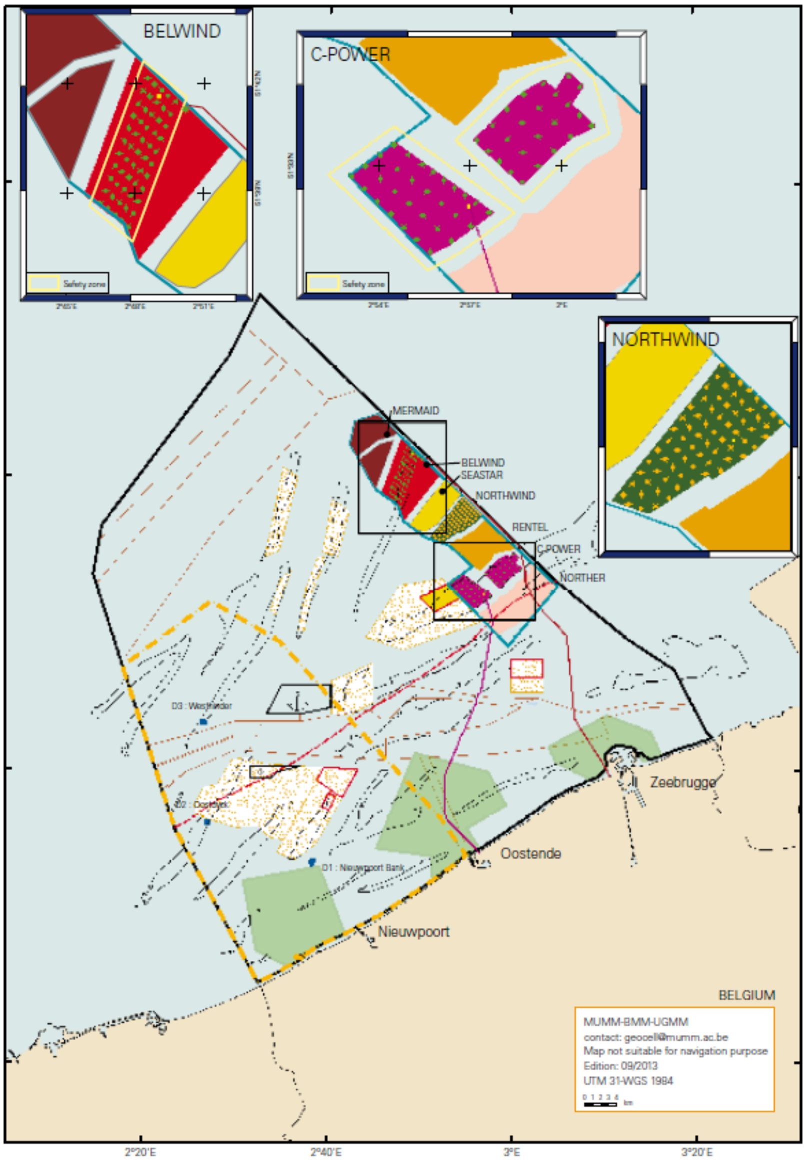

Figure 5-1. *Wind farm areas present within the EEZ of Belgium and the configuration of the windmills within these farms. Taken form Brabant et al., 2013 in Degraer et al., 2013.*

5.1.1 The Belwind wind farm

The Belwind wind farm exist of 110 turbines (monopile foundation) generating a total of 165 MW of energy. This farm became fully operational in 2010. The farm is located at a distance of 49 km from the coast on a sandy seafloor and a water depth varying between 15 and 40 meter. The farm itself is constructed on the Bligh Bank (Vandendriessche et al., 2015). Fishing is not allowed within the farm, but intrusions in the wind farm and its safety buffers are reported (Vandendriessche et al., 2013b).

5.1.1.1 Sampled matrix and methodology

Monitoring of the epifauna- (targeting species that live on top or just below the seafloor), infauna- (targeting species that live within the sediment) in and around the wind farm and the hard substrate communities on the windmill foundations was carried out and results were described in several reports and papers (Vandendriessche et al., 2013a; 2015, Coates et al., 2016 and de Mesel et al., 2013, in Degraer et al., 2013). The followed methods and results found in those studies are described here.

- Epifauna - in between the turbines (Vandendriessche et al., 2013a; 2015)

A 'BACI' design was applied, sampling the epifauna community before and after construction of the wind farm using a shrimp fishing gear. The width of the net was 8 meters and was equipped mesh size of 22 mm. The gear was towed at 4 knots for 30 minutes (first three years) or 15 minutes (last years). Samples were taken within the wind farm, in one reference site and two areas located just at the outer margins of the wind farm. Monitoring took place every autumn and spring from 2008 until 2012. Samples within the wind farm were taken at a distance of 200 meter from the nearest turbines. The number of samples taken varied between two and sixteen over sites and monitoring events.

A wind farm effect was tested for by using statistical analysis following the BACI set-up. Next to the presence of the wind farm, season and habitat (sandbanks and gullies) were used as explanatory factors to reduce the variation. An effect of the wind farm on density, biomass and diversity (species richness) was tested for. Secondly the community structure was explored as well as differences in the size frequency of selected species between sites.

- Infauna - in between the turbines (Coates et al., 2016)

The infauna community was sampled with a van Veen grab (sampled area of 0.1 m^2) in a comparable BACI set-up as the epifauna sampling. Samples were taken within the wind farm, in one reference site, and in two areas just outside the wind farm at yearly intervals (2008 - 2011). Locations of the samples (at the bank or in the gully) were recorded and used as an explanatory variable. The number of samples taken varied between six and eighteen over sites and monitoring events.

- Hard substrate (de Mesel et al., 2013, in Degraer et al., 2013)

The hard substrate community at three monopiles was sampled by divers by scraping off all species present in an area of 25x25 cm (0.0625 m^2) at a depth of 15 meters using a putty knife. Samples were stored in plastic bags. In total twelve campaigns were undertaken and took place from winter 2010 until autumn 2012.

5.1.1.2 Results

- Epifauna - in between the turbines

Effects were limited to a temporal increase in epibenthic biomass (starfish, hermit crab and sea urchins). These differences disappeared in later sampling events. Fringe effects were not found. Several factors were thought of as being the reason of paucity of statistically significant differences within the BACI framework, i.e. the limited number of post-construction observations (two years), the (large) sampling distance relative to the windmills (200m) and finally the incapability of a BACI analysis to pick up small and gradual changes.

➢ Infauna - in between the turbines

No major significant differences in development were found. A subtle change that was observed was an increase in *Gastrosaccus spinifer* (Arthropoda, shrimp), Terebellidae sp. (Annelida) and *Echinocyamus pussilus* (Sea urchin) three years after the wind farm area was closed for fishery.

➢ Hard substrate

A rapid settlement and stabilisation of the community structure was observed, right after the first samples were taken. The colonisation pattern that was found on the foundations of the Belwind turbines was comparable to that found on the foundation of the Thornton Bank turbines, see below. A further increase in both biomass and species coverage was observed in Belwind as well as a small increase in total species richness. However the total number of species recorded was lower in Belwind (64 against 84 in Thornton Bank wind farm). The communities present at the Belwind turbine foundations furthermore showed less pronounced seasonal and long term dynamics compared to the Thornton Bank.

5.1.2 The Thornton Bank wind farm

The C-power wind farm located on the Thornton Bank consists of six turbines that are anchored on the seafloor with gravity based foundations and 48 turbines anchored on the seafloor with jackets. The six turbines with a gravity based foundation became operational in 2009 while the 48 turbines anchored with jackets became operational in 2013. A total of 325 MW of energy is generated. The farm is located at a distance of 27 to 30 km offshore in front of the Belgium coast on a sandy seafloor and at a water depth varying between 12 and 27.5 meter. Fishing is not allowed within the farm, but intrusions in the wind farm and its safety buffers have been reported (Vandendriessche et al., 2013b).

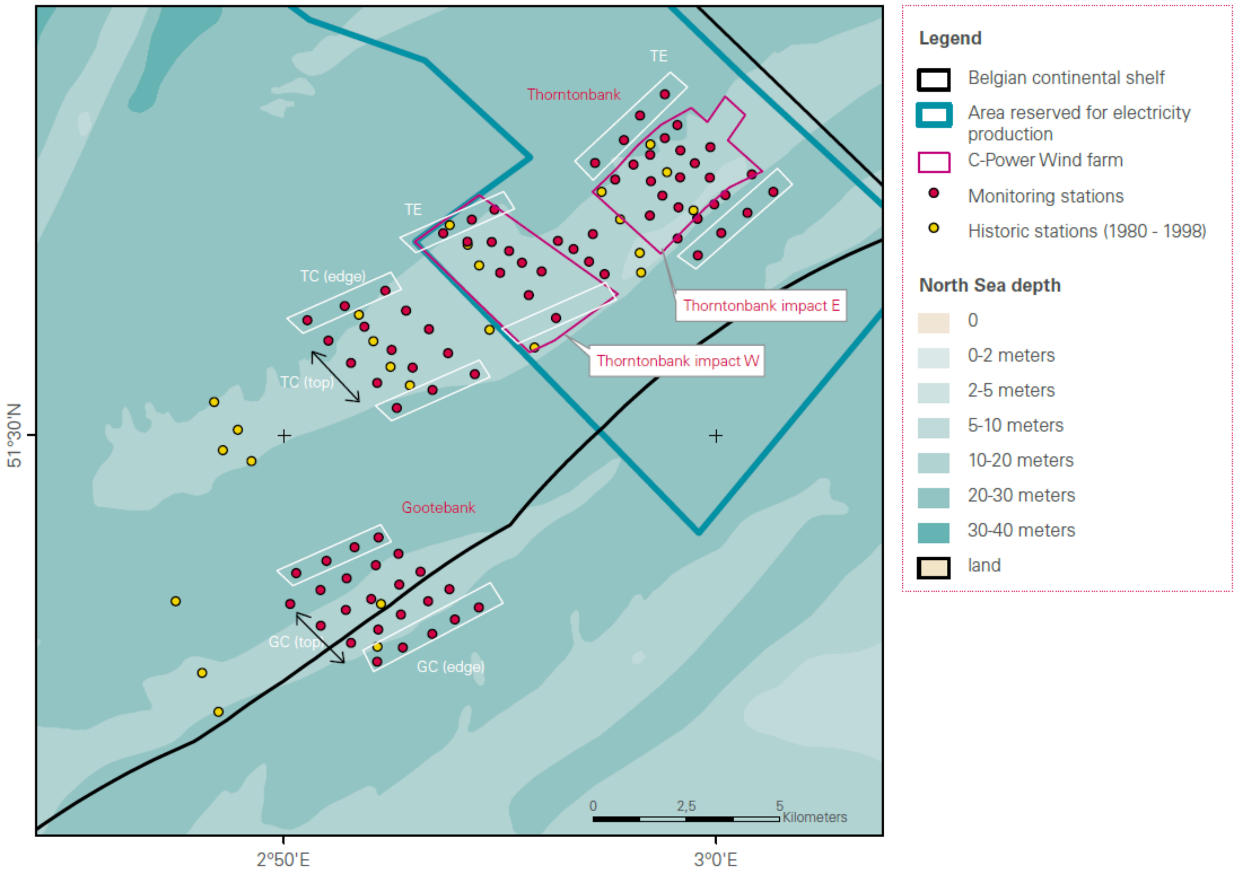

Figure 5-2. *Sampling locations in and around Thornton Bank (C-Power) wind farm. Taken form Coates et al. 2013, in Degraer et al. 2013.*

5.1.2.1 Sampled matrix and methodology

Monitoring of the epifauna- (targeting species that live on top or just below the seafloor), infauna- (targeting species that live within the sediment) in and around the wind farm and the hard substrate communities on the turbine foundations was carried out and results were described in several reports and papers (Vandendriessche et al., 2013a; 2015, Coates et al., 2014; 2016 and de Mesel et al., 2015). The applied research methods and the results of this study are described here.

- Epifauna - in between the turbines (Vandendriessche et al., 2013a; 2015)

A programme, very similar to the monitoring of epifauna in Belwind, was applied. The experimental setup followed a 'BACI' design, sampling the epifauna community before and after construction of the wind farm both within and outside it, using a shrimp fishing gear (width of 8 meters and a mesh size of 22 mm). Samples were taken within the wind farm and in three reference sites. Monitoring took place every six months over the period 2008 till 2012. Samples within the wind farm were taken at a minimum distance of 200m from the turbines. The number of samples taken within each site and during each monitoring campaign conducted, varied between two and thirteen.

A wind farm affect was tested for using statistical analysis following the BACI set-up using season and habitat (sandbanks and gullies) as explanatory factors. The parameters density, biomass and diversity (species richness) were tested. Also the community structure was explored as well as the size frequency of selected species.

- Infauna - in between the turbines (Coates et al., 2016)

The infauna community was sampled with a van Veen grab (sampled area of 0.1 m^2) in a BACI set-up by taking samples before (2005) and after (2008 - 2010) installation of the turbines. Samples were taken within the wind farm, in two reference sites, and in two sites located just outside the wind farm. The number of samples taken within each area and during each sampling event varied between two and twenty-five. Effects were examined by using a Benthic Ecosystem Quality Index (BEQI) in which information about species densities, biomass, number of species and the composition of the community was used. Historical data was also used in the interpretation of results. Information on the infauna community gathered at stations sampled between 1980 till 1998 was used for this purpose.

- Infauna - around individual turbines (Coates et al., 2014)

Around one (gravity based) turbine, samples for species composition and sediment grain size were taken along four gradients (south-west, north-east, south-east, north-west). Samples were taken at 15, 25, 50, 100 and 200 meter distance, starting from the edge of the scour protection boulders. Triplicate samples were collected during late spring of 2011 and 2012 using a van Veen grab sampler (sampled area of 0.025 m^2).

- Hard substrate (de Mesel et al., 2015)

The vertical distribution of the fouling community present at two of the gravity based foundations was studied during the first year; from winter 2009 until summer 2009. Samples were collected with a seasonal frequency (January/February - winter, March - early spring, July - summer, October/November (autumn) and at different depths, ranging from 4 to 22 meter below the water surface. Based on these results, the community present at a water depth of 15 meter was found to be representative for the deeper subtidal and selected to analyse the temporal dynamics over a longer period. For this, two to three replicates were sampled at a water depth of 15 meter from autumn 2009 until summer 2012. All samples were collected by scraping off the surface of the foundations by scientific divers using a putty knife and deploying a square quadrat of 25 cm by 25 cm (0.0625 m^2).

5.1.2.2 Results

- Epifauna

No significant wind farm effects were observed with BACI analysis and no fringe effects were found. However, a significantly higher epibenthic biomass was found in 2009 within the wind farm.

- Infauna - in between the windmills

A significantly higher density of especially the polychaete *Spiophanes bombyx*, was found one year after the construction of the farm, within the BACI framework. This observed difference between the control and impact site disappeared the following year. A recovery of the community after the construction phase was confirmed by the use of the (BEQI) indicator. The BEQI values calculated for the concession area corresponded with the values calculated for the control areas except in 2008 when the turbines were constructed.

The paucity of statistically significant differences found in de epi- and infauna communities using the BACI framework was generally attributed to the limited number of post-construction observations (one year), the large distance between sample and turbines (200m) and the incapability of a BACI analysis to pick up small and gradual changes.

- Infauna - around individual turbines

Close to the turbine foundations (15 meter) the mean grain size diameter decreased while the amount of organic material increased. Infaunal densities and species richness showed an increasing trend towards the foundation. Species richness increased from 10 ± 2 at a distance of 200 meter from the foundation, to 30 ± 5 at 15 meter from the foundation. A change in dominant species was also observed, *Lanice conchilega* dominated the community close to the foundation.

- Hard substrate

A clear vertical zonation was found with a dominance of *Telmatogeton japonicus* (musquito larvae) in the splash zone, a high intertidal zone characterised by the barnacles *Semibalanus balanoides* and a mussel (*Mytilus edulis*) belt in the deep subtidal. Initially the species turnover in the deep subtidal was very high, but became quickly thereafter dominated by the crustacean *Jassa herdmani*, anemone species *Actiniaria* spp. and the hydrozoa *Tubularia* spp.. Since then seasonal dynamics within the species assemblage were observed. Ten non-indigenous species were found.

5.2 Denmark

Thirteen wind farms are currently operational in the EEZ of Denmark of which most are located in the Baltic Sea and in Kattegat. Two wind farms are located in the North Sea namely; Horns Rev I and Horns Rev II. Currently, Vattenfall is building Horns Rev III, scheduled to be connected to the power grid at the end of 2019 / beginning of 2020. The Horns Rev wind farms are depicted in Figure 5-3. The environmental monitoring that took place in and around Horns Rev I & II targeting hard- and soft substrate benthic species is described in this chapter.

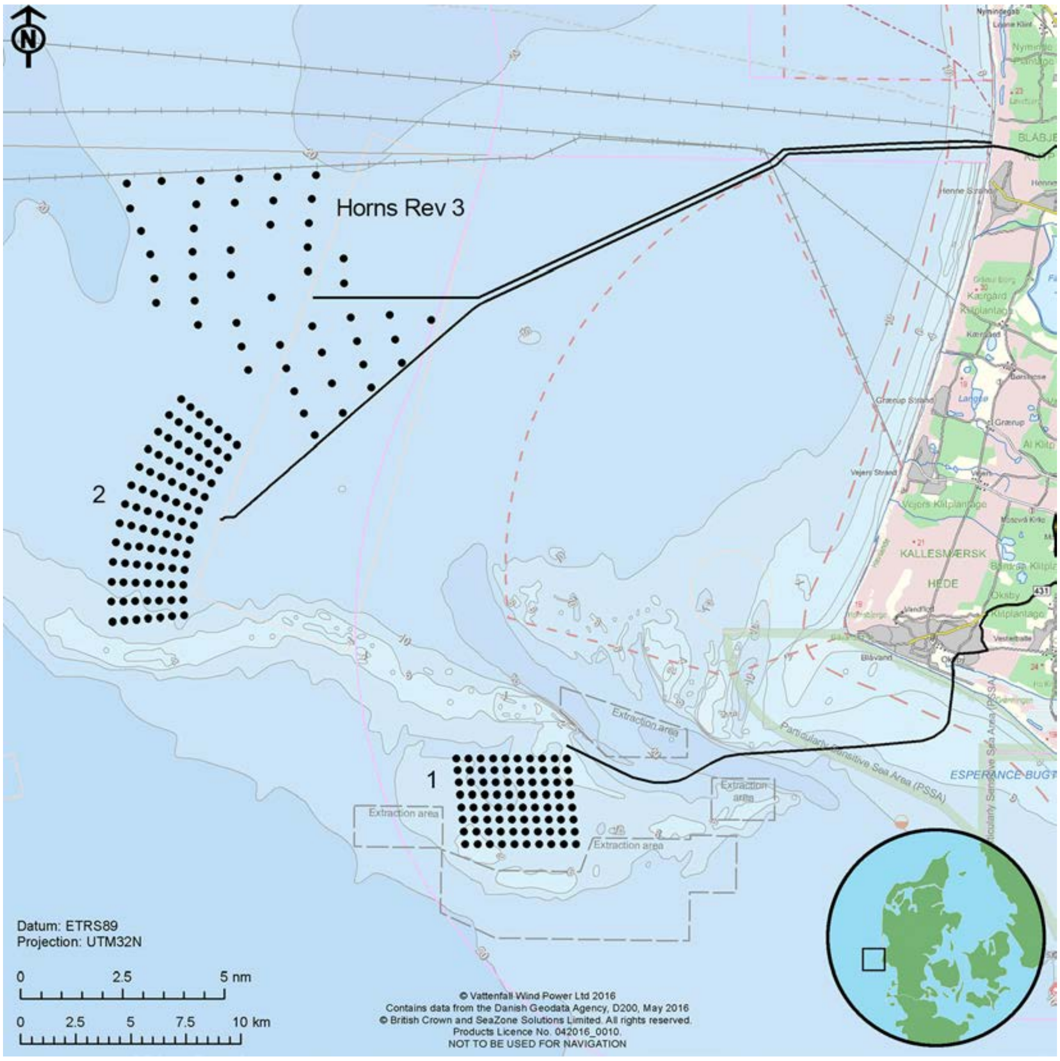

Figure 5-3. *The locations of the windmills in the wind farms Horns Rev I, II and III (under construction). Taken from: https://corporate.vattenfall.com/globalassets/corporate/about_energy/3c_map_horns_rev_123.png).*

5.2.1 Horns Rev I wind farm

The Horns Rev I wind farm, operational since 2002, consists of 80 turbines occupying an area of 20 km^2 and generating a total of 160 MW of energy. The farm is situated on the Horns Rev reef located in south-western direction off the coast of Blåvands Huk at a distance of approximately 14 km. The reef was created during the Eem geological period and glacio-fluvial sediment deposited during the Saale glaciation, consisting of well sorted sediments in the form of gravel and sand. Huge accumulations of Holocene marine sand deposits, up to 20 m in depth, formed the Horns Rev area that is known today with continuous accumulations (Larsen, 2003). The seabed surface sediments at Horns Rev are constantly reworked by waves and currents. The sediments in the Horns Rev area consists generally of pure medium fine sand to coarse sand with no or very low organic content (<1%) (Leonhard & Pedersen,2006). Courser sediments are found towards slopes facing greater depths where currents are stronger.

Water depth varies in the range of 6 to 13 meter and the area is known for its harsh environmental conditions, fully exposed to waves from the North Sea and relatively strong currents up to around 0.8 m/s (Nielsen et al., 2014). The wind turbines are founded on monopiles with a scour protection made of a two-layer cover (quarry run from around 350 mm to 550 mm) and a 0.5 m thick filter layer (marine stones from around 30 mm to 200 mm) between the armour layer and the seabed (Nielsen et al., 2014).

5.2.1.1 Sampled matrix and methodology

Environmental research, commissioned by Vattenfall, targeting the infauna (between and near the windmills) and hard substrate communities has been carried out and described by Bio/consult (Leonhard & Pedersen, 2006). The applied research methods and the results of this study are described here.

- Infauna and sediment - in between the turbines (Leonhard & Pedersen, 2006)

The experimental setup followed a 'BACI' design, sampling the epifauna community before (1999 and 2001) and after (2003, 2004 and 2005) construction of the wind farm both within and outside it. Three sediment cores were collected by divers at each station, two for the determination of the fauna assemblage and one for sediment grain size analysis. With each core a surface area of 0.0123 m^2 was sampled to a depth of approximately 15 cm, see Figure 5-4. The number of samples taken varied between five and nineteen depending on both site and sampling year and the locations of the sampling stations varied over sampling events.

Figure 5-4. *Sediment core samples, taken from Leonhard & Pedersen, 2006.*

- Infauna and sediment - around individual turbines (Leonhard & Pedersen, 2006)

Transects consisting of three stations located at distances of 5, 25 and 100 meter from the edge of the scour protection were sampled at six turbines and six reference sites outside the wind farm. Transects were placed on the leeward side of the turbine foundations with respect to the prevailing current. Sediment core samples for the determination of the faunal composition were collected by divers in September 2003 and 2004 in the same matter the fauna between the turbines was sampled.

- Hard substrate - monopile (Leonhard & Pedersen, 2006)

The vertical distribution of the fouling community on the foundations of three monopile based turbines was studied. For this purpose the fouling community present at each foundation and at both the current- and leeward side was sampled at depths (measured from the bottom of the scour protection) of 0, 2, 4, 6 and 8 meter. At each station, triplicate samples were taken by thoroughly scraping off the fouling community within a frame of 0.04 m^2 using a special scraping tool and an air-lift device. Samples were collected in bags with a mesh size of 1 mm and species composition, abundance and biomass was determined. Surveys were performed each year in March and September in the period 2003 until 2005.

- Hard substrate - scour protection (Leonhard & Pedersen, 2006)

The horizontal distribution of the fouling community present on the scour protection of six turbines was studied. For this purpose, divers collected samples at stations located on a transect that was oriented in the direction of the main current. Stations were placed at distances of 0.5, 2 and 5 m away from the monopile and samples were taken at the same time and in a similar matter as samples that were taken at the foundation of turbines.

5.2.1.2 Results

➢ Infauna and sediment - in between the turbines

A negative correlation was found between depth and median grain size. Both within as outside the wind farm the median grain size increased over the sampling years and no effect of the wind farm was found. Significant changes in species composition between the sampling events were found (from 2001 to 2003 & 2004). For some species, such as *Spisula solida*, changes in density and distribution were linked to a change in sediment grain size. No changes in species composition were found between 1999 and 2005 and no statistically significant changes in designated indicator species from 1999 to 2005 were found. Therefore results show rather a large natural fluctuation than a wind farm effect.

➢ Infauna and sediment - around individual turbines

No correlation could be found between grain size and distance from turbine foundation. The community composition differed significantly between the sampled turbines, but was similar regardless of the distance from the turbine foundation.

➢ Hard substrate - monopile

A rapid colonisation of fouling species was observed on the monopiles with different species composition and vegetation cover at different depth zones. The splash zone of the monopiles was first covered with the filamentous green algae *Urospora penicilliformis* and barnacle species replaced by a more permanent occurring of microscopic green algae and diatoms. High densities of the giant midge *Telmatogeton japonicus* and *Telmatogeton japonicus* were found in this zone. Just beneath the water surface to approximately 2 meters below the sea surface dense mats of the filamentous brown algae *Pilayella littoralis/Ectocarpus* dominated in spring and species of *Ulva clathrata* and *Ulva prolifera* in autumn. At these depths the crustacean *Jassa marmorata* was also abundant. At lower depths the Mollusca *Mytilus edulis* was found showing marked differences in densities between sites (turbines). A large increase in mussel biomass and mussel shell length was found from 2003 to 2005. No clear distribution pattern was found in the lower zones or near the bottom apart from a general lower abundance of the dominant species and increased coverage of sea anemones. The fouling community differed between the current- and leeward side of the monopiles, believed to be a result of current and wave action. Community differed also significantly with the communities found at the scour protection, mainly due to differences in abundance and biomass of few dominant species.

➢ Hard substrate - scour protection

The hard substrate communities present on the scour protection were dominated by seven species determining 98% of the total abundance and between 46 and 97% of the total biomass. In general *Jassa marmorata* was found in the highest densities, but locally sea anemones contributed with a substantial biomass. No differences in species composition were found between the current- and leeward side of the scour protection, while the community closest to the monopile differed significantly from the community closer to the periphery of the scour protection with decreasing *Jassa marmorata*, *Metridium senile* and *Cancer pagurus* coverage/frequencies towards the edge of the scour protection. The sea anemone *Sargartiogeton laceratus* was most frequently present 2-10 meter away from the monopile. The number of edible juvenile crabs *Cancer pagurus* increased significant since 2003. Also other juvenile species were found, such as the masked crab *Corystes cassivelaunus* and juvenile sea urchins *Strongylocentrotus droubachiensis*.

5.2.2 Horns Rev II wind farm

The Horns Rev II wind farm, fully operational since 2009, exist of 91 turbines (arranged in 7 rows in a semi-circular formation) generating a total of 209 MW of energy. The farm, situated on the Horns Rev reef, is located 30 km off the Danish west coast from Esbjerg, see Figure 5-3. The wind farm covers an area of approximately 35 km^2 with a water depth between 4 and 14 m. The wind turbines are founded on monopiles driven into the seabed to depths of 20 to 25 m. The scour protection is approximately 1-2 m in height above the original seabed and consists of a protective stone mattress of large stones with a subjacent layer of smaller stones (Leonhard, 2006).

5.2.2.1 Sampled matrix and methodology

Environmental research targeting the infauna community (between and near the turbines) has been carried out and described by Bio/consult (Leonhard, 2006). Samples were taken prior to construction, but no follow-up campaigns have been undertaken (personal comments B. Hansen, Dong Energy). The applied research methods and the results of this study are described here.

➢ Infauna and sediment - in between the turbines (Leonhard, 2006)

In January 2006 a screening survey was carried out in the designated two wind farm areas, see left picture in Figure 5-4. At 24 stations duplicate sediment core samples with a surface area of 0.123 m^2 were taken, one sample for determination of the sediment characteristics and one for infauna species composition. Samples were taken by divers using polycarbonate tube samples (Figure 5-4) or by a HAPS corer sampler (right figure in Figure 5-5) controlled from the water surface (ship).

Grain size distribution, dry- and organic matter content were determined in the samples taken for sediment characterisation. Species composition, abundance and biomass were determined in the samples taken for infauna characterisation. These samples were sieved through a 1.0 mm sieve. Data acquired from this study have been compared with data obtained from previous campaigns including Horns Rev I.

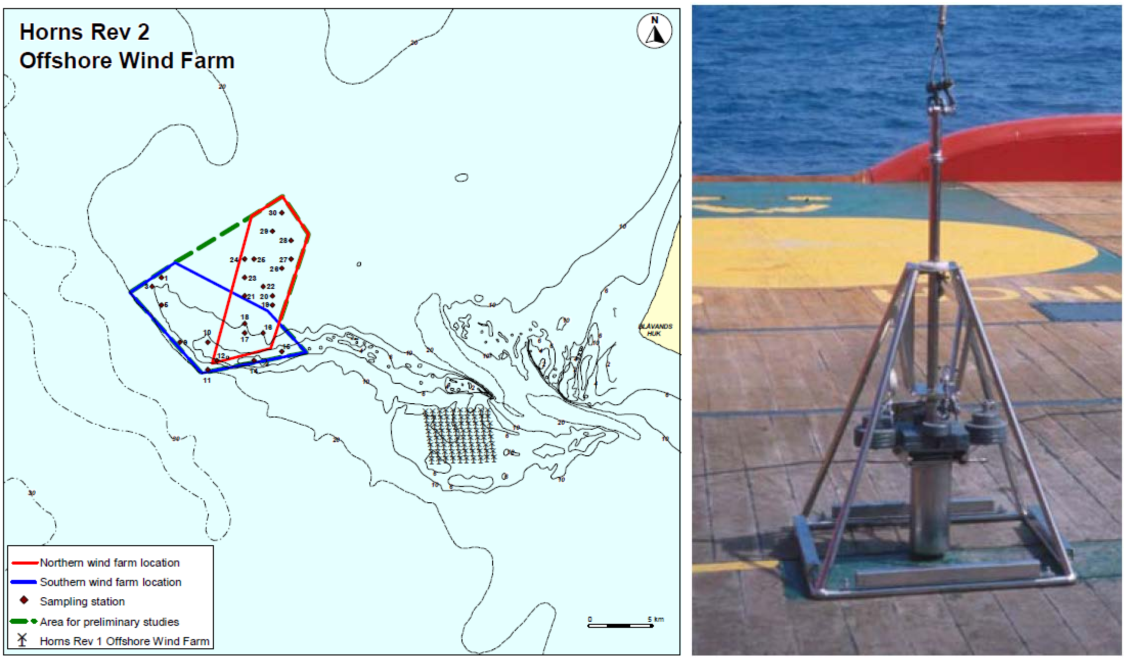

Figure 5-5. *Location of sampling stations at two designated wind farm areas of Hors Rev II (left). a 'HAPS' core sampler, comparable with a small box corer (right). Taken from Leonhard, 2006.*

5.2.2.2 Results

➢ Infauna and sediment - in between the turbines

Bed forms of small sand ripples and mega ripples were seen over the whole area. These were caused by wave impact on the seabed showing evidence of sand transport directions both to the north and to the south. The seabed consists of pure medium to coarse sand with low or very low organic content (<1%). Courser sand was found at the southern part of the reef, probably as a result of stronger currents.

The benthic communities consist of a mixture of two characteristic benthic faunal assemblages; a *Venus* community, found on the more stable and plane seabed outside the reef in the northern part of wind farm area and a *Goniadella-Spisula* community found on more coarser and loose sand in the southern part of the wind farm area. No vegetation was found within the area.

Fishing took place within the area prior installation of the wind farm. Sandeel and brown shrimps were fished on by means of bottom trawling and *Spisula solida* was fished on by dredging.

5.3 The United Kingdom

The United Kingdom is one of the best locations for wind power in the world (Wikipedia) and offshore wind was identified as the main renewable energy source for achieving the 2020 European Union's Renewable Energy Directive (Drew et al., 2015). The United Kingdom is the world leader for installed offshore wind power capacity as pro-active policies and procedures have made it the most attractive location to develop offshore wind farm arrays (Higgins and Foley, 2014). The development of offshore energy in the UK has been managed in three rounds defined by the Crown Estate, which started off by round 1 in 2000. The capacity built within round 3 tends to be located offshore in clusters of very large wind farms (Drew et al., 2015).

Legislative terms considering the monitoring of the benthic communities are broadly described in Walker (2009). Monitoring of the benthos consist of the sampling of in- and epifauna using 2 meter beam trawls and different grab sampling devices as well as the sampling of the fouling communities (MMO, 2014). Prescribed sampling techniques (Boyd, 2000), follow a high degree of standardisation, but deviations are acceptable when dictated by local environmental conditions. Experimental setup and statistical analysis are not pre-defined (Walker, 2009).

The applied research methods and results of the environmental monitoring that took place in and around Scroby Sand, Kentish Flats 1, Lynn and Inner Dowsing and Gunfleet Sands I + II are described in this chapter.

5.3.1 Scroby Sands wind farm

The Scroby Sands wind farm is one of the first wind farms built within round 1, existing of 30 turbines each mounted on a monopile and generating a total of 60 MW of energy, Skeate et al., 2012. The farm is located 2 km off the coast of Great Yarmouth in eastern England on a dynamic sand bank environment exposed to waves and strong currents. The seabed can be characterised as fine to medium sand with mobile bed forms (Whitehouse et al., 2011). Water depths range between 0 and 8 meter. The farm became fully operational in 2004 (Walker, 2009).

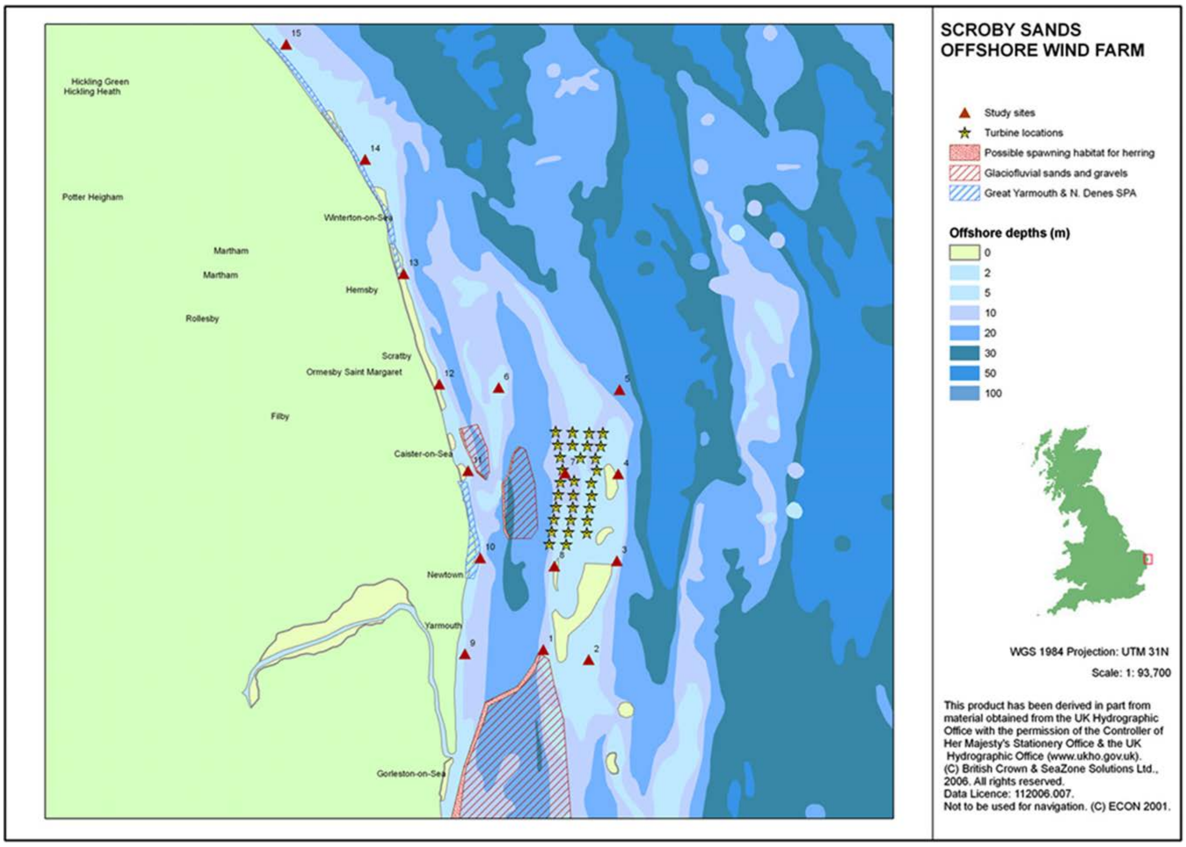

Figure 5-6. *Location of the wind farm Scroby Sands. Taken from Perrow et al., 2011.*

5.3.1.1 Sampled matrix and methodology

Sediment samples were taken for determination of the in- and epifauna species composition and for characterisation of the sediment. No reports or papers describing the field surveys, analyses and results in great detail could be found, except for a report summarizing the environmental work carried out at multiple wind farms in the UK (Walker, 2009). The limited information that is provided in this report is described here.

- Infauna and sediment - in between the turbines (Walker, 2009)

Both in 1998, before construction of the wind farm and one year after construction in 2005, sediment samples for faunal composition and sediment characterisation were taken at 38 stations located within the wind farm site. No samples were taken at reference sites. While in 1998 a 'day grab' was used to take the samples, in 2005 a 'hammon grab' was used, see Figure 5-7. Bot devices are operated via a research vessel. Also dredge samples were taken for the determination of the larger benthic species pool, but only in 1998. The area sampled by these devices, the applied mesh size, the exact location of the sampling stations and the amount of samples taken by each gear type were not specified.

Figure 5-7. *Example of a day grab (left) and hammon grab (right). Taken from Guerra & Freitas, 2012.*

➢ Epifauna - in between the turbines (Walker, 2009)

At each sampling event (1998 and 2005) seven benthic trawls were taken inside the wind farm site using a beam trawl. The sampled area, applied mesh size and the location of the seven sampling stations were all not specified.

5.3.1.2 Results

Only general results were reported. A general reduction in diversity and biomass in post-construction data were observed when compared with data of the pre-construction survey. Because no reference sites were sampled it remains unclear if this reduction was caused by the construction and/or presence of the wind farm or by natural fluctuations.

5.3.2 Kentish Flats wind farm

The Kentish Flats wind farm is located in the Thames Estuary, 10 km off the coast outside the shipping lane, see Figure 5-8. Construction of the farm started in 2004 and became fully operational in September 2005. It consists of 30 turbines (placed in a regular grid) each founded on monopiles and generating 3 MW of energy. It is located on shallow water with water depths ranging from 3 to 5 meter. The area is exposed to waves and moderate currents and has a stable seabed environment consisting of sediment and 'London' clay (Lombardi et al., 2013 and Whitehouse et al., 2011).

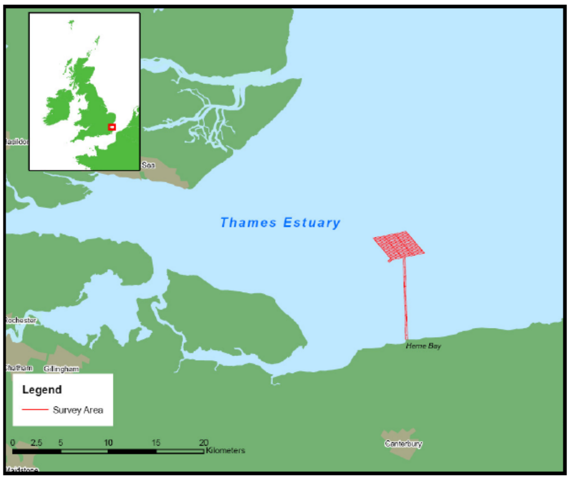

Figure 5-8. *Location of the Kentish Flat wind farm , Vattenfall, 2009.*

5.3.2.1 Sampled matrix and methodology

Comprehensive monitoring took place targeting debris, scour, water turbidity, birds, benthos, the contamination of oysters collected from the oyster bed located at the export cable route, fish, under water operational noise and fouling communities (Vattenfall, 2009). The experimental setup and results of the monitoring effort targeting the in- and epifauna as well as the fouling communities are described here.

➢ Infauna and sediment - in between the turbines (Vattenfall, 2009).

The experimental setup followed a BACI design, sampling stations located inside the wind farm, at reference sites located outside the wind farm and along the export cable route both before and after construction of the farm. One baseline survey (prior installation) was conducted in March 2002. Sediment samples for determination of the species composition and sediment characteristics were taken at in total 46 stations, using a 'hammon grab', see Figure 5-7 and Figure 5-9. At twelve of these stations replicate samples were taken. With the particular hammon grab used an area of 0.1 m^2 could be sampled. In the follow-up surveys, after installation of the farm, triplicate samples were taken at 23 locations in 2005, 2006 and 2007 (sampling took place in the months June-May depending on the survey year). The data generated on species diversity, biomass and abundance, together with sediment characteristics have been analysed using a variety of univariate and multivariate techniques.

➢ Epifauna - in between the turbines (Vattenfall, 2009).

The epifauna program followed a similar BACI design. One baseline survey (prior installation) was conducted in March 2002 sampling the epifauna at 10 stations with a 2 meter scientific beam trawl and at 11 stations with a dredge, see Figure 5-9. The beam trawl used was equipped with a net with a mesh size of 5 mm and samples were collected by towing the gear over a distance of 500 to 1000 meter (data standardized for tow length). In the follow-up surveys, after installation of the park, only beam trawl samples were taken. Follow-up surveys were conducted in 2005, 2006 and 2007. The data generated on species diversity, biomass and abundance have been analysed using a variety of univariate and multivariate techniques.

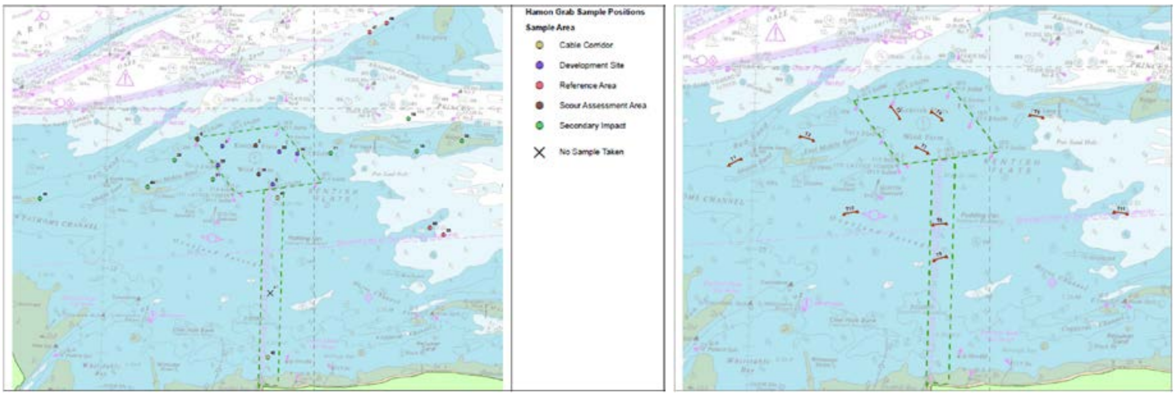

Figure 5-9. *The location of the stations that were sampled with the 'hammon grab' on the left, and the location of stations that were sampled with the beam trawl on the right. Taken from Vattenfall, 2009.*

➢ Hard substrate - monopile (Vattenfall, 2009)

The colonisation of the turbine foundations were monitored in end of July in 2008 by divers. Two turbines were investigated taking video and stills footage and collecting scrape samples. Video and stills photographs have been taken throughout the survey area, recording each observed biological zone. At each monopile, four scrape samples were collected (sampling a quadrant of 0.01 m^2 each) at distant biological zones from surface to seabed. These samples were used for specific species identification and to record wet weight.

5.3.2.2 Results

➢ In-, epifauna and sediment characteristics - in between the windmills

A pattern of sediment distribution has been observed within the sampled area (in- and outside the wind farm area) ranging from sand (moderate to poorly sorted) in the western and northern part to gravely sand and gravely muddy sand in the southern part. These differences persisted over the sampling years. No changes to the physical nature of the seabed were evident that could be attributed to the construction or operation of the wind farm. The benthic communities could be associated with the dominant seabed sediment types across the sampling area. Some temporal variations were observed in the benthic community. Fluctuations of the abundance of individual species (mainly polychaetes worms *Spiophanes bombyx*, *Scoloplos armiger* and *Lanice conchilega*, and bivalve *Abra albra*) were attributed to natural variability caused by variations in recruitment success. Variations in richness and total abundance in general were thought to be caused by seasonal patterns of disturbance such as storms and harsh winters. The main macrofauna assemblages did not change over the monitoring period and variation in the benthic community could not be attributed to the construction or operation of the wind farm.

➢ Hard substrate - monopile

The biological zonation of the fouling community was comparable between the two turbines surveyed and the dominant species (barnacles, mussels and anemones) were considered typical of colonised hard substrata or manmade surfaces. Also the biological zonation discovered is comparable with other wind farms. However the absence of fish in Kentish Flat was notable. The biological zonation can be described as follows: The intertidal (splash) zone was dominated by barnacles (*Balanus crenatus* and *Elminius modestus*). Below this zone, the infralittoral and sublittoral fringe area, was dominated by the common mussel *Mytilus edulis*, especially super abundant on the upper levels of this zone. On the upper areas of this zone also the green algae Ulva spp. was present along with barnacles. In the lower areas of this zone the anemones *Sagartia elegans* and *Metridium senile* were present together with the shrimp *Caprella linearis*, amphipods *Corophium asherusicum* and *Jassa falcata*. Some crabs were also found in this zone. Even lower, abundance of mussels declined and anemones (*Metridium senile* and *Sagartia elegans*) became dominant. At the base of each of the turbines the seabed consisted of sand and gravel with shell fragements of *Mytulis* sp.. The starfish *Astrerias rubens* was dominant but also crab species (*Necora puber*, *Paguridae* sp. and *Liocarcinus* sp.) were recorded.

5.3.3 Lynn and Inner Dowsing

The Lynn and Inner Dowsing wind farms are two wind farms adjacent to each other and constructed within round 1 of the Crown Estate development scheme. Each park consists of 27 monopile based windmills of 3.6 MW each, generating at total of 194.4 MW of energy (both farms combined). The turbines cover an area of 20 km^2 located between 5 and 9 km offshore the Lincolnshire coast, see Figure 5-10. The construction of the farms started in 2007 and both farms became fully operational in March 2009. The wind farm site is underlain by chalk from the Upper Cretaceous era superficial covered by Holocene sediments comprise sandy and gravelly sediments, Carroll et al., 2010. The dominant wave direction is from north-northeast and northeast with wave heights between 0.5 and 1.0 meter (Carroll et al., 2010).

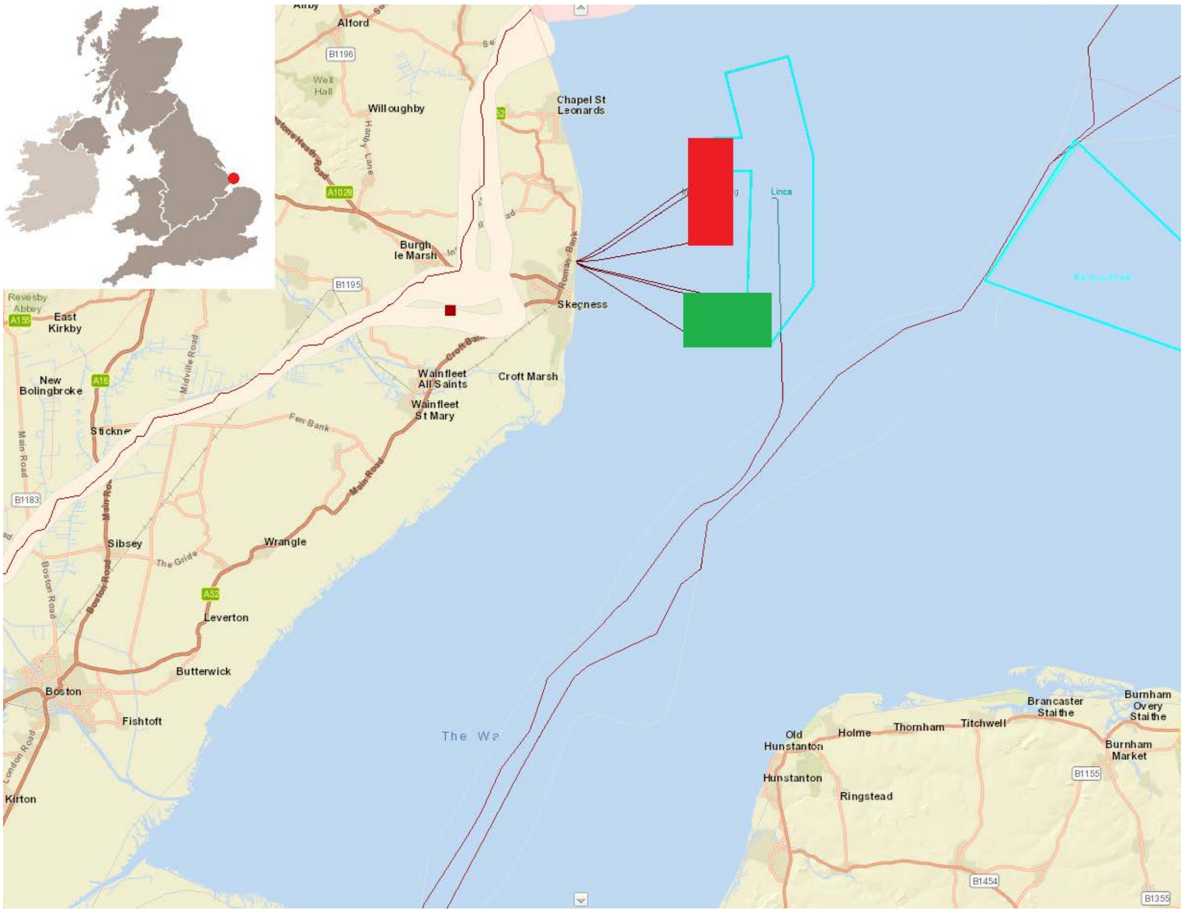

Figure 5-10. *Locations of the Lynn (green) and Inner Downsing (red) win dfarms, taken and modified from www.4coffshore.com/offshorewind.*

5.3.3.1 Monitoring

The only information that was found was an MMO report (MMO, 2014). In this report it was stated that sediment samples (gear type not specified) were taken and monitoring by video and still footages took place within the area to investigate the boundaries of a *Sabellaria* reef. The fouling community on the monopiles were sampled by divers (video recordings). No further details could be found.

In another study, not linked to the wind farm, the presence of a consolidated *Sabellaria spinulosa* reef was confirmed within Lynn Knocks Reef by the use of acoustic side scan, video and photographic stills and grab samples (Curtis et al., 2014).

5.3.4 Gunfleets Sands I + II.

The Gunfleet Sands I & II wind farms are located approximately 7 km south-east off Clacton-on-Sea, see Figure 5-11. The project consists of two parts, Gunfleet Sands 1 with 30 turbines (5x6 array) and Gunfleet Sands 2 with 18 turbines (9x2 array). The capacity of each turbine is 3.6MW, giving the Gunfleet Sands project a total capacity of 172MW. The parks are located on a site with a water depth of 2 to 15 meter on a seafloor characterised by a sandy sediment type. Construction started in 2008 and both parks became fully operational in 2010.

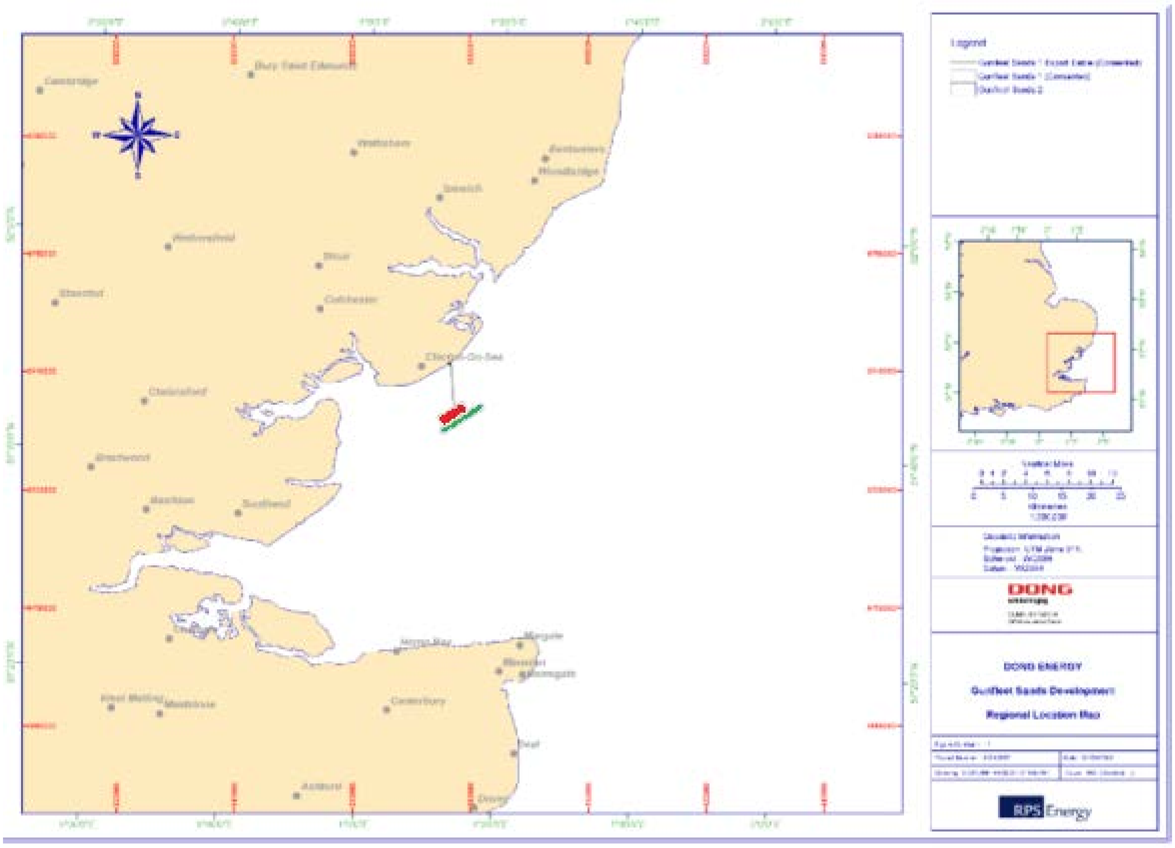

Figure 5-11. *Locations of Gunfleet I (red) and II (green) wind farms, taken and modified from Dong, 207.*

5.3.4.1 Monitoring

The only information that was found was an MMO report (MMO, 2014). In this report it was stated that sediment samples (gear type not specified) were taken and monitoring by video and still footages took place within the area to investigate the boundaries of a *Sabellaria* reef. The fouling community on the monopiles were sampled by divers (video recordings). No further details could be found.

5.4 Germany

Most of the operational offshore wind farms located in the EEZ of Germany are relatively newly built and came into production between 2015 and 2017. A few farms were built earlier: the first German offshore wind farm, Alpha Ventus (operational in 2010), followed by Bard (2013), Riffgat and Meerwind (both 2014). Germany has a significant number of planned offshore wind farms and currently many are in a (certain stage) of development.

The applied research methods and results of the environmental monitoring that took place in and around Alpha Ventus are described in this chapter.

5.4.1 Alpha Ventus

The Alpha Ventus wind farm is the first far-offshore wind farm of the world, located 45 km north of the island of Borkum, Gutow et al., 2014. The park, occupying an area of 4 km^2, consists of 12 turbines that became operational in 2009 generating 60 MW of energy. The farm was considered to be a test site and is relatively small for an offshore farm. Two foundation types were used. Six turbines were installed on a jacket foundation and the other six on a tripod foundation. Water depths are round 30 meters and the seabed is characterized by a homogeneous sediment structure of fine sand (Reichert et al., 2012).

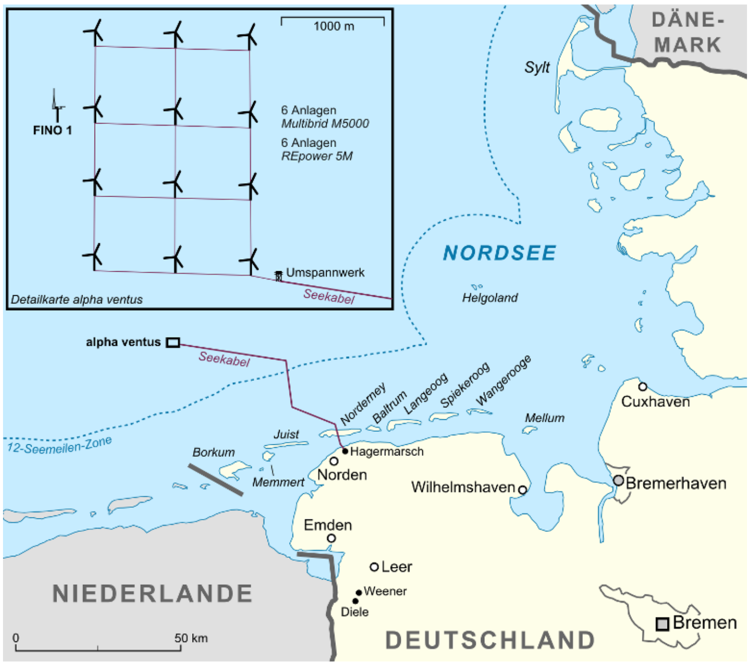

Figure 5-12. *Locations of Alpha Ventus within the EEZ of Germany, taken from Schmidt et al., 2013.*

5.4.1.1 Sampled matrix and methodology

Comprehensive monitoring took place targeting many species groups (benthos, fish, mammals and birds) and propagation of underwater noise during pile driving. Results were bundled and described in BSH & BMU (2014). Ecological monitoring of the benthos, epifauna, infauna and the fouling communities on the windmill foundations was conducted and reported in Gutow et al. (2014) in BSH & BMU, 2014. The methods and results from those studies are described here.

➢ Infauna - in between the turbines (Gutow et al., 2014)

The experimental setup followed a BACI design, sampling stations located inside the wind farm and one reference site both before and after construction. The reference area was similar to the wind farm area in terms of water depth and sediment type. One baseline survey (prior to installation) was conducted in spring 2008. Follow-up surveys after construction of the farm were conducted in spring and autumn of 2009, 2010 and 2011. At each sampling campaign, samples for the determination of fauna composition were collected with a van Veen grab (sampled area of 0.1 m^2) at 20 evenly distributed stations inside the wind farm and at 20 stations in the reference site. At each site replicate samples were taken.

A wind farm effect was tested for in variables such as species richness, abundance and biomass, by using appropriate BACI statistical methods, testing for a significant interaction term (between 'area' and 'time'). Additionally, the variability of these variables found in the wind farm study where compared with the variability of these variables found in benthic samples in the German Bight.

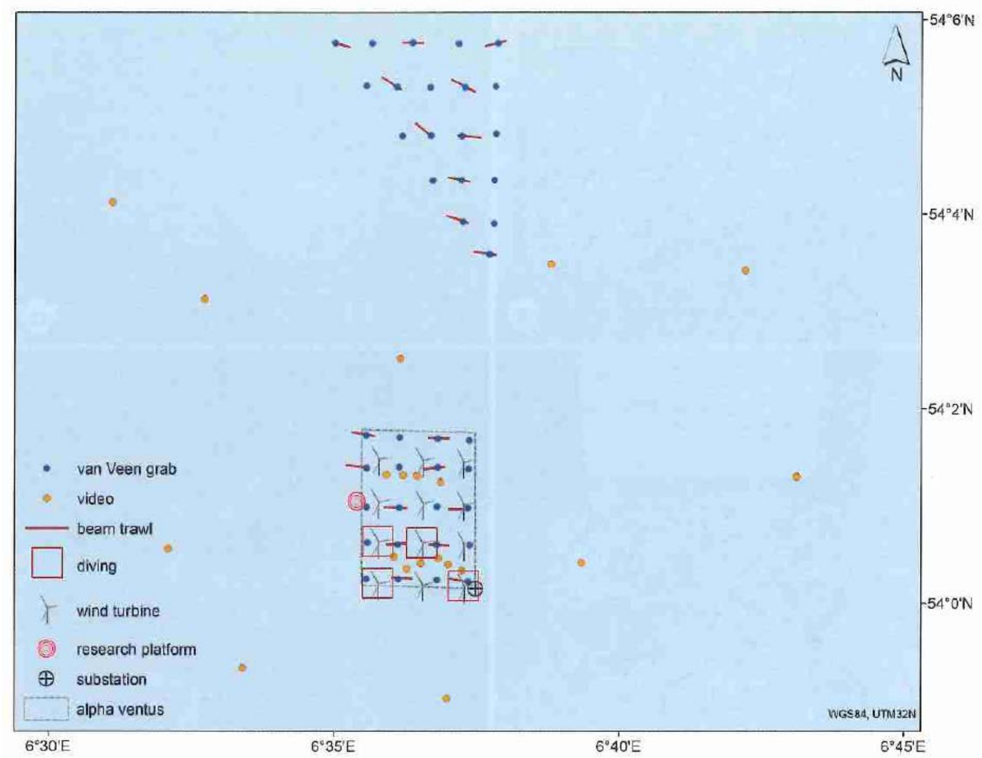

Figure 5-13. *Geographic positions of the sampling stations, in- and outside the wind farm. Blue dots represent van Veen grab samples, red lines beam trawl and yellow dots under water video footages. Taken from Gutow et al., 2014.*

➢ Epifauna - in between the turbines (Gutow et al., 2014)

In a similar (BACI) setup samples were taken inside the wind farm and at one reference location prior to (spring 2008) and after construction of the farm (spring and autumn of 2009, 2010 and 2011), see Figure 5-13. A 2-meter wide beam trawl (mesh 1 cm) was used to collect the samples by towing the gear for five minutes at a trawling speed of 1 to 3 knots. On board the research vessel the catch was sorted, counted and weighed by taxa.
A wind farm effect was tested for variables such as species richness, abundance and biomass, by using appropriate BACI statistical methods, testing for a significant interaction term between 'area' and 'time'.

➢ Hard substrate - turbine foundations (Gutow et al., 2014)

The foundations of two turbines were sampled by divers targeting the fouling communities as well as the demersal megafauna. The first samples were taken in 2009. Sampling was repeated in spring and autumn of 2010 and 2011. On each turbine foundation three replicate scrape samples were taken randomly at water depths of 1, 5, and 10 meter. The fouling community was scraped off from a 20 x 20 cm area and captured in a mesh bag (mesh size: 1mm). Furthermore the mobile demersal megafauna was surveyed visually on belt transects extending on the seafloor away from four turbine foundations. Additionally the megafauna on the three-dimensional underwater structure itself was recorded.

5.4.1.2 Results

- Infauna

A small but significantly different development in species richness, total abundance and biomass between the wind farm and reference site was detected. Species richness and total abundances were reported to have increased in both sites but more so in the reference area. Differences in total abundance and biomass were largely contributed to variations in single species. Considering total abundance, the highly abundant bristle worm *Spiophanes bombyx* played a major role while the sea urchin *Echinocardium cordatum* dominated the total biomass. Because only one reference site was sampled and differences in total abundances and biomass were largely due to single species, results have to be interpreted carefully and continuation of seasonal sampling is necessary to confirm the potential effects. The variation (expressed as coefficient of variation) in species richness and total biomass observed inside the wind farm and at the reference stations were well within the range of the ambient variations of the infauna on fine sand sediments in the German Bight.

- Epifauna

Species richness was higher in the reference site and increased in both sites within the research period with highest numbers in spring 2010. The development in both sites was comparable and no wind farm effect was detected. Total abundance and biomass did show a wind farm effect, with increasing values in the reference site and no change inside the wind farm.

- Hard substrate

Considering the fouling community, the number of different taxa per sampled area increased from around five in 2009 to around 10 at the end of the study period. An increase of the total biomass was only observed for the one meter deep sampling stations, primarily due to the colonisation by blue mussels *Mytilus edulis*. At five and ten meter water depths a stable biomass of around 1 kg/m2 was observed. No distinct depth zonation was observed. Dominant taxa (in terms of biomass) were the blue mussel, the amphipod crustacean *Jassa herdmani* and the starfish *Asterias rubens*.

The foundation near the bottom attracted high numbers of demersal fish and large decapod crustaceans. Species such as common hermit crab *Pagurus bernhardus* and the edible crab *Cancer pagurus* were encountered.

5.5 The Netherlands

In the Netherlands three wind farms are currently fully operational: 'Prinses Amalia', 'Egmond aan Zee' and 'Luchterduinen'. The wind farms 'Prinses Amalia' and 'Egmond aan Zee' are located off the coast of the city Egmond aan Zee while 'Luchterduinen' is located to the south, off the coast of Noordwijk.

The research methods and results of the environmental monitoring that took place in and around the wind farms 'Prinses Amalia' and 'Egmond aan Zee' is described in this chapter.

5.5.1 Prinses Amalia

This wind farm is operational since the year 2008 and consists of 60 turbines generating 120 MW of energy in total. The wind farm is located 26 km off the coast on a sandy seafloor, see Figure 5-14. The average water depth is 22 meters. The turbines are founded on monopiles. Compared to the wind farm 'Egmond aan Zee' individual turbines are placed relatively close to each other (2.4 turbines per km^2 in the case of 'Prinses Amalia' compared with 0.8 turbines per km^2 for 'Egmond aan Zee').

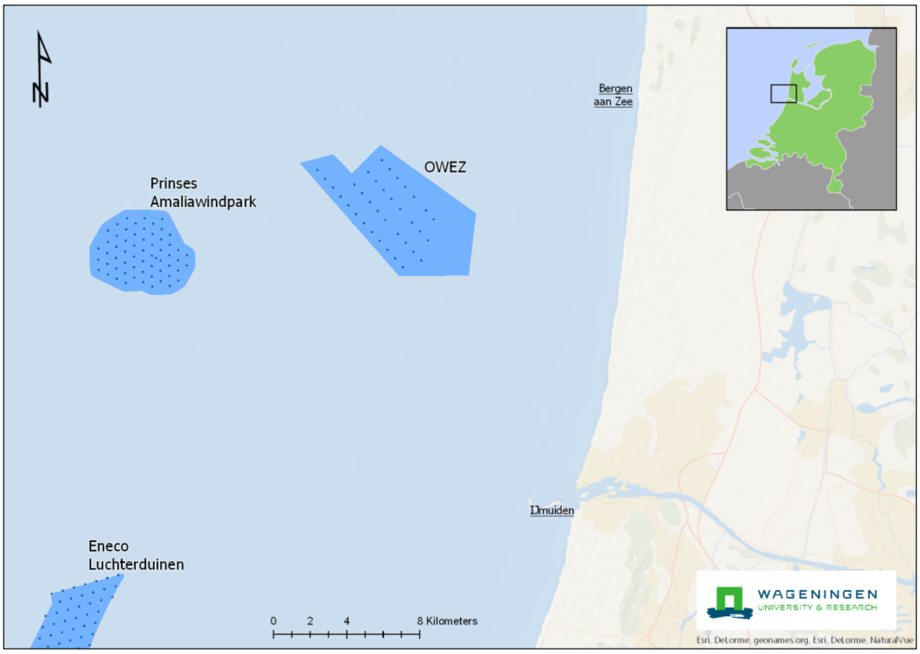

Figure 5-14. *Location of the wind farms Prinses Amalia, Egmond aan Zee (OWEZ) and Luchterduinen.*

5.5.1.1 Sampled matrix and methodology

Both the soft substrate benthos (Jarvis et al., 2004, Vanagt et al., 2013, Lock et al., 2014 and van Hal et al., 2013) and the fouling communities were studied (Vanagt et al., 2011 and Vanagt & Faase, 2014). The followed methods and results found in those studies are described here.

➢ Infauna (Jarvis et al., 2004, Vanagt et al., 2013 and Lock et al., 2014)

The infauna community is studied using a BACI design. Sampling took place within the wind farm and at two reference sites both before (2003) and after (2012 and 2013) construction of the farm. One of the reference sites was located to the north and one to the south of the wind farm. Samples were taken with a box corer and a dredge. With the box corer sediment samples were taken (with a sampled area between 0.0678 and 0.078 m^2) targeting the smaller-sized species buried in the sediment. Samples were sieved over a sieve with a mesh size of 1 mm and retained biota were identified and counted. Sampling consisted of 47 stations inside the wind farm and 25 in each of the reference areas. Dredge sampling consisted of 15 stations inside the wind farm and 9 in each of the references. Samples were sieved over a 5mm sieve and all retained biota were identified and counted.

➢ Epifauna (van Hal, 2013)

Epifauna was sampled once inside the wind farm with two 6 meter wide shrimp gears (one equipped with a mesh of 40mm and the other with a mesh of 20 mm). Four stations located in the middle of the farm and at considerable distances away from the windmills were sampled twice in 2013. Towing duration varied between 15 and 20 minutes at a speed of around 4 knots. The whole catch was sorted and all fish and invertebrate species were identified to species level where possible. Data gathered inside the wind farm was compared to International Beam Trawl Survey (IBTS) sampling points (2004 until 2013) in the area.

➢ Hard substrate (Vanagt et al., 2011 and Vanagt & Faase, 2014)

The fouling communities present at the turbine foundations were sampled twice, in autumn 2011 and July 2014. Both the current- and leeward side of the foundation of four turbines were sampled by divers. Both the intertidal zone was sampled as well as the subtidal zone at different water depths by scraping of an area of 0.25 m^2. Additionally the scour protection rocks were sampled.

5.5.1.2 Results

➢ Infauna

In both the box corer and the dredge samples, a decreasing gradient going from the north to the south was found considering species richness and density with the wind farm occupying an intermediate position. No differences in diversity indices and length distribution of sea urchin and bivalves were found between the reference sites and the wind farm. No significant wind farm effect was found.

➢ Epifauna

No statistically significant differences in catches (number of species, total catch per unit effort (CPUE) and CPUE of herring, sprat, whiting, cod, plaice, dab and greater sand-eel) were found between the wind farm and the surrounding IBTS samples. The field work conducted as part of this study is too limited to draw statistically significant conclusions regarding the refuge function of the wind farm for roundfish. The expectation that larger and older individuals as well as species vulnerable for fisheries would have a better chance to survive and so would increase in size and numbers, was not supported by the data, but could also not be disproved due to a lack of statistical power.

➢ Hard substrate

The initial colonisation was not recorded. An increase in density and biomass was observed between the two sampling events but the species richness remained identical. A clear vertical zonation was observed with a distinctive 'splash' and intertidal zone dominated by green algae and small mussels, a sublitoral zone dominated by mussels *Mytilus edulis* and *Jassa* sp. towards the water surface and anemones towards the bottom and a community present at the scour protecting rocks that included crabs, starfish and hermit crabs. No difference between the sampled windmills or the orientation of the sampling location (current and leeward side) was observed. Noticeable was the recording of the flat oysters *Ostrea edulis*.

5.5.2 Egmond aan Zee

This wind farm is operational since 2007 and consists of 36 turbines generating 108 MW of energy in total. The wind farm is located 14 km off the coast on a sandy seafloor, see Figure 5-14. The average water depth is 19 meters. The turbines are founded on monopiles. Compared to the wind farm 'Egmond aan Zee' individual turbines are placed relatively far away from each other.

5.5.2.1 Sampled matrix and methodology

Both the soft substrate benthos (Jarvis et al., 2004, Daan et al., 2009, Bergman et al., 2012, Lindeboom et al., 2011 and Bergman et al., 2015) and the fouling communities were studied (Bouma and Lengkeek, 2009 & 2012). The methods used and results found in those studies are described here.

➢ Infauna (Jarvis et al., 2004, Daan et al., 2009, Bergman et al., 2012)

The infauna community is studied using a BACI design. Sampling took place within the wind farm and at a number of reference sites both before (2003) and after (2007 and 2011) construction of the farm. After the baseline survey, during which two reference sites were sampled (sites 'R1' and 'R2' in Figure 5-15), it was decided that four additional references sites (sites 'R2' - 'R5' in Figure 5-15) should be monitored based on a statistical power calculation (Daan et al., 2009). Samples were taken with a box corer and a dredge. University of Hull conducted the 2003 sampling while the Netherlands Institute for Sea Research (Koninklijk Nederlands Instituut voor Onderzoek der Zee, NIOZ) conducted the 2007 and 2011 sampling and the number of samples that were taken and the specifications of the gear that was used varied between the different sampling events.

With the box corer, 66 stations were sampled within the wind farm in 2003 (sampled area of 0.0678 m^2) and 25 stations in each of the two reference sites. In the 2007 campaign 30 stations were sampled inside the wind farm and 15 in each of the six reference sites. In 2011 16 stations were sampled inside the wind farm and eight in each of the six reference sites. Both in 2007 and 2011 a similar box corer was used that sampled an area of 0.078 m^2. Sediment samples taken with the box corer were sieved over a sieve with a mesh size of 1 mm and all retained organisms were identified and counted. Shellfish length was measured and stored.

In 2007 and 2011 the 'Triple D' dredge, developed by NIOZ, was used while in the 2003 campaign a different type of dredge was used. In 2003 samples were collected at 25 stations inside the wind farm and at nine stations in each of the reference sites. In 2007 and 2011 14 stations were sampled inside the wind farm. At each reference site two stations were sampled in 2007 while in 2011 samples at six stations were collected.

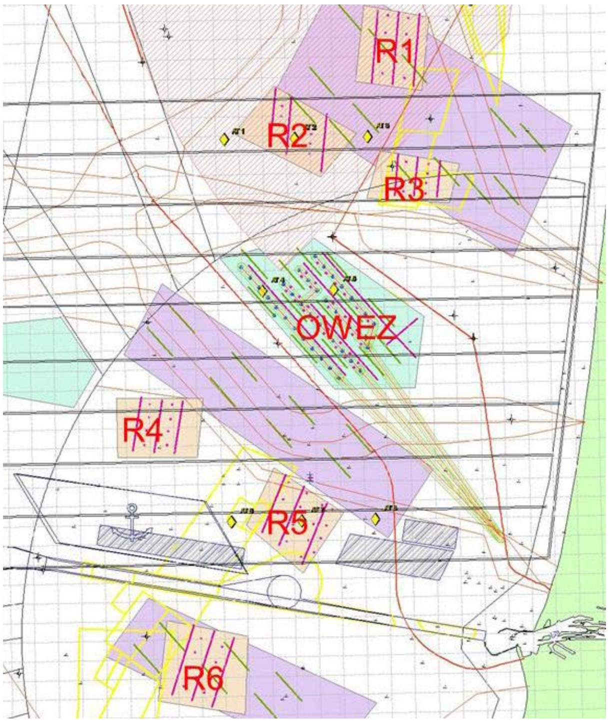

Figure 5-15. *Location of the wind farm 'Egmond aan Zee' and the six reference sites (R1 till R6). Taken from Daan et al., 2009.*

➢ Epifauna (Tien et al., 2014)

Epifauna was sampled once in 2013 with two 6 meter wide shrimp gears (one equipped with a mesh of 40mm and the other with a mesh of 20 mm) both inside and in three reference sites. Towing duration varied between 15 and 20 minutes at a speed of around 4 knots. The whole catch was sorted and all fish and invertebrate species were identified to species level where possible. These data have never been analysed.

➢ Hard substrate (Bouma and Lengkeek, 2009 & 2012)

The fouling communities present at the turbine foundations were sampled in February and September of 2008 and in the same months in 2011. Both the current- and leeward side of the foundation of three turbines were sampled by scientific divers by scraping off an area of 0.25 m^2 using a putty-knife. Samples were collected from 5 zones: the intertidal zone and at 2, 5, 10 and 15 meters below sea surface. Additionally the scour protection rocks were sampled.

5.5.2.2 Results

➢ Infauna

No differences in total species density and biomass were found between samples taken inside the wind farm and in the reference sites, but a higher diversity (Shannon-Wiener) was found inside the wind farm in 2011. The community composition was comparable between the wind farm and the reference sites. The density of the bivalve *Spisula solida* was higher inside the wind farm compared with two of the six reference sites. The length of some species (*Tellina fabula* and *Ensis directus*) was found to be larger inside the wind farm, but for four other species individuals were larger in the reference sites in the 2011 campaign. No proof of a different development in species density, biomass and diversity between the wind farm and reference site over the sampling years was found. Despite this, some non-significant indications of potential wind farm effects were found.

- Hard substrate

The initial colonisation was not recorded. An increase in species density, biomass and richness was observed between the sampling events (in- and over the years). In 2011 23 new species were observed that were not found in 2008 while in 2008 three species were found that were not recorded in 2011. The density of mussels was lower in sampling events conducted in February compared with sampling events conducted in September. The coverage of mussel shells with barnacles and anemones increased over the sampling years. A clear vertical zonation was observed. The intertidal zone was dominated by green algae and different species of barnacles. The intertidal zone of one of the sampled windmill was distinctive from the other two being relatively bare. The shallow sublittoral zone was dominated by mussels *Mytilus edulis* and in areas not covered by mussels crustaceans and anemones were found. Towards the bottom different species of anemones became dominant. Starfish were abundant at all water depths.

5.6 Summary of effects on hard- and soft-substrate benthos communities

In Table 2 an overview of the wind farms described in this chapter is given, as well as some of their technical and environmental specifications and sampled benthos types. Turbines of most of the wind farms that were studied here were founded on monopiles, with the only exceptions being 'Thornton Bank' (gravity and jacket) and 'Alpha Ventus' (tripod and jacket). In most wind farms the seabed can be characterised as being sandy. Considerable variation exists in distance to the coast, ranging from 'Scroby Sand' located just 2 km off the coast to 'Alpha Ventus' located 56 km off the coast. 'Horns Rev' was the oldest wind farm considered here (fully operational in 2002) and 'Thornton Bank' the newest (fully operational in 2013).

Table 2. *Overview of the wind farms that are described in this chapter and their specifications (country, date operational, number of turbines, foundation type, distance off coast, water depth and sediment type) and monitored matrix. BE = Belgium, DM = Denmark, UK = The United Kingdom, GER = Germany, NETH = The Netherlands. Matrix is classified as follows: EP = epifauna, IN = infauna, HS = hard substrate.*

Country	Name of the wind farm	Operational since	Distance off the coast	Water depth	Number of turbines	Foundation type	Sediment type	Sampled matrix
BE	Belwind	2010	49	25	56	monopile	sandy	EP, IN, HS
	Thornton Bank (I t/m III)	2008 / 2013	28	18	54	gravity (6) & jacket (48)	sandy	EP, IN, HS
DM	Horns Rev 1	2002	14	10	80	monopile	mixed	IN, HS
	Horns Rev 2	2009	32	13	91	monopile	sandy	IN
UK	Scroby Sands	2004	2	5	30	monopile	sandy	EP, IN
	Kentish Flats 1	2005	4	10	30	monopile	coarse sediment	EP, IN, HS
	Lynn & Inner Dowsing	2009	7	12	27	monopile	coarse and mixed	IN, HS
	Gunfleet Sands I + II	2010	7	13	48	monopile	sandy	IN, HS
GER	Alpha Ventus	2010	56	29	12	tripod (6) & jacket (6)	sandy	EP, IN, HS
NETH	PAWP	2008	27	22	60	monopile	sandy	EP, IN, HS
	OWEZ	2007	14	19	36	monopile	sandy	EP, IN, HS

5.6.1 Soft sediment

In all studies except one that targeted the in- and epifauna (soft substrate), a BACI experimental setup was adopted with the only exception being 'Scroby Sands' where no reference sites were incorporated, which makes it impossible to show a wind farm effect. A range of gear types were used with varying sampled area (from 0.01 until 2000 m^2). Most of the time samples were taken at considerable distance away from the turbines, at least > 100 meter.

Usually, an unequal number of stations were sampled inside the wind farm and in the reference site(s) and very often adaptations in the number of stations were made during the course of the investigation. For most studies described here, the most recent sampling event was conducted not longer than four years after the wind farm became fully operational. In five studies the most recent sampling event was conducted just one year after the farm became operational, in five others it was two years and in four others it was three years. Research conducted in the Netherlands took place relatively long after the wind farms became operational (four to six years). Therefore, all the studies described here can be considered to give information on the short-term effects of a wind farm only.

Effects that were found on the infauna sampled inside the wind farm and at relatively large distances from the turbines are generally small and/or subtle, either of a temporary nature and/or observed on only a few species/variables (see Table 3). Because a clear response of the soft sediment benthos to the presence of wind farms was absent, a correlation with technical- and environmental properties of the parks could not be made. Changes in the soft sediment benthos close to the turbines generally consisted of an increasing species richness close to the turbine foundations.

5.6.2 Hard-substrate (fouling) community

A quick colonisation of the fouling community was observed, which in most cases showed an increasing number of species, density and biomass over time. A clearly distinct vertical zonation of the fouling species composition was found that was remarkably consistent across wind farms in this study. Only two studies considered here investigated an effect of the orientation relative to the prevailing currents. In one of those (Horns Rev I, Denmark) was an effect of the current orientation observed. This farm is located on an area with shallow water depths and known for its harsh environment.

There is large variation in reported number of species between the investigated studies. Part of this variation stems from differences in sampling method and intensity, but influence of environmental- and technical properties of the wind farms is also considered likely. Without additional (meta)data on sampling details it is impossible to compare these numbers between studies and to relate this to technical- and environmental properties of the wind farms. Sampling methodology, especially sampled area, the number of samples, sampled (sub)habitats, but also identification method (in the field or at the laboratory) determines to a large extent how many species will be found and what the relationship is between the number of samples and number of species.

Table 3. *Overview of gathered information considering experimental setup and results of the ecological monitoring described in this chapter. BE = Belgium, DM = Denmark, UK = The United Kingdom, GER = Germany, NETH = The Netherlands. Matrix is classified as follows: EP = epifauna, IN = infauna, HS = hard substrate. Effect :↑= (larger) increase in wind farm, ↓ = (larger) decrease in wind farm*

Country	Name of the wind farm	Sampled matrix	BACI	Gear	Mesh size (mm)	Sampled area (m^2)	Number of reference sites	Number of stations in each reference site	Number of turbines examined	Number of stations inside the wind farm	Number of campaigns PRIOR to construction	Number of campaigns AFTER construction	Maximum number of years after farm became operational	Minimum distance away from windmills	Effects on diversity / species richness	Effects on biomass	Effect on density	Effect on species length
BE	Belwind	EP	Y	shrimp	22	nb	3	2-16	-	2-8	1	4	2	200		↑		
		IN	Y	vVeen	1	0.1	3	15-18	-	6-16	1	3	1	nb		↑		
		HS	-	scrape	1	0.063	0		3			2	2	-	↑	↑	↑	
	Thornton Bank	EP	Y	shrimp	22	nb	3	2-13	-	2-10	3	4	4	200		↑		
		IN	Y	vVeen	1	0.1	4	4-25	-	2-19	3	2	2	nb	↑			
		IN (CtF[1])	-	vVeen	1	0.025	4	-	1		-	4	4	15	↑	↑		
		HS	-	scrape	1	0.063		-	1		-	4	4	-	↑	↑	↑	
DM	Horns Rev 1	IN	y	HAPS	1	0.0123	1	5-40	6	5-19	2	3	3	5	↑			
		HS (SP[2])	-	scrape	1	0.04	1	nb	6	18	-	3	3	-				
		HS (MP[3])	-	scrape	1	0.04		-	6	60	-	3	3	-	↑			
UK	Scroby Sands	EP	n	vVeen & hammon	nb	nb	0	0	-	38	1	1	1	nb				
		IN	n	beam trawl	nb	nb	0	0	-	7	1	1	1	nb				
	Kentish Flats 1	EP	y	beam trawl	nb	1000 - 2000	4	1-2	-	3	1	3	2	nb				
		IN	y	hammon	nb	0.1	4	2-4	-	8	1	3	2	nb				
		HS	-	scrape	nb	0.01	-	-	2	4	-	3	3	-				
GER	Alpha Ventus (N+Z)	EP	y	beam trawl	10	nb	1	10	1	10	2	2	1	nb		↓	↓	
		IN	y	vVeen	?	0.1	1	20	-	20	2	2	1	nb				
		HS	-	scrape	1	0.04	0	-	2	3	?	?	?	-				
NETH	PAWP	EP	n	shrimp	-	-	0	0	-	4	0	1	4	150				
		IN	y	dredge	6	100	2	9	-	15	1	2	5	150				
		IN	y	box corer	1	0.067-0.078	2	25	-	47	1	2	5	150				
		HS	-	scrape	0.25	0.056	-	-	4	48	-	2	6	-		↑	↑	
	OWEZ	EP	-	shrimp	-	-	3	nb	-	nb	0	1	5	nb				
		EP	y	dredge	6	16-100	6	2-6	-	14-25	1	2	4	150		↑		↑
		IN	y	Box corer	1	0.067-0.078	6	8-25	-	16-66	1	2	4	150		↑		↑
		HS	-	scrape	0.25	0.056	-	-	3	36	-	2	4	-	↑	↑	↑	

[1] Sampling took place in the near vicinity of the turbine foundation

[2] Fouling community present on the scour protection

[3] Fouling community on the monopiles

6 Conclusions and recommendations

We have compared methods and results of studies targeting the effects of offshore wind farm development on the benthic communities in Denmark, Belgium, Germany, The United Kingdom and The Netherlands. This was done in order to learn if general patterns in benthos response to offshore wind farm development can be discerned from comparing across such a wide range of studies.

Furthermore, the results of these studies were related to environmental and technical specifications of wind farms in order to estimate to what extent the conclusions found in existing wind farms elsewhere can be taken as representative for those planned on the Dutch Continental Shelf, and to what extent those for which studies have been conducted are representative of the large number of wind farms currently in various planning phases.

We found that both operational wind farms and those in development in most cases use monopile foundations. We expect that this will remain the dominant foundation type in the Dutch Continental Shelf, where water depth is generally within the range suitable for monopiles.

An increasing trend in height of the turbines and span width of the rotor blades was found, and this trend will most likely result in fewer turbines per unit area in the future. This means more area closed to trawling per unit hard substrate, so that the former mechanism of altering the benthic ecosystem will become increasingly more important. Furthermore, the effect of bottom trawling is stronger in deeper water on the DCS (Van Denderen et al. 2014). On the other hand, the introduction of hard substrate will be lower at reduced turbine density.

Wind farms in development are generally planned further offshore and at greater water depths compared to those currently operational. If this trend continues, the relevance of research results so far will be increasingly smaller, as both diversity and functional composition of the benthic community on the DCS depend strongly on distance to the coast and water depth (Van Denderen et al. 2014, 2016).

We furthermore conclude that the existing Dutch wind farms OWEZ and PAWP are among the best studied (in terms of benthos effect studies) in the wider North Sea area.

Hard substrate

Following construction, rapid colonisation of a fouling community was found on the turbine-related hard substrate (the turbine itself and scour protection), which generally showed an increasing number of species, density and biomass over time. A clearly distinctive vertical zonation (in terms of the dominant species) was found. This pattern (both zonation and dominant species) was consistent across the studied wind farms. The zonation can be described as follows: barnacles and mosquito larvae in the intertidal zone, followed by an inter-/subtidal zone dominated by blue mussels and amphipods. Below this zone, several anemone species dominate and this zone extends towards the bottom. The consistency of this pattern across wind farms implies a clear expectation of the hard substrate fauna on planned wind farms.

Future hard-substrate research is focused on obtaining longer time series from existing locations (rather than more time series from new locations), to understand the long-term dynamics and the potential appearance of invasive species. The location of these studies is of lesser importance as results so far appear very similar throughout the North Sea.

Soft sediment

The vast majority of studies involved a BACI-style experimental setup to show differences in soft sediment benthos as a result of wind farm presence. Often no statistically significant effects were found at all. When wind farm effects were found, they generally were subtle and varied, showing only temporary changes in one or a few variables (such as abundance of specific species or species richness). They also were often on the boundary of statistical significance. Furthermore, effects were regularly found in an unexpected direction (i.e. positive instead of negative). The paucity of observed effects prevents any further exploration in relation to environmental conditions and/or technical specifications. However, a number of methodological shortcomings were noted, which may have eroded the power of the analyses carried out, and which hamper the comparison across wind farms: (1) the number of stations sampled is generally low, (2) a large set of different sampling techniques is adopted, sometimes even among sampling occasions within studies (3) in some studies no follow-up campaigns were conducted, (4) sampling period is generally short (maximum four years after installation of the wind farm), (5) usually a single base line monitoring campaign (the so-called 'T_0') was conducted, (6) a range of different statistical analyses were applied, (7) the number of stations and reference sites are not based on a statistical power analysis, (8) in most cases no comparison with autonomous trends was made.

Given the paucity and subtlety of the effects found, it is tempting to conclude that effects of the presence of a wind farm on soft sediment benthos are small, but the methodological shortcomings listed above do not warrant such a definitive statement. Instead, the conclusion must be that (1) the effect is small, and/or the result of (2) a flawed or inappropriate monitoring design. A third, equally plausible option (3) is that recovery is slow (Bergman et al. 2015) and effects have not yet taken place. Further research will be necessary to distinguish between these options (but note that they are not mutually exclusive).

Options 1 and 2 could be further studied by a *post-hoc* assessment of statistical power. This would allow for policy-relevant conclusions phrased as '*the effect was with 95% certainty smaller than XX*'. Unfortunately, the conducted studies generally do not report post-hoc statistical power, so that for this a reanalysis of the original data is needed. Such a reanalysis is beyond the scope of this study, but is recommended for those wind farms for which the data can be obtained. This will be possible for some, but most likely not for all wind farms, due to data ownership issues in some countries.

Option 3 can be studied by continuing monitoring in existing wind farms. The Dutch wind farms OWEZ and PAWP are good candidates given that a relatively comprehensive sampling program (in comparison with many other wind farms in the area) has already been carried out.
Currently it is not known what the long term effects of the wind farm are, and the results found here can hence not be used to make predictions of the long-term benthic response to wind farms. In general however it has been shown that environmental factors such as depth, sediment type and primary productivity strongly determine both the magnitude and type of effects of bottom trawling on the benthic ecosystem (van Denderen et al. 2014, 2016). This indicates that long-term effects may differ between locations. There may be no effects even in the long term in certain locations.

The few studies which considered the soft sediment community in the near vicinity (~25m) of the turbine foundation showed that species richness, abundance and sediment organic matter content gradually increased towards the turbine. It is not known if the area in which this occurs expands over time, and we recommend this effect be further studied.

We recommend that monitoring of soft substrate in existing wind farms is continued periodically (for example, once every 5 years) to test for long-term effects. OWEZ and PAWP are among the best choices given the monitoring effort so far. However, the relevance of this data should be reconsidered if future wind farms continue to shift to deeper locations further offshore.

Given the difficulty in showing effects using a BACI study design (and the costs involved in carrying out such studies), soft-sediment benthos studies in wind farms should focus instead on uncovering specific potential mechanisms of change to the benthic ecosystem in response to the placement of offshore wind turbines.

7 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2008 certified quality management system (certificate number: 187378-2015-AQ-NLD-RvA). This certificate is valid until 15 September 2018. The organisation has been certified since 27 February 2001. The certification was issued by DNV Certification B.V.

References

Bergman M., G. Duineveld, R. Daan, M. Mulder & S. Ubels 2012. "Impact of OWEZ wind farm on the local macrobenthos community". OWEZ_R_261_T2_20121010.

Bergman, M. J. N., Ubels, S. M., Duineveld, G. C. A., and Meesters, E. W. G. 2015. "Effects of a 5-year trawling ban on the local benthic community in a wind farm in the Dutch coastal zone". ICES Journal of Marine Science, 72: 962-972.

Bouma S., W. Lengkeek, 2009. "Development of underwater flora- and fauna communities on hard substrates of the offshore wind farm Egmond aan Zee (OWEZ)". Report OWEZ_R_266_T1_20090126, Bureau Waardenburg.

Bouma S., W. Lengkeek, 2012. "Benthic communities on hard substrates of the offshore wind farm Egmond aan Zee (OWEZ) Including results of samples collected in scour holes". Report OWEZ_R_266_T1_20120206_hard_substrate, Bureau Waardenburg.

Brabant R., S. Degraer & B. Rumes, 2013. "Monitoring offshore wind farms in the Belgian Part of the North Sea: Setting the scene." In: Degraer, S., R. Brabant & B. Rumes (Eds.), 2013. "Environmental impacts of offshore wind farms in the Belgian pert of the North Sea: Learning from the past to optimise future monitoring programmes". Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management Section.

BSH & BMU (2014). Ecological Research at the Offshore Wind farm alpha ventus – Challenges, Results and Perspectives. Federal Maritime and Hydrographic Agency (BSH), Federal Ministry for the Environment, Nature conservation and Nuclear Safety (BMU). Springer Spektrum. 201 pp.

Daan, R., M. Mulder, M.J.N. Bergman 2009. "Impact of wind farm OWEZ on the local macrobenthos community". NIOZ report OWEZ_R_261_T120091216, pp 77.

Coates, D.A., Y. Deschutter, M. Vincx, and J. Vanaverberke, 2014. "Enrichment and shifts in macrobenthic assemblages in an offshore wind farm area in the Belgian part of the North Sea". Marine Env. Res. 95: 1 - 12.

Coates, D.A., Kapasakalia, M. Vincx & Jan Vanaverbeke, 2016. "Short-term effects of fishery exclusion in offshore wind farms on macrofaunal communities in the Belgian part of the North Sea". Fisheries Research 179: 131–138.

Curtis, M., J. Rance, B. Frojan, 2014. "Baseline Monitoring Survey of Lynn Knocks Reef within IDRBNR SCI, Cefas.

Degraer, S., R. Brabant & B. Rumes (Eds.), 2013. "Environmental impacts of offshore wind farms in the Belgian pert of the North Sea: Learning from the past to optimise future monitoring programmes." Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management Section. 239 pp.

Drew, D.R., Cannon, D.J., Brayshaw, D.J., Barlow, J.F., Coker, P.J., 2015. "The Impact of Future Offshore Wind farms on Wind Power Generation in Great Britain." Resources, 4: 155-171.

Glorius, S.T., Bos, O., Chen, C., 2017. 'Aanbevelingen voor de voortzetting van het benthosonderzoek in de windparken PAWP en OWEZ - Op basis van een power analyse en litertuurrevieuw." WMR report, pp 47.

Green, R. H., 1979. "Sampling Design and Statistical Methods for Environmental Biologists.", Wiley:Chichester.

Guerra, M.T., Freitas, R., 2012. "Recommended Operational Guidelines (ROG) for grab sampling and sorting and treatment of samples." Mesh Atlantic, pp 15.

Hal, R. 2013. "Roundfish monitoring Princess Amalia Wind farm." IMARES report C117/13-A.

Higgins, P., A. Foley 2014. "The evolution of offshore wind power in the United Kingdom". Ren. and Sust. Energy Reviews. 37: 599-612.

ICES, 2015. ICES WGMBRED Report 2015. "Report of the Working Group on Marine Benthal and Renewable Energy Development (WGMBRED)". ICES CM 2015/SSGEPI:17.

Jarvis, S., J. Allen, N. Proctor, A. Crossfield, O. Dawes, A. Leighton, L. McNeill, W. Musk 2004. "Dutch Wind farms: NSW Lot 1 Benthic Fauna". Final Report. ZBB607.2-F-2004, pp.89.

Larsen, B., 2003. "Blåvands Huk – Horns Rev området – et nyt Skagen?" Temanummer Geologi nyt fra GEUS nr. 4.

Leonard S.B. (2006). EIA Report Benthic communities Horns Rev 2 Offshore Wind farm. Bio/consult as. 55 pp.

Leonhard, S.B. & J. Pedersen, 2006. "Benthic Communities at Horns Rev Before, During and After Construction of Horns Rev Offshore Wind farm." Final Report - Annual Report 2005. Bio/consult as. 134 pp.

Lindeboom, H. J., Kouwenhoven, H. J., Bergman, M. J. N., Bouma, S., Brasseur, S., Daan, R., Fijn, R. C., et al. 2011. "Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation". Environmental Research Letters, 6: 035101.

Lock, K., M. Faasse, T. Vanagt, 2014. "An Assessment of the soft sediment fauna six years after construction of the Princess Amalia Wind farm". eCOAST report 2013002, pp. 151.

Lombardi, D., S. Bhattacharya, D.M. Wood, 2013. "Dynamic soil-structure interaction of monopile supported wind turbines in cohesive soil". Soil Dynamics and Earthquake Engineering, 49: 165-180.

Mesel De I., F. Kerckhof, B. Rumes, A. Norro, J-S Houziaux & S. Degraer, 2013. In: Degraer, S., R. Brabant & B. Rumes (Eds.) (2013). "Environmental impacts of offshore wind farms in the Belgian pert of the North Sea: Learning from the past to optimise future monitoring programmes." Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management Section.

Mesel De I., F. Kerckhof, A. Norro, B. Rumes & S. Degraer, 2015. "Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species". Hydrobiologica 756:37-50.

MMO, 2014. "Review of post-consent offshore wind farm monitoring data associated with licence conditions". A report produced for the Marine Management Organisation, pp 194. MMO Project No: 1031. ISBN: 978-1-909452-24-4.

Nielsen, A.W., B.M. Sumer, T.U. Petersen, 2014. "Sinking of Scour Protection at Horns Rev 1 Offshore Wind farm." Coastal Eng. Proceedings, 34:1 - 14.

Perrow, M.R., Gilroy, J.J., Skeate, E.R., Tomlinson, M.L., 2011. "Effects of the Construction of Scroby Sands Offshore Wind farm on the Prey Base Little Stern *Sternula albifrons* at its most Important UK Colony". Marine Pollution Bulletin, 62: 1661-1670.

Reichert K., M. Gusky, L. Gutow. 2012. "Vervollstandigung der Zeitreihen wahrend der Betriebsphase und Ermittlung von Veranderungen des Benthos durch Ausweitung des anlagenbezogenen". Effektmonitorings Jahrlicher Zwischenbericht 2010 zum Projekt, Okologische Begleitforschung am Offshore-Testfeldvorhaben ‘alpha ventus’ zur Evaluierung der Standarduntersuchungskonzeptes des BSH-StUKplus FKZ 0327689A

Schmidt B., U. Smolka, S. Hartmann & P.W. Cheng (2013). Validation of the Dynamic Wake Meander Model with AREVA M5 000 Load Measurements at alpha ventus. EWEA Conference, 2013.

Skeate, W.R., Perrow, M.R., Gilroy, J.J., 2012 "Likely Effects of Construction of Scroby Sands Offshore Wind farm on a Mixed Population of Harbour *Phoca vitulina* and grey *Halichoerus grypus* seals". Marine Pollution Bulletin, 64: 872-881.

Underwood, J.A., 1991. "Beyond BACI: Experimental Designs for Detecting Human Environmental Impacts on Temporal Variations in Natural Populations." Aust. J. Mar. Freshwater Res. 42: 567-587.

Vanagt T & M. Faasse 2014. "Development of hard substratum fauna in the Princess Amalia Wind farm: Monitoring six years after construction". eCOAST report 2013009.

Van Denderen, P. Daniël, Niels T. Hintzen, Adriaan D. Rijnsdorp, Piet Ruardij and Tobias van Kooten. 2014. Habitat-specific effects of fishing disturbance on benthic species richness in marine soft sediments. Ecosystems 17(7):1216-1226.

Van Denderen, P Daniël, Stefan G. Bolam, Jan Geert Hiddink, Simon Jennings, Andrew Kenny, Adriaan D. Rijnsdorp and Tobias Van Kooten. 2016. Similar effects of bottom trawling and natural disturbance on composition and function of benthic communities across habitats. MEPS 541:31-43.

Vandendriessche, S., J. Derweduwen & K. Hostens, 2013a. In: Degraer, S., R. Brabant & B. Rumes (Eds.) (2013). "Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Learning from the past to optimise future monitoring programmes". Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management Section.

Vandendriessche, S., Hostens, K., Courtens, W., Stienen, E., 2013b. "Fisheries activities change in the vicinity of offshore wind farms". In: Degraer, S. et al., (ed.) (2013). "Environmental Impacts of Offshore Wind farms in the Belgian part of the North Sea: Learning from the Past to Optimise Future Monitoring Programmes": 81–85.

Vandendriessche, S., Derweduwen, J., & Hostens, K., 2015. "Equivocal effects of offshore wind farms in Belgium on soft substrate epibenthos and fish as-semblages". Hydrobiologia, 1-17.

Vattenfall, 2009. "Kentish Flats Offshore Wind farm FEPA Monitoring Summary Report, March 2009". pp 74.

Walker R., 2009. "Strategic Review of Offshore Wind farm Monitoring Data Associated with FEPA Licence Conditions Benthic Ecology". Contract ME1117. Cefas, Lowestoft.

Whitehouse, R.J.S, J.M. Harris, J. Sutherland, J. Rees, 2001. "The nature of scour development and scour protection at offshore wind farm foundations". Marine Pollution bulletin, 62: 73-88.

Wizelius, T., 2015. "Wind Power Projects - theory and practice", Routledge UK, ISBN: 978-1-138-78045-3, pp 219.

Justification

Report C043/17
Project Number: 431.51000.48

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved: Dr. Tobias van Kooten
Senior Scientist

Signature:

Date: May 10, 2017

Approved: Drs. J. Asjes
MT-member integration

Signature:

Date: May 10, 2017

Wageningen Marine Research
T +31 (0)317 48 09 00
E: marine-research@wur.nl
www.wur.eu/marine-research

Visitors' address
- Ankerpark 27 1781 AG Den Helder
- Korringaweg 5, 4401 NT Yerseke
- Haringkade 1, 1976 CP IJmuiden

Wageningen Marine Research is the Netherlands research institute established to provide the scientific support that is essential for developing policies and innovation in respect of the marine environment, fishery activities, aquaculture and the maritime sector.

Wageningen University & Research:
is specialised in the domain of healthy food and living environment.

The Wageningen Marine Research vision
'To explore the potential of marine nature to improve the quality of life'

The Wageningen Marine Research mission
- To conduct research with the aim of acquiring knowledge and offering advice on the sustainable management and use of marine and coastal areas.
- Wageningen Marine Research is an independent, leading scientific research institute

Wageningen Marine Research is part of the international knowledge organisation Wageningen UR (University & Research centre). Within Wageningen UR, nine specialised research institutes of the Stichting Wageningen Research Foundation have joined forces with Wageningen University to help answer the most important questions in the domain of healthy food and living environment.