REPORT

2019 Update on the Current state of Knowledge on the Environmental Impacts of Offshore Wind Farms

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Acronym	Acronym description
ADD	Acoustic Deterrent Devices
BBC	Big Bubble Curtain
BCA	Bird Collision Avoidance
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EMF	Electromagnetic Field
FAD	Fish Attraction Device
HSD	Hydrosound Damper
iEF	Induced Electrical Field
INNS	Invasive Non-native Species
NEAS	North Atlantic Environment Strategy
NMS	Noise Mitigation System
O&M	Operation and Maintenance
OSPAR	Oslo Paris Convention (for the Protection of the Marine Environment of the North-East Atlantic)
OWF	Offshore Wind Farm
PBR	Potential Biological Removal
PTS	Permanent Threshold Shift
PVA	Permanent Viability Model
ROV	Remotely Operated Vehicle
SEL	Sound Exposure Level

Acronym	Acronym description
SPL	Sound Pressure Level
SSC	Suspended Sediment Concentration
SST	Sea Surface Temperature
TTS	Temporary Threshold Shift
VH	Vibrohammers

1 Introduction

1.1 Introduction

The development of Offshore Wind Farms (OWFs) has the potential to impact the surrounding marine environment in numerous ways. The challenge is to create a clear understanding of what these impacts might be, how they are assessed and how they can be mitigated so that impacts can be avoided or reduced to acceptable levels.

In 2006, OSPAR (Oslo/Paris convention (for the Protection of the Marine Environment of the North-East Atlantic)) published the "Update on the Current State of Knowledge of the Environmental Impacts of the Location, Operation, and removal/Disposal of Offshore Wind Farms – Status Report". The aim of the report was to provide a review of existing information and to determine the current state of knowledge on the ecological impacts of OWFs within the OSPAR Region. The report allowed for future research to be prioritised and better targeted on key issues of concern. This overview was published as a living document with the below reviews setting out the subsequent iterations to date:

- In 2014 the United Kingdom submitted a Draft Update on the Current State of Knowledge and Studies of the Environmental Impacts of the Location, Operation and Removal/Disposal of OWF, (EIHA 13/3/5) (referred to as Cefas, 2014 in this report); and
- In 2018 and 2019 Rijkswaterstaat Zee & Delta, commissioned Royal HaskoningDHV to undertake an update of the 2006 and 2014 reports resulting in: Review of literature 2014-2019 on ecological impact offshore wind farm development (this report has been included as **Appendix A**).

1.2 Purpose of this Report

OSPAR wishes to update the above mentioned 2014 Draft update on the Current state of knowledge as a basis to review the OSPAR Guidance on Environmental Considerations for Offshore Wind Farm Development (2008-3). The purpose of this report is to provide OSPAR with a clear and concise summary of the information collated in the 2014 Cefas update and the 2019 literature review (see **Appendix A**), setting out the current state of knowledge of the impacts that OWF development can have on environmental receptors within the OSPAR Region.

1.3 Report Limitations

Whilst the information in this report and **Appendix A** is an up to date reflection of the current state of knowledge of the ecological impacts of OWFs, it is important to note that it is not considered to be exhaustive due to a number of factors.

As research is constantly evolving, a cut-off date for the literature review was set at the end of September 2019. The focus has also been on findings from the OSPAR Region[1] only, any information that may be available from other regions, such as the east and west coasts of the US, has not been included. At the time of the 2018 update report, an assumption was also made that any information available prior to the 2014 update was included in the 2014 report and searches were therefore not undertaken to include any earlier work.

Where possible, impacts have been presented for the construction and operation and maintenance (O&M) phases of OWF development. As there is currently no information on the decommissioning of OWFs, potential effects during decommissioning are not considered in this report.

[1] *The OSPAR Region covers the North-East Atlantic and is split into five regions: Arctic Waters, Greater North Sea, Celtic Seas, Bay of Biscay and Iberian Coast, and Wider Atlantic. Signatories are: Belgium, Denmark, the European Community, Finland, France, Germany, Iceland, Ireland, the Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden Switzerland and the United Kingdom.*

1.4 Report structure

The following sections of this report have been structured according to the environmental receptors that can be impacted by OWF development, as follows:

Section 2: Physical Processes (hydrodynamics, sediment transport, water quality);

Section 3: Ornithology and Bats;

Section 4: Benthic Ecology (including shellfish ecology);

Section 5: Fish Ecology;

Section 6: Marine Mammals;

Section 7: Other Receptors;

Section 8: Ecosystem Effects; and,

Section 9: Overarching Findings.

Each of the above sections include subsections on the current state of knowledge and perceived data gaps based on the literature review presented in **Appendix A**. As this is a summary report, full references have not been included. These can be found at the end of **Appendix A**.

The final limitation is that the current literature review, on which this document is based, have only focussed on research papers. There is a significant amount of information available from the Environmental Impact Assessments (EIA) undertaken for OWFs and the monitoring requirements that are often set out in licence conditions for the operational phase of development. To provide a true reflection on the current state of knowledge these sources should also be consulted and findings included in a report.

2 Physical Processes (hydrodynamics, sediment transport, water quality)

OWF developments affect physical processes such as hydrodynamics (tides and currents), sediment transport and water quality (Cazenave *et al.*, 2016; Schuster *et al.*, 2015; Carpenter *et al.*, 2016). The effects on physical processes mostly occurs during the O&M phase, rather than during the construction phase, given it is the actual presence of the structures that gives rise to the effects and which occur for the duration that the structures are in place for. The following effects on physical processes have been identified during the O&M phase of OWFs:

- Wave changes (including wave height);
- Tides and currents;
- Tidal energy dissipation;
- Accumulation of physical processes effects;
- Changes to wind resource; and,
- Stratification and water mixing.

2.1 Construction

The reviewed literature did not include information on the potential impact of offshore wind development on physical processes during the construction phase. Specifically, no information was provided on increased suspended sediment concentrations and deterioration in water quality.

2.2 Operation and Maintenance

Research into the effects of OWF development on physical processes is comparatively limited when compared to other environmental receptors such as marine mammals, particularly when looking at cumulative effects over a larger area. Currently most research focusses on the local impacts of individual wind farms; however, with the current drive to significantly increase the number of OWFs, there is potential for effects to accumulate and lead to larger cumulative effects over a greater spatial scale.

2.2.1 Wave changes

The wave regime looks at how waves are created, how and in what direction they travel, how they change in height and how this is influenced by outside factors. The presence of OWFs has the potential to change the wave regime. The interactions between OWFs, available wind resources (Section 2.2.5) and how this impacts waves forming are commonly assessed for individual wind farms as being local (Deltares, 2018). Structures within OWFs may also impact wave propagation leading to wave diffraction which has the potential to impact the wave regime (Deltares, 2018).

Alari and Raudsepp (2012) quantified the impact of OWF structures on wind driven waves using data from two OWFs located in Estonia with a total of two hundred wind turbines. It was concluded that the reduction of significant wave height near the coast below 10m isobaths does not exceed 1%. Therefore, it seems unlikely that the effects would be significant. The effects of OWFs upon wave height was also assessed by Cefas (2014), which identified small reductions in significant wave height near the coast (Cefas, 2014).

Largescale development of OWF may lead to (as yet poorly quantified) effects on the vertical transfer of energy from the higher atmosphere to the OWF, impacting wind and waves. It is considered that a change of 5% in wind speed can lead to a change of 5 to 10% in significant wave height.. In addition to this, structures within an OWF may also have an impact on wave propagation leading to wave diffraction (Deltares, 2018)

2.2.2 Tides and currents

Tides are characterised by water movements over a long period of time with currents describing the motion of the water. The presence of wind turbines has the potential to change tides and currents.

Horizontal current velocities have been shown to increase either side of foundations and decrease on the leeside (Clark *et al.*, 2014). The effect decreases with distance from the foundation but can extend for hundreds of meters with changes largest in the upper water column (Cazenave *et al.*, 2016). There is also the potential for vertical changes in currents, as slower water layers impact those above and below them; though this is more evident in fully mixed water than in stratified water.

Cazenave *et al.* (2016) also found large-scale effects to the amplitude of tides in particular at the coasts (>2%) as well as offshore related to OWFs.

2.2.3 Tidal energy dissipation

Tidal energy dissipation is the extraction of energy that is produced by the tides in the ocean, most commonly this is caused by bottom friction or wind turbulence. Carpenter *et al.* (2016) found that the turbulence induced by an OWF can be significant and could lead to the total energy that is extracted from the tides playing a significant role in dissipation of tidal energy. Historically areas where tidal energy dissipates are referred to as sinks. Wind turbine foundations are now becoming a potential new sink that is not yet well understood.

2.2.4 Accumulation of physical processes effects

Cazenave *et al.* (2016) and De Dominicis *et al.* (2017) found that the many feedback mechanisms and interconnections in the systems makes it difficult to assess cumulative effects. Various studies show that effects may occur far away from OWFs and that impacts of individual foundations can be magnified when propagated through the systems. Therefore, the construction of large-scale OWFs may result in significant changes in tides and currents (Deltares, 2018).

2.2.5 Stratification and water mixing

Stratification and water mixing depend on a variety of factors including salinity and temperature, within water bodies and water layers that have different characteristics, water mixing does not take place easily. Carpenter *et al.* (2016) found that vertical mixing of stratified layers is enhanced when water flows along foundations, leading to an increased mixing of the water column and decreased stratification. They found that the widespread construction of OWFs could impact stratification of the water column on a large-scale. Floeter *et al.* (2017) found that the stratification index was markedly lower within an OWF than outside, extending around 15km beyond the OWF in the direction of the current. Such effects are expected to occur in areas that are intermittently or seasonally stratified, so mostly during the summer season (roughly from March to September).

2.3 Impacts related to physical processes

2.3.1 Deterioration in water quality and sediment due to contamination[2]

Re-suspension of polluted sediment and increased turbidity during construction and cabling are considered short lived impacts. They do however, have the potential to affect the health and breeding success of organisms using these areas (Simms and Ross 2000 in Shuster *et al.* (2015).

OWF development has the potential to deteriorate water quality and sediment through a number of routes. Shuster *et al.* (2015) reported that the risk of contamination from leaks or spills increases within OWFs due

[2] *Whilst a deterioration of water and sediment quality is not a direct effect on physical processes, the two are closely related particularly when referring to resuspended contaminants. It has therefore been included in this section.*

to potential shipping incidents and leaking turbine components, (e.g. hydraulic fluids from operational devices).

If plastic polymers are used as part of scour protection in OWFs the chemical substances contained within them may be harmful to marine organisms and humans. Sturm *et al.* (2015) showed that under laboratory conditions potentially harmful substances may be released. The geotextile materials used as scour protections around foundations may attract a diverse biota with the potential for any harmful substances to accumulate in these organisms. It should be noted that *in situ* tests have not been undertaken to date with further research required.

2.3.2 Changes to wind resources[3]

Wind is considered to be an inexhaustible resource. However initial studies have found that OWFs can have an impact on wind availability both within the OWF and as a wider resource (Deltares 2018). These potential changes in wind resource can be related to:

- OWFs harvesting wind energy and thereby slowing down the wind velocity at hub height (momentum sink) creating wakes on the leeward side which then requires replenishment from higher levels not affected by the turbines.
- As wind turbines turn, air will be mixed, increasing wind speed at the lowest part of the rotor and decreasing the wind speed at the highest part of the rotor. Wind turbines may transform stable wind profiles into less stable or neutral wind profiles.
- Wind turbines form obstacles with wind having to pass around them. This slows down wind in front of turbines and speeds it up along the sides.
- On a large scale, OWFs may lead to more wide spread effects on the vertical transfer of energy from the higher atmosphere to the OWF (i.e. draw down of wind). These potential effects on a large scale are currently poorly understood and have not yet been quantified/studied.

The above impacts become more important as OWFs and turbines increase in size and number. Differences between upwind and downwind turbines become noticeable if energy cannot be replaced between turbines (Deltares 2018).

3 Ornithology and Bats

Displacement is the loss (or reduced usage) of the wind farm area for purposes of feeding, roosting etc.

Barrier effect is when birds that would previously have transited through the wind farm (e.g. when commuting between nesting colony and feeding areas) take a flight route that circumvents the wind farm.

Avoidance encompasses avoidance of turbine rotors and avoidance of the windfarm.

The construction, and O&M of OWFs can impact birds and bats in a number of ways. The literature upon which this report is based only included limited information on bats. This information has therefore been covered in a single section. All other sections relate to birds only unless specifically otherwise stated. The following potential impacts were identified for birds during construction:

- Disturbance due to human activities;
- Avoidance and attraction;
- Displacement / barrier effect; and,
- Construction sound.

[3] *Whilst changes to wind resources do not fall within physical processes, the two are closely related as effects on wind resources will have an effect on wave formation.*

During the O&M phase of OWFs, bird and bats have the potential to be affected by:

- Collision risks;
- Avoidance and attraction;
- Displacement / barrier / habitat loss; and,
- Change in prey resource.

3.1 Construction

As set out above, no information was identified relating to construction impacts on bats, this section therefore only looks at potential impacts on birds.

3.1.1 Disturbance due to human activities

Disturbances from human activities may cause seabirds to avoid certain areas and show a change in behaviour. Sensitsivity and the level of disturbance is species-specific and influenced by parameters such as the scale of development, season, breeding and feeding behaviour. Schwemmer *et al.* (2011) found red-throated diver and common scoter to be particularly sensitive to vessel activity.

Perrow (2019b) suggested that disturbance caused during the construction phase of OWFs may be mitigated by limiting the number and size of vessels as well as by temporal coordination of construction activity and planning of routes and frequency of vessel movements.

In addition, a study by Mendel *et al.* (2019) found that construction vessel traffic had significant negative impacts on the distribution of loons (*Gavia* spp.), highlighting the extensive effects of OWFs and vessels on a large spatial scale. Whilst not specifically related to the offshore wind industry the findings from Miller *et al.* (2019) have been included as they are of relevance to the development of impact assessment for OWFs. Miller *et al.* (2019) used a Population Viability Model (PVA) for various scenarios of anthropogenic mortality. Miller *et al* (2019) found that the model proved to be an effective tool in determining the environmental and anthropogenic factors that regulate population growth

3.1.2 Avoidance and attraction

Avoidance of OWFs by birds can occur at three spatial scales: (1) *Macro-avoidance* – total avoidance of the wind farm footprint and in some cases a buffer of up to 3km; (2) *Meso-avoidance* – any responses to turbines within the windfarm site, e.g. flying between rows or within a specific buffer around the rotor swept zone; and, (3) *Micro-avoidance* – 'last-minute' action to avoid collision (i.e. with blades within a defined buffer during operation).

Artificial light sources used during the construction phase of OWFs can attract nocturnally migrating and foraging seabirds. Rebke *et al.* (2019) undertook a study on nocturnally migrating passerines. It was determined that no light variant was constantly avoided. Whilst intensity did not influence the number of birds attracted, birds were drawn more towards continuous than towards blinking lights, when stars were not visible.

3.1.3 Displacement / barrier effect

The construction of OWFs can cause displacement of birds, where individuals avoid specific areas (e.g. for feeding), which can potentially impact adult survival and productivity (Searle *et al.*, 2016).

Baarsch *et al.* (2015) investigated bird communities at the German OWF BARD Offshore 1, which is located c. 80 km north of Borkum, looking specifically at common guillemot (*Uria aalge*) and northern fulmar (*Fulmarus glacialis*). Results showed that densities of guillemots and northern fulmars decreased in the

OWF area during construction when compared to the reference area. The highest densities were observed in the reference area during and post construction indicating local avoidance behaviour resulting in small scale displacement.

However, a 10-year study by Vallejo *et al.* (2017) analysing the effects of all phases of the Robin Rigg OWF on common guillemot (*Uria aalge*), found relative abundance of common guillemot to be similar across pre-construction, construction and operational phases, contradicting the findings above.

Searle *et al.* (2018) developed a tool called “SeabORD” to estimate the cost of displacement and barrier effects to seabirds in terms of changes in adult survival and productivity. Results showed that the magnitude of effects resulting from OWFs depended on the size and shape of the site, proximity to colonies and species in question. For black legged kittiwake (*Rissa tridactyla*), the model predicted that different breeding colonies responded differently to the construction of single or multiple OWFs. Adult mortality was highest when birds were affected by both displacement and barrier effects. It was concluded that barrier effects on their own cause the greatest increase in mortality, as the birds experiencing barrier effects only were affected more than those that were only displaced.

3.1.4 Construction sound

Sound introduced during construction activities has not been highlighted as a major direct impact for birds (Cefas, 2014). There have been reports of indirect effects on birds due to construction sound through trophic prey-predator relationships (see also Section 5 for information on impacts on prey species). however, little information is available on direct impacts from construction noise (Cefas, 2014).

Perrow *et al.* (2011) described a potential link between the construction of OWFs and food web interaction with herring (*Clupea harengus*) and little tern (*Sternula albifrons*). Reductions of herring were observed during the construction of 30 OWF turbines in the UK, resulting in reduced tern abundance.

According to Perrow (2019b) the application of noise-mitigation methods during piling may also help to minimise any indirect impacts on birds by reducing the effects on their fish prey.

3.2 Operation and maintenance

3.2.1 Collision risk

Bird mortality due to collision risk with turbine blades is one of the most significant environmental concerns of OWFs. Collision risk is dependent on several factors including species and turbine height (De Lucas *et al.,* 2008), with Furness *et al.* (2013) identifying flight height as the most influencing factor. It is worth noting that the volume of information available for birds is extensive and, in order to avoid unintentionally leaving out findings we have reported this in a bulleted format. The following research has been carried out and published relating to collision risk.

- According to a multiyear study using vertically rotating marine radar, the highest bird flight activity appears to be below 200m over all seasons (Schuster *et al.*, 2015; Hill *et al.*, 2014). Ross-Smith *et al.* (2016) found that gulls flew highest over land and lowest near the coast. The flight height offshore was between 8-12 meters above sea level 50% of the time. For great skuas, no significant relationship was found between flight height, time of day and location.
- Species that previously were assumed to have a high collision risk, such as large gull species and gannets, display meso- and micro-avoidance behaviours that significantly reduce their risk of collision rates (Fox & Peterson, 2019). Thus, collision risk for gulls and gannets is less than previously assumed. In addition, a study has shown that immature and mature gannets have minimal levels of flight and diving activity at night, potentially requiring correction factors to reduce the uncertainty of collision risk models (Furness *et al.*, 2018).

- Several research projects have shown that birds tend to choose corridors between the turbines, dependant on the spacing of turbines (e.g. Krijgsveld *et al.*, 2011; Schuster *et al.*, 2015).
- Studies on bird flight height has, to some extent, been limited to boat surveys and/or radar observations. GPS tracking devices have been found to provide more detailed information of the flight path of individual birds over a larger area. The flight altitude of birds can differ depending on the time of day, location and weather conditions (Zydelis *et al.*, 2015 in Koppel and Schuster, 2015; Ross-Smith *et al.*, 2016). Birds migrating over the sea are more likely to collide with turbines in poor weather, when individuals are more likely to fly at altitudes swept by turbine blades and visibility is reduced (Shamoun-Baranes *et al.*, 2017).
- Cleasby (2015) used data from GPS-loggers and barometric pressure loggers to track three-dimensional movements of northern gannets rearing chicks at a large colony in south-east Scotland (Bass Rock), located <50km from several major wind farm developments with recent planning consent. The results showed that the gannets foraged in and around planned OWF areas. The probability of flying at collision-risk height was low during commuting between colonies and foraging areas (median height 12m) but was greater during periods of active foraging (median height 27 m). This indicates that gannets are at risk of collision as they fly at heights within the rotor swept area (Cleasby, 2015).
- A Bird Collision Avoidance (BCA) study was conducted by Bowgen & Cook (2018) on seabird collision and avoidance rates at the operational Thanet OWF. The study revealed that empirical avoidance rates may not be directly comparable to the avoidance rates that are currently used in collision risk models (e.g. the Band model).
- Studies have shown that guillemot, divers and scoters avoid collision risk as very few are recorded flying through the footprint of OWFs (Langston, 2010; Walls *et al.*, 2013; Vallejo *et al.*, 2017).
- Mass bird migration events take place on only a few occasions and seem to be mostly at night (Schuster *et al.,* 2015, Hill *et al.*, 2014). Hill *et al.* (2014) confirmed high rates of bird calls predominantly after midnight, especially during spring and autumn migration (peak migration seasons). Thus, the potential for collision can also vary throughout the year and depend on the season (Schuster *et al.,* 2015).
- There is a higher risk of collision in areas where vulnerable bird species are concentrated and where flight activity is high from nearby breeding sites (Langston *et al.,* 2010). For example, breeding birds may pass through a wind farm several times a day during foraging activities.
- Perrow *et al.* (2015) in Koppel and Schuster (2015) reported that the flight height distribution shifted downwards during operation, meaning that the proportion of birds at collision risk height declined by more than half. A model starting with passage rates derived from boat-based data incorporated a number of steps: measurements from tracks; orientation of operational turbines relative to the main SW-NE flight axis from the colony; and the industry standard collision risk model to. The probability of a tern colliding with a rotor was predicted to be approximately 1 collision in every 10,000 passages.

Several publications suggest that various levels of mitigation may reduce the risk of collision as follows:

- Standing still procedures: Coppack *et al.* (2015) showed that during operation of turbines the nocturnal micro-avoidance rates ranged from 95.62% to 98.03%. However, when the turbine was standing still the micro-avoidance rate of the OWF site decreased to 40.73%.
- Fox & Peterson (2019) suggests that locations where concentrated migration may take place due to coastal topography should be avoided.
- Perrow *et al.,* (2019) suggests shutdown of turbines during weather conditions that increase collision risk (e.g. storms) during key migration periods*et al.*
- Use of fewer, larger, turbines (Barrios & Rodriguez 2004; Johnston *et al.*, 2014; Everaert, 2014, Shamoun-Barnes *et al.,* 2017, Perrow *et al.,* 2019).
- Shamoun-Barnes *et al.* (2017) suggest that “Micro-siting” can also be effective, whereby particular turbines that cause high levels of mortality are removed (de Lucas *et al.*, 2012; May *et al.*, 2015).

Perrow *et al.* (2019) suggests this could also increase permeability of the site and thereby reduce barrier effects or collision risk.

- Painting one turbine blade black or all blades with a UV paint has been suggested to reduce the risk of collisions (May *et al.*, 2017; Perrow *et al.*, 2019b). However, results of studies using these methods have been varied as different species have different sensitivities to UV light (May, 2017). Furthermore, any painting is not likely to be effective if the bird is looking downwards whilst searching for roosting sites or food (Martin & Shaw, 2010).

3.2.2 Avoidance and attraction

During the O&M phase of OWFs some bird species will avoid wind farms which could affect feeding and migration. On the other hand, there are also certain species that are attracted to the turbine structures as a roosting ground.

Avoidance

- Studies have shown that gannet's exhibit avoidance behaviour in spring and autumn (Krijgsveld *et al.*, 2011) therefore limiting the risk of exposure to collisions.
- A study of a lesser black-backed gull (*Larus fuscus*) breeding colony around nearby OWFs found only 1.3% of the birds visited the OWFs, suggesting meso-scale avoidance (Thaxter *et al.*, 2018).
- Visual Automatic Recording System (VARS) was deployed near the Alpha Ventus OWF in the German North Sea and found around 82% of all observed flights through the rotor-swept area occurred at night. Lower numbers of birds were detected within the rotor-swept area when the turbine was running, indicating significant micro-avoidance (avoidance of the rotor-swept area) (Coppack *et al.*, 2015 in Koppel and Schuster, 2015).
- Hill *et al.* (2014) in Schuster *et al.* (2015) investigated bird distribution at the German Alpha Ventus OWF during nights and found that migration intensity can be considerably higher inside than outside the wind farm. Hill *et al.* (2014) hypothesized that this possibly indicated micro-avoidance of the turbines connected to blade movement.
- As reported in Koppel and Schuster (2015), Perrow *et al.* (2015) reported avoidance behaviour of constructed and operational turbines by tracking seabirds. Prior to operation, 98.8% of tracks heading towards the OWF entered while only 65.8% of tracks entered the OWF during operation. Of the 49.4% of birds passing within 50m of a turbine base and thus falling within potential span of the rotors prior to construction, just 4.7% did so afterwards.
- As reported in Degraer *et al.* (2017), after four years of post-impact monitoring at the Thornton Bank OWF, the impact area appeared to be avoided by four species: northern gannet, little gull, black-legged kittiwake and common guillemot. In the OWF area, these species dropped in numbers by 97%, 89%, 75% and 69% respectively. These results are highly similar to those reported in Vanermen *et al.* (2016).

Attraction

As reported in Degaer *et al.* (2017), there is currently little information available on the behaviour of large gulls inside OWF areas, and it remains unclear whether these birds visit the wind farms because of enhanced foraging conditions or simply for roosting. Degraer *et al.* (2017), reported on a study in to the occurrence and behaviour of large gull species in the Thornton Bank wind farm area.

While the limited amount of data collected does not allow any definite conclusions to be drawn, first results indicate that the time spent loafing was higher inside the OWF when compared to outside the OWF. Turbine foundations were mainly used for roosting, but during a short time period around low tide, small numbers of birds were observed foraging on mussels growing on the lower reaches of the foundations. As reported in Degraer *et al.* (2018), it was confirmed that much more time was spent roosting on outer than on inner turbines. Degraer *et al.* (2017) and Vanermen *et al.* (2016) also reported that great black-backed gulls and sandwich terns are attracted to OWF.

Fox & Peterson (2019) reported that species such as the larger *Larus* gull species and cormorants are undoubtedly attracted to the superstructure of turbines, meteorological masts and transformer stations with a preference for the outer turbines (Fox & Peterson, 2019). With regards to the behaviour of large gulls and cormorants inside OWFs, this paper reiterated that a study undertaken in the Thornton Bank OWF determined that 89% of roosting great cormorants were found to be roosting on the turbine foundations, with a clear preference for outer rather than inner turbines (Petersen *et al.*, 2006 in Perrow, 2019a).

Birds that migrate nocturnally, such as songbirds and waders, seem to be attracted to illuminated structures. This has been observed for offshore gas production and research platforms, lighthouses, and offshore wind turbines (Schuster *et al.,* 2015; Aumüller *et al.*, 2011; Hill *et al.*, 2014; Rebke *et al.*, 2018; van de Laar, 2007). This behaviour has also been observed in other types of birds. Welcker & Nehls (2016) observed that two gull species (lesser and great black-backed gull), were attracted to an OWF. The abundance of these two species was 79-100% higher inside the windfarm than in neighbouring areas.

Dierschke *et al.* (2016) found that several gull species and red-breasted merganser also showed weak attraction, while great cormorant and European shag showed strong attraction to OWFs. Responses in other species are low. Attraction of cormorants relates at least in part to their use of structures for roosting and for drying plumage, but increases in food availability at OWFs appears to be an important influence for several species.

Schamoun-Barnes *et al.* (2017) suggests that measures can be taken to make the wind farm less attractive to animals, or more conspicuous in the case of enhancing avoidance. Such techniques include altering the paint colour, lighting regime, using lasers, electromagnetic fields and acoustic deterrents (Cook *et al.* 2011; Nicholls and Racey 2007). However, care must be taken that birds do not habituate to these measures (MacKinnon *et al.*, 2004).[4]

3.2.3 Displacement / barrier effect / habitat loss

OWFs can cause displacement and barrier effects, which can arise through birds being displaced completely or being deterred form their original migration or flying route as a consequence of avoidance behaviour. Barrier effects which result in increased flight patterns / routes to avoid turbines result in birds increasing flight time and therefore increase overall endurance (due to higher energy expenditure) (Cefas, 2014).

According to Fox & Peterson 2019, barrier effects impact breeding birds commuting in particular, as they are commuting between offshore foraging grounds and a breeding colony several times a day, resulting in energetic costs. Consequently, this could affect survival and reproduction and have long-term impacts on overall population size (Fox & Peterson, 2019). The degree of energetic costs is highest for species with high wing loadings such as cormorants or species that commute frequently such as terns.

As reported in Schuster *et al.* (2015), there is evidence across studies that auks, gannets and particularly divers are displaced by OWFs. However, estimated response distances that are observed vary between species and between studies. Avoidance distances vary from zero (no displacement) to 13km (Percival 2013; 2014; Vanermen *et al.*, 2013; 2015; Petersen *et al.*, 2014; Webb *et al.,* 2015; Welcker & Nehls, 2016).

Within species responses can be variable. Lindeboom *et al.* (2011) observed red throated divers were not detected between turbines at one site but did so at another windfarm, whilst Mendel *et al.* (2019) found red throated divers showed major displacement from windfarms out to at least 16km.

Dierschke *et al.* (2016) reviewed post-construction studies of seabirds at 20 OWFs in European waters to extract and classify evidence for displacement or attraction of 33 different species. Divers and northern gannets showed consistent and strong avoidance behaviour/displacement. This may also be the case for

[4] *Comments received on this document identified further papers that could be included in future updates including Garthe et al., 2018 on the impacts of OWF on seabirds and mammals.*

great crested grebe and northern fulmar. Longtailed duck, common scoter, Manx shearwater, razorbill, common guillemot, little gull and sandwich tern showed less consistent displacement by OWFs. Other species showed either weak or strong attraction or no response. Displacement seems to be mainly due to bird responses to OWF structures and appears stronger when turbines are rotating, though this could in part be due to boat traffic to and from OWFs.

Wade *et al.* (2014) used GPS tracking devices to study movements of Great skua breeding in Scotland in relation to marine renewable energy developments including offshore wind. The results showed that failed breeders overlapped with larger areas of offshore wind developments than breeding birds but the overall overlap with core areas used remained low.

Maintenance activities would affect bird species that are sensitive to vessels. Red throated divers and common scoters have been observed to show disturbance to shipping activities and to avoid OWFs (Mendel *et al.* 2019; Fox and Peterson 2019).

3.2.4 Change in prey resource

As reported in Schuster *et al.* (2015), seabirds of different foraging guilds were found to feed inside offshore wind farms. Foraging around the foundations is reported for herring gull (May, 2008), with lesser black-backed gulls reported to feed on the epifauna of foundations after potential prey organisms had settled there (Vanermen *et al.*, 2013a, 2013c, 2015a). Diving for epibenthic prey e.g. by common eiders was not observed but diving by great cormorants was (May, 2008).

Other species attracted to fish inside OWFs are red throated divers and gannets – in some cases overcoming their general avoidance of OWFs as well as more frequently European shag, sandwich tern, little tern and common guillemot (e.g. Krijgsveld *et al.*, 2010, 2011; Leopold & Camphuysen, 2008; Perrow *et al.*, 2006; Petersen *et al.*, 2006; Walls *et al.*, 2008). Diving for bivalves was reported explicitly only for common scoters in Horns Rev 1 and 2 (Petersen and Fox, 2007; Petersen *et al.*, 2014), but this certainly also applies to common scoters and long-tailed ducks seen in other OWFs, especially in the Baltic Sea. An increase in numbers of observations of auks and northern gannets within an OWF following avoidance during the beginning of the operational phase was attributed to increasing fish stocks (Krijgsveld *et al.*, 2011; Vanermen *et al.*, 2011).

3.2.5 Cumulative impacts

As reported in Koppel and Schuster (2015), serial development of OWFs are an important consideration in determining the potential cumulative effect of wind developments on populations, but the extent to which both offshore and onshore wind farms occur along migration routes has received relatively little attention (Rees *et al.* 2015).

3.2.6 Impacts on Bats

Several studies provide evidence that bats are regularly found offshore (Lagerveld *et al.* 2017a, 2017b, Degraer *et al.* 2018). The occurrence of bats at sea is highly seasonal which indicates that individuals recorded at sea are on migration (Lagerveld *et al.*, 2017a). Langeveld *et al.* (2015) as reported in Koppel and Schuster (2015) found that bat activity is strongly associated with the weather conditions; virtually all bats were only recorded during nights with low or moderate wind speeds, no precipitation, and a high ambient pressure.

Like on land OWFs may impact bats through collision risk which can result in mortality However, no studies to date have provided evidence of this. As this is a relatively new field of research and there is still limited knowledge on the presence of bats offshore, most studies currently focus on researching the behaviour of bats.

Lagerveld *et al.*, (2017c) identified the requirement that continued monitoring offshore is required to increase the number of bat observations and the understanding of the potential impacts of OWF development on bats. Whilst Barclay *et al.* (2018) suggested larger turbines may be more dangerous for bats.

4 Benthic Ecology (including shellfish ecology)

The construction and O&M phases of OWFs can impact benthic ecology in various ways. The following potential impacts on benthic ecology have been identified during the construction of OWFs:

- Habitat loss;
- Habitat disturbance; and,
- Underwater sound.

During the O&M phase of OWFs benthic ecology has the potential to be affected by:

- Increased suspended sediments and smothering;
- Disturbance due to maintenance activities;
- Introduction of new substrate / altered substrate;
- Underwater sound; and,
- Electromagnetic fields.

4.1 Construction

4.1.1 Habitat loss

Habitat loss can be caused by the footprint on the seabed of the foundations, cables and/or any scour protection associated with either the foundations or the cables. The actual loss of habitat and the seabed disturbance depends on the type and size of the foundation used, the method applied for cable laying and the sensitivity of the local habitat.

Foundations

The loss of habitat due to the foundation used is related directly to the size of the foundation. In addition, the flow of water around turbine bases can create scour pits in soft sediment which also result in a habitat loss/disturbance. Figure 2-1 illustrates that a 5m diameter monopile (without scour protection) will have a 20m^2 footprint on the sea bed, and a 16m diameter gravity-base foundation (without scour protection) will have a 200m^2 footprint on the sea bed.

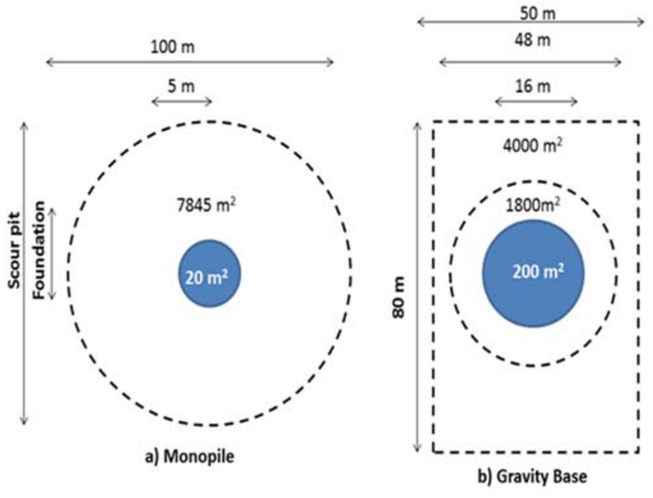

Figure 2-1 Turbine Footprint (illustration from Cefas, 2014)

OWFs are developing rapidly, with monopile diameters are becoming larger (up to 10m); however, at the same time the number of turbines needed for the same amount of energy is decreasing. Thus, in total the direct loss of habitat will probably not increase by increasing the number of MW installed.

Cable laying

Cables are laid in trenches in soft sediments or across the surface on hard substrates. Where cables are laid on the surface, they will require protection with rock or concrete. The trench or any protection will be 1-2m wide. The cables which link the individual wind turbines are several hundreds of metres in length (intra-array) whereas the cables to shore or export will be several kilometres or tens of km in length. Cables are buried by plough, trencher or a jetting device (where water released at pressure cuts a trench). Impacts will increase due to suspended sediment concentrations and loss or disturbance of sea bed habitat (see Section 4.1.2).

In general, the literature reviewed suggests that the net habitat loss or change is suggested to be small as benthic communities and soft-sediment habitats are known to rapidly recolonise in areas impacted by cable burial. The significance of such losses, however, needs to be assessed on a site-specific basis (i.e. the sensitivity and biological importance of the area needs to be assessed in the EIA).

4.1.2 Habitat disturbance

Dredging activities, cable laying and installation of foundations associated with the construction of OWFs, cause habitat disturbance. The disturbance may cause directs effects to the macrofauna in the seabed due to increase suspended sediments and smothering and or changes in hydrodynamics, sediment transport and water quality.

A few studies have looked at the impacts of habitat disturbance on benthic ecology (Berger *et al.*, 2003, Dong Energy *et al.* 2006, Didrikas and Wijkmark 2009, Coates *et al.*, 2015). These studies conclude that even though the construction creates a physical disturbance to the seabed, the impacts are local and short term. The macrobenthic community of sediments, sandy in particular, have illustrated a fast recovery potential. The influence on hydrodynamics from an OWF is localised to individual structures and appears to have minimal influence on the benthos ecology. In areas where suspended sediment is relatively low, an increase in suspended sediment load may cause effects to sensitive benthic organisms within the plume (Cefas, 2005).

In addition, there are general studies on impacts of remobilised sediments and settlement. The spatial scale, timing rate and depth of placement all contribute to the relative importance of the recovery mechanisms: planktonic recruitment of larvae; lateral migration of juveniles / adults; and vertical migration. When sediment deposits accumulate to >20cm most species of marine biota are unable to adapt. For accumulations of sediment deposits of <20cm vertical overburden (smothering) most biota may be able to adapt, i.e. vertically migrate through the deposited sediment. Impacts of sedimentation on hard substrate is expected to have a larger effect than sedimentation on seabeds with mainly sand or gravel (Cefas, 2014).

There are only a few studies on the impact of habitat disturbance on the benthic ecology. Most studies to date indicate a local and temporary impact on benthic ecology. As most OWFs are built in areas with mostly sand or gravel seabeds, significant impacts on benthic ecology on habitat disturbance are less likely.

4.1.3 Underwater sound

There are two types of underwater sound (impulsive and continuous sound sources) which can have different impacts on marine life. Impulsive sound sources are typically characterised by brief sounds with a sudden onset and a high peak pressure and are caused by activities such as impact pile driving. Continuous sounds are generally characterised as having a slow onset and are continuous or over a longer duration and are associated with activities such as shipping, dredging, operational wind turbines (see Section 4.2.3). The potential impacts related to underwater sound during construction of OWFs primarily relate to loud impulsive sound produced during pile-driving activities. Knowledge on the impact of impulsive sound on benthic species is still limited. However, there are indications that benthic species such as mussels do react to the vibrations (Roberts *et al.*, 2015).

The literature review provided only a few publications on the impact of underwater sound on benthic invertebrates. One study found that for benthic ecology characterising the emitted sound using the sound exposure level of a single stroke (SEL_{ss}) combined with total time of piling and the total number of strokes is more appropriate than cumulative sound exposure level (SEL_{cum}) as used in marine mammals (Hawkins and Popper, 2016).

Pile driving produces particle motion[5] (caused by vibration) that could affect bottom-dwelling animals. Roberts *et al.* (2015) specifically looked at the behaviour of the mussel *Mytilus edulis.* The sensitivity of the mussel to substrate-borne vibration was quantified by exposure to vibration under controlled conditions. The mussel showed a clear behavioural response to vibration stimulus, with greatest sensitivity to vibration measured at 10Hz. This lead to clear behavioural changes mostly related to valve closure. This was further reported in Weilgart (2018). Particle motion is likely to affect overall mussel health and reproduction in both individuals and mussel beds, because valve closure is an energetically costly behaviour, also disrupting breathing and accelerating heart rate and excretion (Weilgart, 2018). Therefore, water-borne particle motion and acoustic pressure[6] need to be considered when looking at the effects of underwater sound on sedentary animals such as shellfish.

Overall very little literature on effects of impulsive underwater sound on benthic ecology is currently available. Effects of underwater noise on benthic ecology can therefore not reliably be predicted given the lack of understanding of the causalities.

4.2 Operation and maintenance

The literature provided did not include information on the potential impacts listed below in relation to benthic ecology; however, these potential impacts are important to address when assessing impacts:

- Potential impact of increased suspended sediment concentrations (SSC); and,
- Disturbance due maintenance activities

4.2.1 Introduction of new substrate / altered substrate

The presence of offshore wind foundations and scour protection in the North Sea introduces artificial hard substrate in a predominantly sandy habitat. The introduction of hard substrate may alter the species composition in the OWF.

There are a few long term studies that have looked at the introduction of offshore wind farms on the benthic community. In general, none of the studies reviewed showed a significant change of infaunal and epifaunal benthic communities within OWFs (Degraer *et al.*2017, 2018, Bergström *et al.* 2013, Leewis *et al.*2018). Changes in macrofaunal species was only found in very close proximity to the offshore wind foundation (<50m) due to a refinement in sediment grain size and enrichment of the sediment (Degraer *et al.* 2018).

On the structures of the offshore wind foundations, a rapid colonisation of fouling communities has been observed. This results in an increase in number of species, density and biomass over time in wind farm sites. Observations of species assemblages suggest a transitional situation with increasing species richness, and a decrease in number of early colonisers.

[5] *Particle motion is the displacement or movement of fluid particle within a sound field (Boyle & New, 2018).*
[6] *Acoustic pressure is the local pressure deviation from the ambient.*

What is still poorly understood and should be further investigated is the impact of hydrodynamic changes altering primary production, with potential consequences for filter feeders and the introduction and range expansion of non-native species (through stepping stone effects).

4.2.2 Changes to fishing activity

Various publications have shown that substantial populations of edible crab can occur near monopiles (Tonk & Rozemeijer *et al.*, 2019; Tallack, 2002 in Tonk & Rozemeijer *et al.*, 2019). The presence of OWF structures can also induce changes to fishing activity creating opportunities for decapod fisheries. Monopiles have been shown to function as nursery grounds and larvae collectors for edible crab (Tonk & Rozemeijer, 2019), which could benefit local populations and has the potential for edible crabs to exploit the new substrate. Fisheries can benefit from the substrate of monopiles to help restock depleted populations of edible crabs (Krone *et al.*, 2011, 2013, 2017; Lengkeek *et al.*, 2017 in Tonk & Rozemeijer *et al.*, 2019), as well as European lobster (*Homarus gammarus*), to help protect the fisheries from over-exploitation. The economic potential for lobster in OWFs is low, however, as one individual of this territorial species (Tonk & Rozemeijer *et al.*, 2019) will utilise and defend an entire monopile.

4.2.3 Underwater sound

During O&M, offshore wind turbines and vessels generate continuous underwater sound. The effects of underwater sound during the operational phase may impact benthic species (Gill *et al.*, 2012; De Backer and Hostens, 2017). Further research is required investigating causal underwater sound parameters such as particle motion and acoustic pressure and their subsequent effects on benthic fauna. There is still a lack of understanding of the causal underwater sound parameters and their effect on marine fauna (Dannheim *et al.*, 2019).

Pine *et al.* (2012) in Weilgart (2018) found that sound from wind turbines inhibit larval settlement and delay metamorphosis in two crab species. This was due to sound masking important natural acoustic settlement cues.
Overall very little literature on effects of operational underwater sound on benthic ecology is currently available; however, it did show that benthic species can be sensitive to underwater sound. Further research is required investigating causal underwater sound parameters such as vibration and acoustic pressure, and their subsequent effects on benthic fauna. There is still a lack of understanding of the causal underwater sound parameters and their effect on marine fauna. Effects of underwater noise on benthic ecology cannot be reliably predicted given the lack of understanding of the causalities.

4.2.4 Electromagnetic fields

Offshore installations require subsurface cables, which generate Electromagnetic Fields (EMF) into the marine environment. Several factors affect the levels of EMF, including cable insulation, burial depth, number of conductors, cable configuration distance between cables, current flow and cable orientation relative to the earth's magnetic field (direct current (DC) only). Ultimately, these factors are site specific with relation to both the magnitude of the EMF emitted and the ecology of area affected.

There is a general concern that EMF may confuse the signals for migration and foraging for food sources. The inability to find plentiful food sources, may untimely lead to overall energetic loss and therefore may impact populations.

Scott *et al.* (2018) studied the effects of simulated EMFs emitted from sub-sea power cables on the commercially important edible crab. Exposure to EMF had significant physiological effects, such as L-Lactate, D-Glucose, Haemocyanin and respiration rate, on the edible crab and changed their behaviour showing a clear attraction to EMF.

Only a few studies looked at the tolerance of invertebrates to electromagnetic fields. A review by Bergström *et al.* (2012) found the impact on benthic fauna from EMFs is considered to be very small or non-existent at the levels that exist around the cables of the OWF.

5 Fish Ecology

The construction, O & M of OWFs have the potential to affect fish ecology in a number of ways. During construction, these include:

- Habitat disturbance;
- Increased suspended sediment concentration (SSC);
- Deterioration in water quality due to resuspended contaminants;
- Changes in prey resource; and,
- Underwater sound.

During the O & M phase, these include:

- Habitat loss;
- Introduction of new substrate;
- Changes to fishing activity;
- Electromagnetic fields; and
- Underwater sound[7].

5.1 Construction

The literature provided did not include information on the potential impacts listed below in relation to fish ecology. However, these potential impacts are important to address when assessing impacts:

- Habitat disturbance;
- Increased SSC; and,
- Deterioration in water quality due to resuspended contaminated sediments[8].

5.1.1 Underwater sound

There are two types of underwater sound (impulsive and continuous sound sources), which can have different impacts on marine life. The potential impacts related to underwater sound during construction of OWFs primarily relate to extremely loud impulsive sound produced during pile-driving activities. Such sound may cause injury or mortality in fish and temporal and spatial disturbance (Bolle *et al.*, 2011).

Fish with swim bladders that are in close proximity to the inner ear and/or are connected to the inner ear (e.g. they have an otophysic connection) have increased hearing sensitivity.

Injury or mortality

Research on underwater sound on fish has been done on several fish species such as cod (*Gadus morhua*), sole (*Solea solea*), European sea bass (*Dicentrarchus labrax*) and herring (*Clupea harengus*). In addition, the studies have looked at different life stages of fish (larvae, juvenile and adults). In general, fish with swim bladders are thought to be more susceptible to injury than those without (see reviews in (Normandeau Associates Inc., 2012; Popper and Hastings, 2009a, 2009b, Casper *et al.* 2013). Also, fish larvae and eggs

[7] *Comments received on this document identified further papers that could be included in future updates including Popper & Hawkins, (2019) and Weilgart, (2018) on impacts to fish and shellfish during operation and maintenance phases of OWFs.*

[8] *Comments received on this document identified further papers that could be included in future updates including Inger et al., 2009 on impacts to biodiversity with marine renewable energy.*

are thought to be more susceptible to injury than adult fish as they do not have the capability to swim away from the sound source (Bolle *et al.*, 2011).

Only a limited number of articles have reported actual fish fatalities due to pile driving (Caltrans, 2001). It is expected that possible fatal effects on all life stages of fish may only occur at very close distances to the piling activity (<100 meters) (Bolle *et al.* 2014; De Backer *et al.*, 2017 in Degraer *et al.* 2017, Bolle *et al.* 2015). Various studies do show evidence of sound-induced injury due to pile driving on juvenile and adult fish (Popper *et al.* 2003; Popper & Hastings 2009a, Popper & Hastings 2009b, Bolle *et al.* (2015), *et al.*De backer *et al.*, 2017 in Degraer *et al.* 2017). Based on a field experiment, the results show that swim bladder barotrauma can occur in fish with a swim bladder, like Atlantic cod, when they are within a radius of 750m distance around the sound source during pile driving (*et al.*De Backer *et al.*, 2017 in Degraer *et al.* 2017).

Because relatively few experiments on the hearing of fish have been carried out under suitable acoustic conditions, valid data that provide actual hearing thresholds are available for only a few species (Popper & Hawkins, 2019). However, Popper and Hawkins (2019) proposed interim criteria for assessing the potential of mortality and recoverable injury in fish from exposure to pile driving signal. Popper & Hawkins (2019) reported exposure to sounds may result in hearing loss as a result of damage to sensory cells of the inner ear or the innervating neurons. Smith *et al.* (2004) suggest that it may take 28-35 days to fully repair any temporary threshold shifts (hearing sensitivity). While temporary hearing loss (TTS[9]) occurs in fish, there is no evidence for permanent hearing loss (PTS).

The research shows that there can be a small impact of underwater sound on different species of fish and fish larvae which are in close proximity of the piling activities. However, the consequences of this impact on a population level are still unknown. Most studies express and assess the potential impact of underwater sound based on the level of sound exposure level rather than particle motion (caused by vibration). However, in addition to the sound level, particle motion is expected to play an important role in the detection of sound by fish and shellfish (Boyle & New, 2018). Since this is an important second component of sound, studies need to also measure particle motion. The relative role of particle motion in the overall effects of impulsive sound on fish is still poorly understood.

Fish behavioural effects

Sound is used for communication between fish, mating behaviour, the detection of prey and predators, orientation and migration and habitat selection. Thus, anything that interferes with the ability of a fish to detect and respond to biologically relevant acoustic cues can decrease survival and fitness (Popper & Hawkins, 2019). Very few studies have investigated the behavioural effects of piling sound on fish. Mueller-Blenkle *et al.* (2010) carried out large fish pen studies on the effects of pile driving sound on cod and sole. Their results showed that both cod and sole reacted to pile driving sounds by changing their swimming speed drastically. However, these findings are difficult to extrapolate to population level.

Within the UK, concerns that piling sounds might displace herring from their spawning grounds have led to mitigation measures in the form of no piling periods. For example, herring spawn within the vicinity of the Scroby Sands wind farm, where a temporary decrease in number was observed during the construction period only (Perrow *et al.* 2011). The authors suggested that pile driving sound from the construction was linked to a decrease in success of herring spawning within the area. The effect seen at Scroby Sands was short term, but for larger OWFs constructed over several years, or where there are a number of sites in relatively close proximity, there is the potential to cumulatively affect populations over longer time scales.[10]

[9] *TTS is a short duration decrease in hearing sensitivity resulting from exposure to intense sounds. After termination of the sound, normal hearing ability returns over a period that may range from minute to days, depending on many factors, including the intensity and duration of exposure (Smith & Monroe, 2016).*

[10] *Comments received on this document identified papers that could be included in future updates including Stenberg et al., 2015 and Barbut et al., 2019. It is recommended this is included in future updates.*

Despite extensive academic literature and survey work, and their use in Environmental Impact Assessments (EIAs), uncertainty remains on both the accuracy of the fish spawning information currently available and the level/significance of impacts from piling activity on fish species (Boyle & New, 2018). As there are perceived impacts of piling on herring related to underwater acoustic pressure and particle motion, it is important to identify locations of spawning of fish species in relation to the offshore wind construction site. In addition to established sound thresholds for fish (Popper & Hawkins 2019), thresholds need to be established in terms of particle motion.

Very little is known about stress effects in fish and the significance of such effects in response to anthropogenic sound is even less clear (Tennessen *et al.*, 2016). Stress responses can include an increase in oxygen uptake. Wale *et al.* (2013) in Weilgart (2018) reported that crabs subjected to ship noise used 67% more oxygen than those exposed to ambient noise (received levels: 108 – 111 dB_{rms} re 1 uPa). The increased oxygen consumption was not due to greater crab movement but to a higher metabolic rate, which in turn, can indicate higher cardiovascular activity from stress (Wale *et al.*, 2013).

5.2 Operation and maintenance

5.2.1 Habitat loss

No research was identified that specifically considered the potential impacts of habitat loss of fish and shellfish ecology from the O & M of OWFs.[11]

5.2.2 Introduction of new substrate

The presence of OWFs introduces hard substrate that can change the local habitat. The size and scale of the effect of habitat change on fish is dependent on the species present within the area, the seabed type, the environmental conditions at the site and the type of turbine foundation (Degraer *et al.*, 2018).

Artificial hard substrata are known to attract many marine species. A few studies observed that offshore wind turbine foundations do act as Fish Attraction Devices (FAD) (Wilhelmsson *et al.* 2006a, Wilhelmsson *et al.* 2006b, Lindeboom *et al.* 2011, Kerchoff *et al.*, 2018 in Degraer *et al.* 2018). In addition, there are a few studies that give evidence to suggest that species compositions at OWF sites may change with the introduction of the wind turbine structures as hard substrata-frequenting fish species may increasingly benefit (Lindeboom 2011, Van Hal *et al.* 2012)[12].

5.2.3 Changes to fishing activity

OWF can act as a refuge for commercially exploited fish species (Winter *et al.*, 2010, Methratta and Dardick 2019). Most wind turbines have a safety exclusion zone around them to prevent accidental damage from vessels. Vessels, including fishing vessels, are usually not permitted to enter even the safety zone. Elsewhere in Europe trawling is not permitted through an OWF at all. Thus, the fishing activity is reduced within the OWF areas. However, this might result in higher fishing pressure in the immediate vicinity around OWFs. This effect has been demonstrated for Marine Protected Areas, defined as fishery exclusion zones (see e. g. Marshall *et al.* 2019, FREE 17(7): 407-413) .

For some species, higher abundance near the turbines may lead to protection from fishing and therefore have a potential positive effect on their populations. Only one study was reviewed comparing fish abundance inside and outside of an OWF in the Dutch Coastal Zone (Koppel & Schuster, 2015)[13]. The results show

[11] Comments received on this document identified papers that could be included in future updates including Inger et al., 2009 and Methratte & Dardick, 2019 on habitat loss. It is recommended these are included in future updates.
[12] Comments received on this document identified papers that could be included in future updates including Couperus et al., 2010 and Leonhard et al., 2011 on introduction of new substrate. It is recommended these are included in future updates.
[13] Comments received on this document identified papers that could be included in future updates including Couperus et al., 2010 and Floeter et al., 2017 on changes in fishing activity. It is recommended these are included in future updates.

that the presence of wind farms seems to have a limited effect on the fish community in the Dutch coastal zone. For a few species local benefits occurred possibly due to a combination of creation of new hard substrate habitats and exclusion of fisheries. However, on a larger scale (when comparing to the entire Dutch Coastal Zone) no significant differences in fish abundance were found in the wind farm compared to the reference sites. (Winter *et al.* 2015 in Koppel & Schuster, 2015).

5.2.4 Electromagnetic fields

Subsea power cables generated electromagnetic fields (EMFs) and induced electric fields (iEFs). OWFs are likely to become the biggest source of anthropogenic EMFs in the marine environment. It is known that many fish and shellfish species can detect EMF. Sharks and rays (elasmobranchs) are thought to be particularly sensitive to EMF. Snoek *et al.* (2016) identified four potential effects due to EMFs: i) disturbance of behavioural responses and movement (attraction, avoidance); ii) disturbance of navigation and migratory behaviour; iii) disturbance of predator-prey interactions and distribution of prey; and iv) disturbance of embryonic and cellular development (Snoek *et al.*, 2016).
Avoidance and attraction to elevated EMF field strengths has been observed in several species in multiple studies (presented in Snoek *et al.* 2016). However, studies of field magnitudes within the range emitted by subsea cables, let alone field studies, are scarce and inconclusive. Much of the current understanding is based on theoretical or trial with exaggerated experimental EMF strengths. Determining impacts of realistic EMFs on species is therefore a key priority.

5.2.5 Underwater sound

During O & M, offshore wind turbines and vessels generate continuous underwater sound. The underwater sound can interfere with critical aspects of fish behaviour such as masking the fish’s ability to detect sound of biological importance (Popper & Hawkins, 2019). The acoustic pressure levels during the operational phase is not high enough to cause either mortality or hearing loss in fish (Popper & Hawkins, 2019). Although masking of important acoustic environmental cues could theoretically occur, there are limited studies providing evidence of this in practice.

In addition, Casaretto *et al.* (2015) showed that male haddock (*Melanogrammus aeglefinus*) attract females to their territory acoustically, with specific sound signals triggering courtship behaviour which will eventually lead to mating. OWF turbine sound affects the detection of biologically important sounds by females (Jong *et al.*, 2018).

Overall, there are knowledge gaps in the literature on effects of operational underwater sound on fish and their relationships with EIA-requirements should be outlined. With the scale of offshore wind development increasing larger scale impacts cannot be excluded. Further research is required to review the long-term effects of continuous exposure to anthropogenic sound, particularly examining the behaviour of wild fish under more natural conditions.

6 Marine Mammals

The construction and O&M of OWF have the potential to impact marine mammals in a number of ways. Potential impacts from OWF development on marine mammals are one of the more well studied topics with wide ranging research taking place to date from the individual to population level.

The following potential impacts on marine mammals have been identified during the construction phase of OWFs:

- Disturbance due to human activities;
- Underwater sound; and,
- Collision risk.

During the O&M phase these include:

- Underwater sound;
- Electromagnetic fields; and,
- Changes in prey resources.

6.1 Construction

6.1.1 Disturbance due to human activities

Disturbance to marine mammals due to human activities relate to movements of vessels, remotely operated vehicles (ROVs), helicopters and similar machinery. The majority of human activity occurs during the construction phase and has the potential to disrupt marine mammal behaviour. Disturbance can also be caused by increased levels of underwater sound, this is further described in Section 6.1.2.

Based on the literature reviewed, there are limited studies available that specifically studied the disturbance due to human activities on marine mammals. Brandt *et al.* 2018 investigated the disturbance impact of the first seven German offshore windfarms under construction with and without sound mitigation measures. Whilst undertaking this study it was also observed that harbour porpoise (*Phocoena phocoena*) detections in the vicinity of the construction site started to decline several hours prior to piling commencing, although not to the extent found during piling. A likely explanation of this decline is an increase in construction-related activities, such as an increase in shipping traffic in combination with enhanced sound transmission during the calm weather conditions during which piling activities occur (Degraer *et al.* 2017 and Dragon *et al.* 2016). In addition, the duration of the disturbance was longer with sound mitigations systems than for piling events without. In a follow up study by Rose *et al.* (2019) similar disturbance effect was found before and after piling.

The above studies suggest that there may be a disturbance effect on harbour porpoise due to the increase in construction-related activities of OWFs.

6.1.2 Underwater sound

Impacts of underwater sound

There are two types of underwater sound (impulsive and continuous sound sources) which can have different impacts on marine life (see Section 5.1.1) The potential impacts for marine mammals related to underwater sound during construction of OWFs primarily relate to extremely loud impulsive sound produced during pile-driving activities. Such sound may cause temporal and spatial disturbance and in a worst-case scenario may cause hearing damage over a considerable distance.

There are a wide range of studies on marine mammals which aim to quantify the impacts of underwater sound. In the OSPAR Region, the research has primarily been focussed on the North Sea region and on the following species: harbour porpoise, grey seal (*Halichoerus grypus*) and harbour seal (*Phoca vitulina*). Studies can be categorised in to those undertaken on individuals kept in captivity to determine their sensitivity to underwater sound and studies *in situ* to determine the actual impact observed in the field. The following section provides a brief overview of the current state of knowledge on this topic.

Behavioural response and displacement

The behavioural response and displacement studies reviewed provided results for the species harbour seal and harbour porpoise during the construction of an offshore wind farm. Two studies were reviewed which provided information on harbour seal of which one study by Russel *et al.* (2016) showed a clear displacement impact during piling. Seal abundance was significantly reduced up to 25km from the piling activity. The second study, by Hastie *et al.* (2016), only provided information on the distribution of tagged seals during the construction of an offshore wind farm. The distance from the piling varied from 6.65km to 46.1km. No conclusions were drawn on the behavioural response and displacement.

Several studies were reviewed on the behavioural response and displacement of harbour porpoise related to underwater sound during the construction of different OWFs. The amount of displacement was determined based on acoustic detection rates. Multiple studies suggest that the distance at which pile driving induced deterrence occurs is unlikely to exceed 20km (Graham *et al.*, 2019, Hawkins and Popper 2016, Norre *et al.* 2013, Haelters *et al.* 2016). Of course, the distance at which pile driving induced deterrence occurs is depend on the sound levels perceived by the marine mammals.

In order to more accurately assess the spatial and temporal extent of pile-driving induced deterrence of harbour porpoise the consequences of repeated piling events need to be understood (Degraer *et al.*, 2017). Although Thompson *et al.* (2010) suggested that the distance over which cetaceans are disturbed becomes larger with each successive piling event, no such effect was observed in the German Bight (Brandt *et al.* 2016).

Temporary and permanent threshold shift

When sound exposure exceeds specified levels it can result in a temporary or non-temporary hearing damage also referred to as temporary threshold shift (TTS) and permanent threshold shift (PTS). A number of different threshold criteria have been developed in recent years for marine mammals (e.g. Southall *et al.*, 2007, 2019; NOAA, 2013, 2015; Lucke *et al.*, 2009).

In 2007, Southall *et al.* (2007) developed threshold criteria for underwater sound for marine mammals. These thresholds have recently been updated to new criteria presented in Southall *et al.* (2019). The new threshold values are set out in Table 3 in **Appendix A**. Southall *et al.* (2019) stated that sound source measurements should be applied based on signal features likely to be received by animals rather than by signal features at the sound source. The two metrics that should be used for impulsive sound criteria are: (1) *frequency-weighted sound exposure level* (SEL), and (2) *unweighted peak sound pressure level* (peak SPL).

Mitigation

Several recent studies investigated the effectiveness of mitigation measures such as piling alternatives (i.e. vibration piling), Noise Mitigation Systems (NMS), deterrent devices or other measures. A brief summary of the results of these studies and the current state of knowledge has been set out in the following sections.

Alternatives to percussive piling

To mitigate potential negative impacts of percussive piling, alternatives such as vibration piling are often encouraged. However, there is limited information on the effectivity of these alternatives compared to sound mitigation during percussive piling. The literature review provided one article by Graham *et al.* (2017) which studied the impact of vibration piling on bottlenose dolphins and harbour porpoise during harbour construction work in northeast Scotland. No clear difference was found in the number bottlenose dolphins and harbour porpoises displaced when using different methods of piling. Based on the limited literature available on this topic it is still unclear whether vibration piling is an effective alternative from an ecological perspective.

Noise Mitigation Systems

There are many different noise mitigation systems used to mitigate underwater sound during OWF construction. Each having their own pros and cons which will not be discussed exhaustively in this report. The most frequently used mitigation systems are the: big bubble curtain (BBC), the IHC Noise Mitigation Screen and the Hydrosound damper (HSD). In addition, new promising technologies are being developed such as the BLUE Hammer.

Sound reduction
The noise mitigation systems such as the BBC and VHs have shown to be effective in water depths up to 40 m. The effectivity of the noise mitigation system (NMS) in water depths beyond 40 m is still questionable. Casings (NMS and HydroNAS) and resonators (Hydrosound damper and AdBm Noise Abatement System) may be of future use but currently lack field experience and are only in use for water depths less than 50m (Dähne *et al.*, 2013).

The sound reduction achieved by NMS depends on many factors (location, pile size, system etc.). Studies have aimed to quantify the level of sound reduction that can be achieved by NMS. With the BBC, IHC Noise Mitigation Screen and HSD, broadband sound levels can be reduced by at least 10dB and reductions have been demonstrated of up to 20dB and more for the SEL when combining two NMS. To achieve sound threshold set in several countries such as Belgium, Germany and the Netherlands a combination of NMS is necessary in most cases.

Behavioural change
During the construction of large-scale wind farms several studies (Brandt *et al.* 2018, Rose *et al.,* 2019, Degraer *et al.* 2018, Köppel & Schuster, 2015) investigated and reported on the disturbance of OWF construction in the German Bight and Belgium North Sea with and without NMS on harbour porpoise. The studies show that the number of harbour porpoise decline strongly during piling but also several hours before the onset of piling and 1-2 days after piling. The reduction of harbour porpoise before and after piling may be attributed to the increased disturbance due to vessel activity (see Section 6.1.1).

When looking at the effectivity of the NMS applied, the earlier studies based on first generation NMS (Brandt *et al.* 2018 and Köppel & Schuster, 2015) showed that the harbour porpoise avoidance behaviour did reduce when applying NMS. However, in a more recent study by Rose *et al.* (2019), based on more recent offshore wind developments and improved NMS, no reduced displacement effect could be shown even when considerable sound reduction was achieved. Rose *et al.* (2019) suggested a complex causality beyond disturbance effects observed on harbour porpoise due to pile driving events that might also depend on factors other than underwater sound. Thus, the studies do not provide conclusive results.

Population effects
There is currently little information on population level effects on marine mammals. Degraer *et al.* (2018) used a population model to quantify how differences in regulatory regimes with regards to OWF construction impact a simulated harbour porpoise population. Degraer *et al.* (2018) modelled the likely construction schedules for the Rentel, Norther and Seastar OWFs and tested 17 scenarios with and without various mitigating measures. The results of this study are indicative rather than absolute outcomes. Nevertheless, the results indicate that the impact of pile driving on the harbour porpoise population is strongly influenced by the timing of the activities, but that this effect is reduced when effective sound mitigation measures, i.e. BBC and/or NMS, are used. The combination of a seasonal pile driving restriction and an acoustic deterrent device (ADD) was not enough to lower the impact on the harbour porpoise population to acceptable values. The results also show that building an OWF every year affected the harbour porpoise population more than building two OWFs at the same time within the Belgium exclusive economic zone (EEZ).

Field experience with the deployment of all NMS in OWF-projects at water depth beyond 45m is lacking, however, most NMS are applicable in theory. Also, experience with the deployment of NMS during the installation of piles with a diameter greater than 8m is lacking.

Project-specific assessment are recommended to be conducted to ensure the most suitable NMS option and configuration is chosen, considering the environmental conditions of the OWF site, and the specification of the planned installation vessel and method.

Deterrent Devices
There are several types of ADDs which have been/are used during the construction of OWFs. The following ADDs were reviewed: Lofitech seal scarer and the Faunaguard.

As set out by Köppel & Schuster (2015), Brandt *et al.* conducted two investigations on the effects of the Lofitech seal scarer on harbour porpoise. Depending on the location (i.e. water depth) the effective range of the seal scarer to deter harbour porpoises can differ. Based on these two investigations the deterrence range exceeded 2.5km. Previously, it was assumed that seal scarers provide an appropriate tool to deter harbour porpoise from offshore construction sites because danger zones, where animals may suffer from TTS of their hearing system, reached up to about 2.5km. Since then, sound mitigation techniques have come a long way and during installation of OWFs and sound threshold levels for TTS and PTS have been revised (see Section 6.1.2). Therefore, the area at which marine mammals are exposed to levels of underwater sound that can cause hearing damage (TTS or PTS) is less than previously assumed. A seal scarer may reach far beyond the needed deterrence distance and may cause unnecessary disturbance that affects an even larger area than pile driving itself. Therefore, seal scarers no longer seem to be an appropriate mitigation tool during wind farm construction, on the other hand the application of three pingers with deterrence radii of about 200m is not sufficient either.

The FaunaGuard, a specific porpoise deterrent device, was developed as mitigation measures for the construction phase of the Eneco Luchterduinen Wind Farm in the Dutch North Sea. The FaunaGuard is meant to deter harbour porpoise during piling activities to avoid hearing damage. As set out by Köppel & Schuster (2015), van der Meij *et al.* tested the effectiveness of the FaunaGuard on harbour porpoise and showed that when the FaunaGuard was turned on the harbour porpoise avoided a larger area then during control sessions. The effective range of the FaunaGuard was not stated in the paper but can be calculated and was sufficient to prevent PTS in harbour porpoise due to pile driving sound (Köppel & Schuster, 2015).

6.1.3 Collision risk

Vessel movement have the potential to lead to vessel strikes, which are a common cause of death for cetaceans. A limited number of studies have provided evidence of the risk of collision with marine mammals during construction. The results were limited to two studies provided in the 2014 update (Cefas 2014) on northern right whales (*Eubalaena glacialis*) and seal species. The results of these two studies are summarised below:

- The northern right whale's endangered status and its particular vulnerability to ship strikes has attracted temporal spatial research into its migration routes, breeding and feeding grounds. Through the findings reported as part of this research and mitigation measures put in place, northern right whale ship strikes have reduced by 72% in regional calving grounds (Lagueux *et al.,* 2011).

It has been suggested that seals may be killed in interactions with ducted propellers as used by construction vessels. Fatal interactions between seals and ships are likely to occur when the ships are manoeuvring slowly or maintaining a stationary position in areas of high seal density (Bexton *et al.*, 2012).[14]

Though collision risk is a potential impact that should be considered when assessing the impacts of OWF development, there is limited empirical evidence quantifying the impact on marine mammals in the OSPAR Region.

[14] *Authors note: Whilst not covered in the papers included in the literature review, the document authors are aware of further research that has been undertaken on this topic demonstrating potential predation from grey seals on harbour seals and harbour porpoise leading to similar looking injuries. An example paper can be found at this link https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0156464*

6.2 Operation and maintenance

6.2.1 Underwater sound

The issues with underwater sound during the O&M of OWFs primarily relates to sound from the turbines and vessels. The underwater sound generated by operating turbines is dominated by low frequency pure tone signals below 1kHz with a generally low intensity. Operational underwater sound may affect marine mammals through audibility and masking; displacement and behavioural influence; and, potentially hearing damage.

Limited studies have been done on the impacts of operational sound compared to the impact of impulsive sound on marine mammals. In general, studies have shown there is likely to be overlap between the hearing capabilities of mid – high frequency cetaceans and low-frequency phocid (earless) seals and underwater sound associated with operational OWFs. As seals have a better low frequency hearing than cetaceans, they are predicted to detect operational OWF signals over greater distances (Kastelein *et al* 2009). Though it is likely that marine mammals can detect OWFs, the risk of hearing damage is not considered likely (Kastak and Southall, 2005 as referenced in Cefas, 2014).

6.2.2 Electromagnetic fields

The cables at OWFs create electromagnetic fields (see Section 4.2.2). Studies suggest that cetaceans can sense geomagnetic fields and possibly use it during their migrations. Marine mammals may therefore react to local variations of the magnetic field caused by cable EMFs. Depending on the strength of the EMFs generated, effects can consist of e.g. (temporary) change in swimming direction, or a longer detour during migration.

Reports on tests of EMFs as seal deterrents appeared to show that phocid and otariid (eared) seals may be extremely sensitive to EMFs (e.g. Forrest *et al.* 2009 as referenced in Woods *et al*, 2014). However, seals are not known to have specially adapted electrical sense organs. The maximum electrical fields that will be generated by buried cables from OWFs are significantly lower than those found to elicit an effect among seals and there is no evidence for higher electrical sensitivity among seals than in terrestrial mammals (humans or dogs) (Milne *et al.* (2012), Gill *et al.* 2005, as referenced in Woods *et al.* 2014). It is therefore unlikely that seals would be able to detect these signals and extremely unlikely that any avoidance behaviour would result from exposure.

6.2.3 Changes in prey resource

Foundations of OWFs have the potential to provide substrate for artificial reefs, resulting in localised increases in fish and crustacean density (see Section 4). This increase in biodiversity potentially provides a food source for marine mammals. Both the positive and negative impacts on fish distribution are set out within Section 5 and should be taken in to account when considering the impacts on changes to prey resource as the number of studies on fish as a prey species is limited.

A total of three studies provide information on the impact of change in prey resources on harbour porpoise, harbour seal and grey seal. The results of these three studies are summarised below:

- At the Egmond aan Zee OWF found harbour porpoise activity increased during operation within the OWF (2). This may indicate an attraction effect due to increased food availability (reef effect) and / or sheltering effect from heavy ship traffic.
- A study on harbour seal and grey seal found that seal do exploit OWFs and clearly showed a grid like movement within the OWF boundary (Russel *et al.*, 2014).
- A later study by Russell *et al.* (2016) found that within an operational wind farm, there was a close-to-significant increase in seal usage compared to prior to wind farm development.

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However, the wind farm was at the edge of a large area of increased usage, so the presence of the wind farm was unlikely to be the cause.

Based on these studies it can be concluded that harbour porpoise and seals exploit OWFs; however, it is unclear whether the OWF sites are used more than other areas.

6.2.4 Displacement

The introduction of OWFs could potentially lead to the displacement of marine mammals. None of the studies reviewed found significant changes in harbour porpoise distribution due to the presence of OWFs (Cefas, 2014 and **Appendix A**). Attraction due to changes in prey resources is more likely (see Section 6.2.4).

7 Other Receptors

Whilst most receptors fall within the main receptor categories as set out above, the literature review identified two additional receptors that can be affected by OWF development, namely marine insects and turtles. There was very limited information on these receptors.

7.1 Marine insects

Large assemblages of insects have been noted anecdotally on OWFs around the UK, however very little is known about these communities; what species inhabit offshore structures, their abundances, and origin (Bloxsom *et al.*, 2015 as set out in Köppel & Schuster *et al.* 2015). Bloxsom *et al.* (2015) conducted a study which provides an initial look into the communities of marine insects inhabiting offshore structures. Findings included the presence of insects on OWFs around the UK with six different families of insect being identified.

7.2 Turtles

Turtles are known to be sensitive to magnetic fields and are believed to use natural magnetic fields in migration. Normandeau *et al.* (2011) concluded that turtles can probably detect magnetic fields from sub-sea cabling. It was suggested that at short range, magnetic fields from sub-sea cabling may cause turtles to deviate from migration cues**.** However, turtles should be able to correct their course using other natural cues (Cefas, 2014).

8 Ecosystem Effects

The construction and operation of OWFs have the potential to impact entire ecosystems, directly and indirectly. This is a relatively new field of research, and knowledge on the potential impacts of OWFs on an ecosystem scale are largely unknown. No literature was identified that specifically looked at the construction phase. The following potential impacts on ecosystems have been identified during the O & M phase of OWFs:

- Effects on nutrients;
- Changes to primary production and impacts on higher trophic levels;
- Changes in zooplankton and benthos affecting higher trophic levels;
- Stepping stone effects; and,
- Coastal food web sensitivity.

It is worth bearing in mind that as we are looking at potential impacts on the ecosystem as a whole, these impacts are often heavily linked to individual receptors.

8.1 Operation and maintenance

8.1.1 Nutrients

The availability of nutrients is key to an ecosystem as it is the first building block in the food web. The presence of OWF structures can lead to the level of these nutrients fluctuating and in doing so impacting higher trophic levels. Floeter *et al.*, (2017) found that with vertical mixing enhanced within OWFs there were changes to how nutrients were distributed throughout the water column with potentially more nutrients reaching the surface mixed water layers.

8.1.2 Changes to primary production and impacts on higher trophic levels

Changes to sea surface temperature (SST) related to changes in meteorological conditions, mixing and stratification affect the onset of primary production and zooplankton growth, abundance and composition. In addition, changes to tidal currents influence nutrient transport and its availability to phytoplankton. The related changes to total food availability and quality has been shown to have a major influence on zooplankton growth (Suchy, 2014).

With the introduction of OWF structures, the zoobenthos (e.g. shellfish and other filter feeders) that may colonise the structures have the potential to reduce the available algae/phytoplankton due to competition, which could decrease primary production and a decrease in zooplankton (Smaal *et al.,* 2013)

8.1.3 Changes in zooplankton and benthos affect higher trophic levels

Changes to a system at the level of primary and secondary trophic levels are likely to influence higher trophic levels. The direction and magnitude of these effects are very hard to assess and are still not well understood. Partly because the direction and magnitude of the effects on the lower trophic levels are uncertain. There are further complications when trying to split out the impacts that are directly related to changes in the food web from direct effects of physical and chemical ecosystem changes to fish, marine mammals and birds.
Herring and sandeel are important pray species for animals higher up the food chain so it stands to reason that impacts on recruitment for these species will have a knock-on effect higher up the food chain. Failing recruitment of herring showed a correlation between decreased availability of important larval herring prey copepod species and recruitment (Hufnagl *et al.,* 2017; Payne *et al.,* 2008). Arnott & Ruxton (2002) reported a comparable relationship between sandeel recruitment and the temperature density of Clanus spp, a lichen species.
The increased presence of hard substrate in OWFs has the potential to result in increased feeding opportunities for fish and so the increased presence of fish species within OWFs (e.g. Degraer *et al.,* 2012; Bergström *et al,.* 2013; Deltares, 2018). This increase in fish within OWFs provides a potential food source for marine mammals and birds (Russell *et al.*, 2014; Hartman *et al.,* 2012).

8.1.4 Potential Spread of Invasive/Non Native Species

There is the possibility that the introduction of new hard substrate in areas that otherwise consist of sandy seabeds may lead to the introduction of invasive/non-native species (INNS) by what is known as the stepping stone effect (i.e. the relevant species can colonise the new structures and use these to move in to areas previously outside of their natural boundaries) (Vanagt *et al.*, 2013; Krone *et al.*, 2013; Mesel *et al.*, 2015). For species in the subtidal environment Deltares (2018) found that the additional hard substrate in OWFs may provide stepping stones that tip the ecosystem balance.

9 Overarching Findings

This section sets out the overarching findings from the literature review with each topic summarised under its own heading and threads that run throughout all topics listed below:

- The knowledge concerning OWFs and their associated marine environmental impacts is rapidly evolving however some topics have been researched in far more detail than others. The impacts on ornithological and marine mammal receptors for example are far better understood than ecosystem effects or marine turtles.
- Available research is largely sourced from Denmark, Germany, Belgium, Sweden, the Netherlands and the UK. Whilst this is understandable as these countries have the most developed offshore wind markets in the OSPAR Region, the drive for new areas to develop their offshore wind capabilities provides a clear knowledge gap that requires filling. Example areas where the offshore wind industry is rapidly taking shape include the Irish Sea and the French, Portuguese, Spanish and Norwegian regions.
- The cumulative effects that multiple OWFs will have on receptors requires research going forward to effectively assess impacts on a regional scale. Currently the focus heavily lies with assessments on single OWFs.
- Industries that are likely to have similar impacts to offshore wind should be considered in combination or cumulatively with offshore wind related impacts to provide a true holistic overview of the impacts of offshore wind in the OSPAR region. This includes currently existing projects such as operational oil and gas platforms as well as activities planned in future.

9.1 Physical processes

Physical processes may be affected by the development of OWFs. Effects on physical processes identified during the literature review include:

- Wave changes (including wave height);
- Tides and currents;
- Tidal energy dissipation;
- Accumulation of effects;
- Changes to wind resource; and,
- Stratification and water mixing.

Research in to this topic is currently limited with only two papers included in the literature review informing this report and these focussed almost exclusively on the impacts during the O&M phase. Effects upon the above listed physical processes should all be further researched. Evident gaps include potential increases in suspended sediment during construction, larger scale cumulative effects focussing on multiple OWFs combined with current research focussing on single OWFs. These requirements are also highlighted in Deltares (2018).

9.2 Ornithology and Bats

Ornithology and bats may be impacted by the development of OWFs. Impacts identified in the literature review during the construction phase include:

- Disturbance due to human activities;
- Avoidance and attraction; and
- Displacement / barrier effect.

Impacts identified in the literature review during the O&M phase include:

- Collision risks;
- Avoidance and attraction;
- Displacement / barrier / habitat loss; and
- Change in prey resource.

Potential impacts to ornithology during wind farm construction and operation have been widely researched at a local scale with some research having taken place on a wider scale. However, considering the level of predicted impacts during the operational phase, further research is required including in to the effectiveness of mitigation measures. There is also a need for research to be undertaken on a wider range of species and for collision risk modelling to incorporate the latest research.

Research in to the potential impacts on bats is far less advanced than for ornithology. Little is known on offshore migration and feeding behaviour. The literature recommends that further research should be undertaken on all aspects of potential impacts on bats.

9.3 Benthic Ecology (including shellfish ecology)

Benthic ecology may be impacted by the develop of OWFs. Impacts identified in the literature review during the construction phase include:

- Habitat disturbance;
- Habitat loss;
- Habitat disturbance;
- Underwater sound.

During the O&M phase of OWFs benthic ecology have the potential to be affected by:

- Increased suspended sediments and smothering;
- Disturbance due to maintenance activities;
- Introduction of new substrate / altered substrate;
- Underwater sound;
- Electromagnetic fields; and

Potential impacts on benthic ecology during wind farm construction have not been widely researched. Research has mostly taken place on a local scale within individual windfarms. Most of the literature and information available focus on the impact of introduction of new substrate. Other potential impacts due to construction and operation and maintenance such as underwater sound on benthic species are still poorly understood. The literature recommends that further research should be undertaken on all aspects.

9.4 Fish Ecology

Fish and shellfish ecology may be affected by the development of OWFs. Impacts identified in the literature review during the construction phase include:

- Habitat disturbance;
- Increased SSC;
- Deterioration in water quality due to resuspended contaminants;
- Changes in prey resources; and,
- Underwater sound.

Impacts identified in the literature review during the O & M phase include:

- Habitat loss;
- Introduction of new substrate;
- Changes to fishing activity;
- Increased SSC;
- Electromagnetic frequencies; and,
- Underwater sound.

Potential impacts to fish during wind farm construction have been widely researched at a local scale, though potential impacts from habitat disturbance, increased SSC and deterioration in water quality are currently poorly understood.

The literature review did not identify any information on potential impacts from habitat loss and increased SSC during the O & M phase.

Current knowledge on the potential impacts from EMFs and underwater sound are largely based on theoretical studies and trial experiments. Little is known about the behaviour of fish under natural conditions through in situ studies. Furthermore, questions also remain on baseline conditions such as all aspects of spawning and nursery grounds. These areas are currently poorly understood.

9.5 Marine Mammals

Marine mammals may be impacted by the development of OWFs. Impacts identified in the literature review during the construction phase include:

- Disturbance due to human activities;
- Underwater sound;
- Collision risk; and,
- Changes in prey resources

Impacts identified in the literature review during the O&M phase include:

- Underwater sound;
- Displacement; and,
- Electromagnetic frequencies.

Potential impacts on marine mammals during wind farm construction have been widely researched at a local scale with some research having taken place on a wider scale. However, considering the level of predicted impacts due to increased underwater sound, further research is further required including in to the effectiveness of mitigation measures this is particularly the case during the construction phase.

During the O&M phase the literature review did not identify a lot of information relating to the potential impacts from displacement; collision risk; physical barriers; or, changes in habitats and prey resources. These areas are currently poorly understood.

9.6 Other Receptors

Very little is known about receptors that do not directly fall within the most widely considered research topics as set out above. Receptors specifically identified in the literature review that require further research are insects, turtles and the spread of non-indigenous species. These areas are currently poorly understood.

9.7 Ecosystem Effects

Ecosystem effects may take place in relation to the development of OWFs. This is a relatively new field of research with the literature review not identifying any papers that considered impacts during construction. Impacts identified in the literature review during the O&M phase include:

- Effects on nutrients;
- Changes to primary production and impacts on higher trophic levels;
- Changes in zooplankton and benthos affecting higher trophic levels;
- Stepping stone effects; and,

- Coastal food web sensitivity

As stated above, potential ecosystem effects are a little studied subject with the literature review only identifying two papers covering the topic. The lack of literature available indicates that more research is required to identify impacts on an ecosystem scale. This is particularly the case for higher trophic levels. On an ecosystem scale a requirement has also been identified to research the cumulative effect of all marine and coastal human activities

Similarly, Raoux *et al.* (2019) concluded that as marine ecosystems face many natural and anthropogenic stressors, there is an urgent need to understand how these interact and influence each other.

Appendix A Review of literature 2014-2019 on ecological impact offshore wind farm development

REPORT

Review of literature 2014-2019 on ecological impact offshore wind farm development

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Acronyms

Acronym	Acronym description
ADD	Acoustic Deterrent Device
AMSL	above mean sea level
BBC	Big Bubble Curtain
BPNS	Belgian part of the North Sea
Cefas	Centre for Environment, Fisheries and Aquaculture Science
EIA	Environmental Impact Assessment
EIHA	Environmental Impact of Human Activities Committee
EU	European Union
GBF	gravity-based foundation
ILVO	Institute for Agricultural and Fisheries Research
iPCoD	interim Population Consequences of Disturbance
NMS	Noise Mitigation Systems
OSPAR	Oslo/Paris convention (for the Protection of the Marine Environment of the North-East Atlantic)
OWEZ	Offshore Wind Farm Egmond aan Zee
OWF	Offshore wind farm
OWFA	Offshore wind farm area
PAM	Passive Acoustic Monitoring
PAWP	Princess Amalia Wind Farm
PTS	Permanent Threshold Shift
RHDHV	Royal HaskoningDHV

SPA	Special Protection Area
TTS	Temporary Threshold Shift
VARS	Visual Automatic Recording System

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1 Introduction

The development of Offshore Wind Farms (OWFs) may lead to changes in the environment. Over the past years it has become clear that there is a challenge in creating a clear understanding of what these changes might be, how they are assessed and how they may be mitigated so that any impacts are acceptable.

In 2006 OSPAR (Oslo/Paris convention (for the Protection of the Marine Environment of the North-East Atlantic)) published the Update on the Current State of Knowledge of the Environmental Impacts of the Location, Operation, and Removal/Disposal of Offshore Wind Farms – Status Report. The aim of the report was to provide a review of existing information on offshore wind development and to determine the current state of knowledge on the ecological impacts of OWF. This would allow for future research to be prioritised and better targeted on key issues of concern. In 2014 the United Kingdom submitted a Draft Update on the Current State of Knowledge and Studies of the Environmental Impacts of the Location, Operation and Removal/Disposal of OWF, (EIHA 13/3/5).

In the 2018 Environmental Impact of Human Activities Committee (EIHA) meeting, the Netherlands offered to update OSPAR Agreement 2008-03 on a Guidance on Environmental Considerations for Offshore Wind Farm Development with Germany offering to co-lead later in the year. Rijkswaterstaat (RWS) commissioned Royal HaskoningDHV (RHDHV) to provide an overview of recent knowledge on possible ecological impacts of OWF on species and habitats living and protected by OSPAR and or European Union (EU) regulations in the OSPAR region in 2018 with an additional follow up undertaken in 2019 to reflect the current state of knowledge as of the end of September 2019.

This document presents a literature review setting out new information on the impacts of offshore wind developments in the OSPAR region. It is intended to be an update of the 2014 Status Report produced by the Centre for Environment, Fisheries and Aquaculture Science (Cefas) (Wood *et al*. 2014) and where possible filling knowledge gaps that were identified in 2014. If knowledge gaps and further research were identified in the reviewed literature, these have also been included in this report.

Whilst care has been taken to include the most up to date knowledge on potential impacts relating to offshore wind development it is important to note that this document is not considered to be an exhaustive overview of all available information. This is due to a number of factors including that research is constantly evolving so a cut-off date for inclusion was set at the end of September 2019. The focus has also been on findings from the OSPAR Region only, any information that may be available from other regions such as the east and west coasts of the US has not been included at this time. An assumption has also been made that any information available prior to the 2014 update was included in the 2014 report, searches were therefore not undertaken to include earlier work.

1.1 Document structure

This document has been structured to provide a clear and concise overview of environmental receptors impacted by offshore wind development based on literature provided to RHDHV in 2018 and 2019 and literature sourced by RHDHV through an online search. Where possible, impacts on each receptor have been split across the construction and operation phases of the OWFs. As there is currently limited information on decommissioning OWFs, this stage of the developments has only been considered in some sections of this report. The following receptors have been included:

1 Physical Processes (hydrodynamics, sediment transport, water quality);

2 Ornithology and Bats;

3 Benthic Ecology;

4 Fish and Shellfish Ecology;

5 Marine Mammals;

6 Other receptors;

7 Ecosystem Effects.

It should be noted that in some cases topics haven't been split out as the research undertaken or findings presented are closely linked. This is also the case where impacts are closely related and it was deemed appropriate to keep them together. In these cases, the impacts have been left as reported in the reviewed literature.

1.2 Our Approach

For the 2018 report RHDHV was provided with a list of literature which was published between 2014 and 2018 (i.e. after the 2014 status report). A first selection was made of the provided papers. When papers were not within the scope i.e. not related to offshore wind or published before 2014, they were not included in the update (see **Appendix I**).

As part of the 2019 update a combination of provided literature and literature identified during online searches was included. The 2018 and 2019 papers can be found in **Table 1** and **Table 2** with full references provided in the references section alongside references taken from the reviewed literature.

Once a selection of the papers had been made these were summarised and organised per receptor topic as set out under Section 1.1.

As previously mentioned the literature referenced in this document is by no means exhaustive but is intended as a starting point to which additional information can be added in due course.

1.3 List of literature

1.3.1 Reviewed in 2018

The papers reviewed in 2018 have been set out in **Table 1**.

Table 1 Papers included in 2018

Topic	Paper
Benthic Ecology	Coates *et al*. 2015 - Rapid macrobenthic recovery after dredging activities in an offshore wind farm in the Belgian part of the North Sea (BPNS)
Benthic Ecology	Roberts *et al*. 2015 - Sensitivity of the mussel *Mytilus edulis* to substrate-borne vibration in relation to anthropogenically-generated noise
Marine Mammals	Brandt *et al*. 2018 – Disturbance of harbour porpoises during construction of the first seven offshore wind farms in Germany
Marine Mammals	Farcas *et al*. 2016 – Underwater noise modelling for environmental impact assessment
Marine Mammals	Graham *et al* 2017 – Responses of bottlenose dolphins and harbour porpoises to impact and vibration piling noise during harbour construction

Topic	Paper
Marine Mammals	Hastie *et al*. 2015 – Sound exposure in harbour seals during the installation of an offshore wind farm: predictions of auditory damage
Marine Mammals	Hastie *et al*. 2016 – Multiple-Pulse Sounds and Seals: Results of a Harbour Seal (*Phoca vitulina*) Telemetry Study During Wind Farm Construction
Marine Mammals	Jones *et al*. 2015 – Patterns of space use in sympatric marine colonial predators reveal scales of spatial partitioning
Marine Mammals	Jones *et al*. 2017 – Fine-scale harbour seal usage for informed marine spatial planning
Marine Mammals	Lucke *et al*. 2016 – Aerial low-frequency hearing in captive and free-ranging harbour seals (*Phoca vitulina*) measured using auditory brainstem responses
Marine Mammals	Russell *et al*. 2014 – Marine mammals trace anthropogenic structures at sea
Marine Mammals	Russell *et al*. 2016 – Avoidance of wind farms by harbour seals is limited to pile driving activities
Multiple topics	Degraer *et al*. 2017 - Environmental impacts of offshore wind farms in the Belgian part of the North Sea: A continued move towards integration and quantification
Multiple topics	Degraer *et al*. 2018 - Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Assessing and Managing Effect Spheres of Influence
Multiple topics	Schuster *et al*. 2015 - Consolidating the State of Knowledge: A Synoptical Review of Wind Energy's Wildlife Effects
Ornithology	Cleasby *et al.* 2015 – Three-dimensional tracking of a wide-ranging marine predator: flight heights and vulnerability to offshore wind farms
Ornithology	Koppel & Schuster 2015 - Book of Abstracts. Conference on Wind energy and Wildlife impacts
Ornithology	Dierschke *et al.* 2016 – Seabirds and offshore wind farms in European waters: Avoidance and attraction
Ornithology	Grecian *et al*. 2018 – Understanding the ontogeny of foraging behaviour: insights from combining marine predator bio-logging with satellite-derived oceanography in hidden Markov models

Topic	Paper
Ornithology	Ross-Smith *et al*. 2016a – GPS telemetry reveals differences in the foraging ecology of breeding Lesser Black-backed Gulls between three Special Protection Area colonies
Ornithology	Ross-Smith *et al*. 2016b – Modelling flight heights of lesser black-backed gulls and great skuas from GPS: a Bayesian approach
Ornithology	Schamoun-Baranes *et al*. 2017 – Sharing the Aerosphere: Conflicts and Potential Solutions
Ornithology	Thaxter *et al*. 2013 – Connectivity between seabird features of protected sites and offshore wind farms: Lesser Black-backed Gulls and Great Skuas through the breeding, migration and non-breeding seasons
Ornithology	Thaxter *et al*. 2014 - A trial of three harness attachment methods and their suitability for long-term use on Lesser Black-backed Gulls and Great Skuas, Ringing & Migration
Ornithology	Thaxter *et al*. 2015 - Seabird–wind farm interactions during the breeding season vary within and between years: A case study of lesser black-backed gull *Larus fuscus* in the UK
Ornithology	Thaxter *et al*. 2018 – Dodging the blades: new insights into three-dimensional space use of offshore wind farms by lesser black-backed gulls *Larus fuscus*
Ornithology	Wade *et al*. 2014 – Great skua (*Stercorarius skua*) movements at sea in relation to marine renewable energy developments
Ornithology	Welcker & Nehls 2016 - Displacement of seabirds by an offshore wind farm in the North Sea

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1.3.2 Reviewed in 2019

Table 2 Papers included in 2019 update

Topic	Paper
Bats	Lagerveld, S., Limpens, H.J.G.A., Schillemans, M.J. & Scholl, M. (2017a). Bat 1: Estimate of bat populations at the southern North Sea. Supporting note to ZDV report no. 2016.031 Migrating bats at the southern North Sea. Wageningen, Wageningen Marine Research (University & Research Centre), Wageningen Marine Research report no. C014.17/Dutch Mammal Society report no. 2017.08. 14 pp.
Bats	Lagerveld, S., Kooistra, G., Otten, G., Meesters, L., Manshanden, J., de Haan, D., Gerla, D., Verhoef, H. & Scholl, M. (2017b). Bat flight analysis around wind turbines – a feasibility study; Wageningen, Wageningen Marine Research (University & Research Centre), Wageningen Marine Research report C026/17. 40 p.
Bats	Limpens, H.J.G.A., Lagerveld, S., Ahlén, I., Anxionnat, D., Aughney, T., Baagøe, H.J, Bach,L., Bach, P., Boshamer, J.P.C., Boughey, K., Le Campion, T., Christensen, M., Dekker, J.J.A. Douma, T., Dubourg-Savage, M.-J., Durinck, J., Elmeros, M., Haarsma, A.-J., Haddow, J., Hargreaves, D., Hurst, J., Jansen, E.A., Johansen, T.W., de Jong, J., Jouan, D., van der Kooij, J., Kyheroinen, E.-M., Mathews, F., Michaelsen, T.C., Møller, J.D., Pētersons, G., Roche, N., Rodrigues, L., Russ, J., Smits, Q., Swift, S., Fjederholt, E.T., Twisk, P., Vandendriesche B. & Schillemans, M.J. (2017). Migrating bats at the southern North Sea - Approach to an estimation of migration populations of bats at southern North Sea. Rapport 2016.031. Zoogdiervereniging (Dutch Mammal Society), Nijmegen/ Wageningen Marine Research
Bats	Lagerveld, S., Gerla, D., van der Wal, J.T., de Vries, P., Brabant, R., Stienen, E., Deneudt, K., Manshanden, J. & Scholl, M. (2017c). Spatial and temporal occurrence of bats in the southern North Sea area. Wageningen Marine Research (University & Research centre), Wageningen Marine Research report C090/17; 52 p.
Bats	Lagerveld, S., Janssen, R., Manshanden, J., Haarsma, A-J., de Vries, S., Brabant, R. & Scholl, M. (2017d). Telemetry for migratory bats – a feasibility study; Wageningen, Wageningen Marine Research (University & Research Centre), Wageningen Marine Research report C011/17. 47 pp.
Benthic Ecology	Floeter, J., van Beusekom, J.E.E., Auch, D., Callies, U., Carpenter, J., Dudeck, T., Eberle, S., Eckhardt, A., Gloe, D., Hänselmann, K., Hufnagl., M., Janßen., Lenhart, H., Möller, K.O., North, R.P., Pohlmann, T., Reithmüller, R., Schulz, S., Spreizenbarth, S., Temming, A., Walkter, B., Zielinski, O and Möllmann, C (2017) Pelagic effects of offshore wind farm foundations in the stratified North Sea. Progress in Oceanography 156 (2017) 154-173.

Topic	Paper
Benthic Ecology	Leewis, L., P.M. van Bodegom, J. Rozema, G.M. Janssen, 2012, Does beach nourishment have long-term effects on intertidal macroinvertebrate species abundance? Estuarine, Coastal and Shelf Sci-ence 113, 172-181
Benthic Ecology	Bicknell, A.W.J., Sheehan, E, V., Godley, B.J., Doherty, P.D., Witt, M. J (2019) Assessing the impact of introduced infrastructure at sea with cameras: A case study for spatial scale, time and statistical power. Marine Environmental Research 147 (2019) 127-137.
Benthic Ecology	Jak, R., and Glorius, S (2017) Macrobenthos in offshore wind farms: A review of research, results and relevance for future developments. Wageningen University & Research Report C043/17.
Benthic Ecology	Fowler, A.M., Jørgensen, A.M., Coolen, J.W.P., Jones, D.O.B., Svensden, J.C., Brabant, R., Rumes, B and Degraer, S (2019) The ecology of infrastructure decommissioning in the North Sea: what we need to know and how to achieve it. ICES Journal of Marine Science (2019) doi:10.1093/icesjms/fsz143.
Benthic Ecology	Coolen, J.W.P., Lengkeek, W., van der Have, T and Bittner, O (2019) Upscaling positive effects of scour protection in offshore wind farms: Quick scan of the potential to upscale positive effects of scour protection on benthic macrofauna and associated fish species. Wageningen University & Research Report C008/19.
Benthic Ecology	Coolen, J.W.P., van der Weide, B., Cuperus, J., Blomberg, M., Van Moorsel, G.W.N.M., Faasse, M.A., Bos, O.G., Degraer, S and Lindeboom, H.K (2018a) Benthic biodiversity on old platforms, young wind farms and rocky reefs. ICES Journal of Marine Science. doi:10.1093/icesjms/fsy092
Benthic Ecology	Dannheim, J., Bergström., Birchenoff, S.N.R., Brzana, R., Boon, A.R., Coolen, J.W.P., Dauvin, J.C., De Mesel, I., Dorweduwen, J., Gill, A.B, Hutchison, Z.L., Jackson, A.C., Janas, U., Martin, G., Raoux (A., Reubens, J., Rostin, L., Vanaverbeke, J., Wilding, T.A., Wilhelmsson, D and Degraer, S (2019) Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. ICES Journal of Marine Science. doi:10.1093/icesjms/fsz018.
Fish and Shellfish Ecology	Weilgart, L. (2018). The impact of ocean noise pollution on fish and invertebrates. Oceancare & Dalhousie University. 1 May 2018.
Fish and Shellfish Ecology	Popper, A. & Hawkins, A. (2018). An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishes. Journal of Fish Biology, 94(5), pp692-713.

Topic	Paper
Fish and Shellfish Ecology	Boyle, G., New, P. (2018). ORJIP Impacts from Piling on Fish at Offshore Wind Sites: Collating Population Information, Gap Analysis and Appraisal of Mitigation Options. Final report – June 2018. The Carbon Trust. United Kingdom. 247 pp.
Fish and Shellfish Ecology	Snoek, R., de Swart, R., Didderen, K., Lengkeek, W. & Teunis, M. (2016). Potential effects of electromagnetic fields in the Dutch North Sea. Phase 1: Desk Study. Rijkswaterstaat Water.
Fish and Shellfish Ecology	Scott, K., Harsanyi, P. & Lyndon, A. (2018). Understanding the effects of electromagnetic field emissions from Marine Renewable Energy Devices (MREDs) on the commercially important edible crab, *Cancer pagurus* (L.). Front. Mar. Sci. Conference Abstract: IMMR'18 | International Meeting on Marine Research 2018. doi: 10.3389/conf.FMARS.2018.06.00105
Fish and Shellfish Ecology	Bolle, L., de Jong, C., Bierman, S., de Haan, D., Huijer, T., Kaptein, D., Lohman, M., Tribuhl, S., van Beek, P., van Keeken, O, Wessels, P. & Winter, E. (2011). Shortlist Masterplan Wind. Effect of piling noise on the survival of fish larvae (pilot study). Institute for Marine Resources & Ecosystem Studies, June 2011.
Fish and Shellfish Ecology	Tonk, L. & Rozemeijer, M. (2019). Ecology of the brown crab (*Cancer pagaurus*) and production potential for passive fisheries in Dutch offshore wind farms. Wageningen Marine Research, July 2019.
Marine mammals	Graham, I. M., Merchant, N. D., Farcas, A., Barton, T. R., Cheney, B., Bono, S., and Thompson, P. M. 2019. Harbour porpoise responses to pile-driving diminish over time. Royal Society Open Science, 6: 190335.
Marine mammals	Kastelein, R. A., Hoek, L., Kommeren, A., Covi, J., and Gransier, R. (2018). “Effect of pile driving sounds on harbour seals (*Phoca vitulina*) hearing,” J. Acoust. Soc. 143, 3583–3594.
Marine mammals	Rose, A., Brandt, M.J., Vilela, R., Diederichs, A., Schubert, A., Kosarev, V., Nehls, G. and Freund, C.K., Effects of noise-mitigated offshore pile driving on harbour porpoise abundance in the German Bight 2014-2016 (Gescha 2). Assessment of Noise Effects. Final Report Husum, June 2019 Prepared for Arbeitsgemeinschaft OffshoreWind e.V
Marine mammals	Southall, B.L., Finneran, J.J., Reichmuth, C., Nachtigall, P.E., Ketten, D.R., Bowles, A.E., Ellison, W.T., Nowacek, D.P. and Tyack, P.L., 2019. Marine mammal noise exposure criteria: updated scientific recommendations for residual hearing effects. Aquatic Mammals, 45(2), pp.125-232.

Topic	Paper
Marine mammals	Verfuss, U.K., Sinclair, R.R. & Sparling, C.E. 2019. A review of noise abatement systems for offshore wind farm construction noise, and the potential for their application in Scottish waters. Scottish Natural Heritage Research Report No. 1070.
Multiple topics	Deltares (2018) Assessment of system effects of large-scale implementation of offshore wind in the southern North Sea
Multiple topics	Raoux, A., Lassalle, G., Pezy, J.P., Tecchio, S., Safi, G., Ernande, B,. Mazé, C., Le Loc'H, F., Lequesne, J., Girardin, V. (2019) Measuring sensitivity of two OSPAR indicators for a coastal food web model under offshore wind farm construction. Ecological Indicators, Elsevier, 2019, 96, pp.728-738. 10.1016/j.ecolind.2018.07.014. hal-01938892
Ornithology	Rebke, M., Dierschke, V., Weiner, C.N., Aumüller, R., Hill, K. and Hill, R., 2019. Attraction of nocturnally migrating birds to artificial light: The influence of colour, intensity and blinking mode under different cloud cover conditions. Biological Conservation, 233, pp.220-227.
Ornithology	Mendel, B., Schwemmer, P., Peschko, V., Müller, S., Schwemmer, H., Mercker, M. and Garthe, S., 2019. Operational offshore wind farms and associated ship traffic cause profound changes in distribution patterns of Loons (*Gavia* spp.). Journal of environmental management, 231, pp.429-438.
Ornithology	Fox, A.D. and Petersen, I.K., 2019. Offshore Wind Farms and their effects on birds. Dansk Ornitologisk Forenings Tidsskrift, 113, pp.86-101.
Ornithology	Furness, R.W., Garthe, S., Trinder, M., Matthiopoulos, J., Wanless, S. and Jeglinski, J., 2018. Nocturnal flight activity of northern gannets *Morus bassanus* and implications for modelling collision risk at offshore wind farms. Environmental Impact Assessment Review, 73, pp.1-6.
Ornithology	Cleasby, I.R., Owen, E., Wilson, L.J. and Bolton, M., 2018. RSPB Research Report 63 September 2018.
Ornithology	Miller, J.A., Furness, R.W., Trinder, M. and Matthiopoulos, J., 2019. The sensitivity of seabird populations to density-dependence, environmental stochasticity and anthropogenic mortality. Journal of Applied Ecology, 56(9), pp.2118-2130.
Ornithology	Searle, K.R., Mobbs, D.C., Butler, A., Furness, R.W., Trinder, M.N. and Daunt, F., 2018. Finding out the fate of displaced birds. CEH Report to Marine Scotland FCR/2015/19.

Topic	Paper
Ornithology	Vallejo, G.C., Grellier, K., Nelson, E.J., McGregor, R.M., Canning, S.J., Caryl, F.M. and McLean, N., 2017. Responses of two marine top predators to an offshore wind farm. Ecology and evolution, 7(21), pp.8698-8708.
Ornithology	Bowgen, K. and Cook, A., 2018. JNCC Report No: 614.
Ornithology	Fox, A.D. and Petersen, I.K., 2019. Offshore Wind Farms and their effects on birds. Dansk Ornitologisk Forenings Tidsskrift, 113, pp.86-101.
Ornithology	Perrow, M. ed., 2019a. Wildlife and Wind Farms-Conflicts and Solutions, Volume 3: Offshore: Potential Effects. Pelagic Publishing Ltd.
Ornithology	Perrow, M. ed., 2019b. Wildlife and Wind Farms-Conflicts and Solutions, Volume 3: Offshore: Monitoring and Mitigation. Publishing Ltd.
Ornithology	Thaxter, C.B., Ross-Smith, V.H., Bouten, W., Masden, E.A., Clark, N.A., Conway, G.J., Barber, L., Clewley, G.D. and Burton, N.H., 2018. Dodging the blades: new insights into three-dimensional space use of offshore wind farms by lesser black-backed gulls Larus fuscus. Marine Ecology Progress Series, 587, pp.247-253.

2 Physical Processes (hydrodynamics, sediment transport, water quality)

2.1 Construction

The reviewed literature did not include information on the potential impact of offshore wind development on physical processes during the construction phase[1]. Specifically no information was provided on:

- Increased Suspended Sediment Concentrations; and
- Deterioration in water quality due to resuspended contaminated sediments.

2.2 Operation and maintenance

2.2.1 Deterioration in water quality and sediment due to contamination

A review by Shuster *et al.* (2015) identified that the risk of contamination from leaks or spills increases due to higher risk of ship collision within OWF, along with the use of hydraulic fluids from operational devices (Schuster *et al.* 2015). Effects from re-suspension of potentially polluted sediment together with turbidity during construction and cabling cannot be ignored, but are only short lived. Contamination with pollutants

[1] Comments received on this document identified further papers that could be included in future updates including, Forster (2018) and it's references. The reviewers also acknowledged that information is not always available as published literature but access could be gained to these sources. It is recommended this is further investigated with Natural England who provided the comments and action is taken to include this information in future updates. These inclusions would provide information on turbid suspended sediment wakes seen downstream from turbines, suspended sediment from cable installation and potential interruption to coastal processes from cable protection and sandwave clearance.

could affect the health and breeding success of species, and also indirectly due to an accumulation within the food web (Simms and Ross 2000 in Shuster *et al.* (2015)).

Contamination of sediment and water quality may also occur depending on the material that is used for scour protection. Scour protection to mitigate seabed erosion around turbine foundations consisting of natural rocks and boulders is a commonly used measure to enhance the stability of offshore wind turbines in European waters (Sturm *et al*. (2015) in Koppel and Schuster (2015)). As an alternative to natural lithogenic scour protection, geotextile sand filled containers consisting of synthetic polymers are increasingly used. Plastic polymers contain a variety of chemical substances which have been added during the production process in order to improve the mechanical properties and durability of the polymer. Some of these additives are known to be hazardous to marine organisms and humans potentially causing endocrine disruption or cancer. Sturm *et al*. tried to quantify the release of these hazardous chemicals under *in situ* conditions in the marine environment but so far this has not been possible. Under controlled laboratory conditions Sturm *et al*. conducted experiments with eight different geotextile materials commonly used for coastal protection at both limnic and marine shores. The results showed that potentially hazardous plastic additives like plasticisers and UV-filters were leached out by shaking with seawater for at least 24 hours, indicating that geotextiles, employed in the marine environment for stabilisation of sediments and anthropogenic constructions, release environmentally hazardous chemicals. Geotextile materials, especially nonwoven fabrics, used as scour protections around turbine foundations can attract a diverse biota consisting of mobile and sessile invertebrates and fish. It can be assumed that chemicals from the geotextiles accumulate in associated organisms.[2]

2.2.2 Wave changes

Using a number of idealised wave model computations, interactions were identified between OWFs and wind resource and how this impacts waves forming (Deltares, 2018). It was found that effects are commonly assessed as being local. However, largescale development of OWF may lead to (as yet poorly quantified) effects on the vertical transfer of energy from the higher atmosphere to the OWF, impacting wind and waves. It is considered that a change of 5% in wind speed can lead to a change of 5 to 10% in significant wave height. In addition to this, structures within an OWF may also have an impact on wave propagation leading to wave diffraction.

2.2.3 Tides and currents

Horizontal velocities have been shown to increase at the sides of each foundation and decrease on the leeside of the foundation (Clark *et al.*, 2014). The impact decreases with distance from the foundation but can extend for hundreds of meters with changes largest in the upper water column (Cazenave *et al*., 2016). The exact influence of a wind farm on currents depends on the design and the angle of incidence between the current and wind (Zhang *et al.*, 2009). Vertical velocities are also influenced by the foundation with a downward flow upstream of the foundation and upward flow downstream of the foundation. The strongest effect is in the lower part of the water column (from 10 m depth to the seabed). Stratified water will experience smaller vertical velocities than fully mixed waters due to the increased energy that is required to overcome the density gradient.

Cazenave *et al.* (2016) showed that the construction of offshore wind farms in the Irish Sea can have large-scale impacts and change the amplitude of the tides at the coasts in particular (>2%), but also offshore. This was calculated from a model using time series analysis of data from Liverpool Balt CObs yields.Large effects

[2] *Comments received on this document identified further papers that could be included in future updates including Kirchgeorg et al 2018 on the effect of corrosion protection systems in OWF.*

are particularly found in the vicinity of the amphidromic points[3], which may reflect the limitations of the model boundaries or be the result of the absolute amplitude near these points being close to zero. Similar effects are found for the construction of tidal turbines (De Dominicis *et al.*, 2017) with an increase in tides near the turbines, while far-field effects show decrease in tides in the order of 2 cm.

2.2.4 Tidal energy dissipation

Wind turbine foundations and the scour protection lead to the production of turbulence. High dissipation levels are generally observed close to the water surface and near the sea bed, which is explained by turbulence caused by wind drag and bottom friction of the tidal currents (Schultze *et al.*, 2017). Carpenter *et al.* (2016) found that the turbulence induced by the wind farms is equal to 4-20% of the turbulence produced at the bottom (per surface unit). This will increase linearly with greater depths. This implies that the total energy that is extracted from the tides could be significant.

2.2.5 Accumulation of effects

Because of the many feedback mechanisms and interconnections in the systems, it is difficult to assess whether effects will accumulate and give an estimate of the overall impact of the construction of wind farms on the hydrodynamics in the North Sea. Many effects of the construction of OWFs, such as changes in flow velocities and production of turbulence, will be near-field effects that act on a local scale. However, the local scale effects can propagate through the system and as such have a far-field effect, as illustrated by e.g. Cazenave *et al.* (2016) and De Dominicis *et al.* (2017).

Generally, the larger the number of offshore wind turbines the more tidal energy will be dissipated and hence the larger the impact on hydrodynamics. However:

- Impacts on tidal amplitude can have large spatial variations which are difficult to predict.
- A change in the location of the amphidromic point can result in large relative changes.
- The deeper the water, the larger the energy dissipation.
- Dissipation through bottom friction is lower in deeper areas, the relative impact of water depth is therefore expected to be even larger.

How hydrodynamic effects will accumulate may also depend on the location of the wind farm with the tide and wind acting on a short time scale and large scale circulation patterns acting on larger time scales.

Various studies show that effects may occur far away from the wind farms and that impacts of individual foundations can be magnified when propagated through the systems. Therefore, Deltares (2018) cannot rule out that the construction of large-scale wind farms may result in significant changes in tides and currents.

2.2.6 Wind Resource

Deltares (2018) presents a number of impacts on wind resource and behaviour at OWF sites. Unless otherwise stated the information set out in this Wind Resource section has come from the Deltares (2018) report. These all have an impact on wind availability both within the OWF and wider further reaching impacts on other OWFs in the area.

Momentum sink

OWFs harvest wind energy and thereby slow down the wind velocity at hub height (momentum sink) creating wakes on the leeward side. The wind behind individual turbines then increases again. However, it largely

[3] *An amphidromic point is a geographical location which has zero tidal amplitude for one harmonic constituent of the tide. The tidal range from that harmonic constituent increases with distance from this point.*

depends on the ability of the atmosphere to mix with higher levels not affected by the turbines to determine how quickly this occurs. Key points to consider include:

- Wakes will extend further at 10m height than at hub height (the wind speed recovers first at higher altitudes and then downward). At sea surface level wakes will extend even further.
- Wake effects occur downstream of a wind turbine or OWF. This makes the wind rose (distribution of wind direction and wind speed) and more specifically the prevailing wind direction key.
- At 10m height, the wake of a turbine will only become apparent at a certain distance behind the turbine (depending on the type of turbine and the wind speed). This is why at 10m height, wake effects are probably absent at the first few upstream rows of turbines in a wind farm.

Mixing

In general, operating wind turbines will transform stable wind profiles into less stable or neutral wind profiles. Neutral/unstable wind profiles will remain neutral/unstable. Offshore, the sea surface temperature (below) and the air temperature (above) determine the stability. Turbulent transfer of momentum from the higher speeds at higher levels (despite the extraction of momentum by the rotor) may lead to an increase in wind speed at the surface (Cui *et al*., 2015, Mittelmeier *et al*., 2017 and Remco Verzijlbergh, personal communication as referenced in Deltares, 2018).

Blockage effect

Wind turbines form obstacles with wind having to pass around them. This slows down wind in front of turbines and speeds it up along the sides. For a single wind turbine, this effect would manifest itself as a ring with increased velocity just outside the rotor swept area disk. At the first row(s) of wind turbines this effect will not be noticed at sea surface level, but the effect of the obstacle (the foundation or other structure supporting the wind turbine) will be noticeable, since the effect propagates downward (and upward). This effect will most likely be gone before the flow reaches the next turbine (at a distance of typically 7 times the diameter of the turbine rotor). Including the effect of the turning rotor blades on the flow makes the situation a lot more complicated. For wind farms as a whole, or clusters of multiple wind farms, blockage effects can also play an important role in changing wind speed .

Far field effects

As the size of OWFs increases, several turbines will start to interact with each other within the OWF. Turbulent wakes reduce efficiency of downstream turbines which is considered in OWF design. At the same time blockage becomes relatively more important affecting the design of OWFs relative to each other. Momentum sink/extraction becomes more important as the wind farm and turbine size increases leading to decreasing wind speeds downstream of the OWF at sea surface level. Differences between upwind and downwind turbines become noticeable if energy can’t be replaced between turbines.

2.2.7 Stratification and water mixing

When water flows along foundations this leads to an increased mixing of the water column and a decrease of stratification, enhancing the vertical transport of water. In a study by Carpenter *et al.* (2016) the wind turbines near the tidal mixing front changed the hydrodynamics sufficiently to decrease stratification by 5–15%. Using an idealised modelling approach Carpenter *et al.* (2016) showed, that widespread construction of wind farms could impact the large-scale stratification. For present wind farms with a spatial scale of 10 km^2, the effect is limited, but it could become very significant when the farms are scaled up to ~100 km^2.

Floeter *et al.* (2017) found that within a wind farm the stratification index was markedly lower than outside with the effect on stratification appearing to extend around 15 km beyond the wind farm in the direction of the current. These features could confidently be assigned to the presence of the OWFs present.

Such effects are expected to occur in areas that are intermittently or seasonally stratified, so mostly during the summer season (roughly from March to September). Areas that are permanently stratified are likely not easily mixed due to the strong stratification present. The assessment is that wind farms do not create enough turbulent energy to remove stratification in such areas.

2.2.8 Knowledge gaps

The information provided above on impacts from offshore wind development on physical processes also identifies a number of knowledge gaps or recommendations. For clarity these have been pulled out and are summarised below[4]:

- Much of the research on physical processes has been undertaken for singular OWFs and not on a large scale. This requires caution when interpreting the information presented in the current state of knowledge and further wider scale modelling and interpretation of effects is required (Deltares 2018).
- Whilst the North Sea is one of most researched seas in the world and there is a good understanding of the North Sea system and the hydrodynamic processes that determine the tides and currents, there are several topics that require further research. These include the coupling of the hydrodynamics with water quality and ecosystems, the momentum exchange between atmosphere and ocean that is determined by the influence of waves on surface roughness, the exchange and transport between the shelf and oceanic water, and the production of turbulence and influence on the bottom drag. Nevertheless, the current state-of-the-art methodologies and knowledge are sufficient to investigate the hydrodynamic effects of large-scale development of wind farms in the North Sea. In principle all instruments needed to carry out an in-depth study are available.
- Deltares (2018) identified a knowledge gap relating to the highly debated impact of the large-scale development of (offshore) wind farms reaching the limits of the amount of kinetic energy transferred from higher atmospheric layers to the wind farm level. There are large uncertainties on the rate and mechanisms of vertical transport of kinetic energy, and current knowledge levels and modelling tools fall short on properly quantifying this vertical transfer. However, considering that there is a risk of the large-scale wind power plans for the North Sea approaching this (highly debated) limit, and the possible regional knock-on effects on ecosystem functioning, it is a subject that merits further and more detailed measurements and modelling development (Dupont *et al*., 2018).

3 Ornithology and Bats[5]

Displacement is the loss (or reduced usage) of the wind farm area for purposes of feeding, roosting etc.

Barrier effect is when birds that would previously have transited through the wind farm (e.g. when commuting between nesting colony and feeding areas) take a flight route that circumvents the wind farm.

Avoidance encompasses avoidance of turbine rotors and avoidance of the windfarm

[4] Comments received on this document identified further knowledge gaps including the impact of rock protection or turbines on the form and functioning of sandbanks. Natural England included a recommendation to look at findings in Pidduck et al. (2017).
[5] Comments received on this document identified further papers that could be included in future updates including, Allen et al. (2020).

3.1 Construction

3.1.1 Disturbance due to Human Activities

Mendel *et al.* (2019) investigated the impacts of OWF construction and vessel traffic on loon (Gavia spp.) distributions in the North Sea. They used a vessel model and found that vessel traffic had significant negative impacts on loons. This is the first proof of extensive effects of OWFs and vessel on a large spatial scale.

Whilst not specifically related to OWF development Miller *et al.* (2019) has been included in this literature review as the findings may be of use in future impact assessments for OWF. Miller *et al.* (2019) used Bayesian state-space models fitted to time-series from three sympatric seabird populations (northern gannet *Morus bassanus L*., black-legged kittiwake *Rissa tridactyla L*. and common guillemot *Uria aalge Pontoppidan*) with varying life histories.

Miller *et al*. ran a realistic Population Viability Model for various scenarios of anthropogenic mortality both proportionally and as a fixed quota using Potential Biological Removal. The model proved an effective tool in determining the environmental factors that regulate population growth and a realistic tool to determine the impacts of anthropogenic activities on a population considering the influence of natural factors. The paper highlighted the need to consider the risk of over-precaution (economic constraint) and under precaution (endangering populations) when natural environmental regulation is not considered during population modelling for impact assessment.

3.1.2 Attraction by light

Artificial light sources are used during the construction phase of OWFs when working outside of daylight hours (Rebke *et al.,* 2019). These light sources can attract nocturnally foraging seabirds. Additionally, a systematic investigation of the literature revealed that specific weather conditions such as; heavy clouds, fog and drizzle are responsible for concentrations of birds around artificial lights. Anecdotal evidence of bird attraction to light was found though a knowledge gap was identified for a long-term study investigating the effect of different light characteristics in combination with environmental factors potentially influencing behaviour of migrating birds.

To address this knowledge gap, Rebke *et al*. (2019) conducted a spotlight experiment on a North Sea island. Birds were exposed to combinations of light colour (red, yellow, green, blue, white), intensity (half, full) and blinking mode (intermittent, continuous) while measuring numbers of birds at each light source. They determined that no light variant was constantly avoided. Intensity did not influence the number of birds attracted, however, birds were drawn more towards continuous than towards blinking illumination, when stars were not visible. Continuous green, blue and white light attracted significantly more birds than continuous red light in overcast situations.

3.1.3 Displacement / barrier effect

As reported in Koppel and Schuster (2015), Baarsch *et al.* (2015) investigated the bird community at the German OWF BARD Offshore 1 which is located c. 80 km north of Borkum. They specifically looked at two offshore bird species: common guillemot (*Uria aalge*) and northern fulmar (*Fulmarus glacialis*). Both species show a distinct seasonal distribution pattern with highest densities during summer, which coincides with synchronized post-breeding dispersal of juvenile guillemots. The results show that densities of guillemots and northern fulmars decreased in the OWF area during construction when compared to the reference area. The highest bird densities were observed in the reference area during and post construction. This indicates local avoidance behaviour of both species resulting in small scale displacement from the (construction) site of the offshore wind farm “BARD Offshore 1”.

A 10 year study looking at the effects of all phases of the Robin Rigg OWF on common guillemot was undertaken by Vallejo *et al.,* (2017)[6]. Only guillemots recorded 'on sea' were included in the analysis, and birds 'in flight' were excluded from the analysis because it was not known if birds 'in flight' were passing through the study area or actively using the habitat. The study found relative abundance of common guillemot to be similar across pre-construction, construction and operation phases (Vallejo *et al.,* 2017).

Searle *et al.* (2018) developed a tool to estimate the cost of displacement and barrier effects to seabirds in terms of changes in adult survival and productivity. The tool, called "SeabORD" runs within MATLAB Runtime and was developed during the chick-rearing period for common guillemot, razorbill, Atlantic puffin, and black-legged kittiwake in the Forth and Tay region in south east Scotland. The model allows spatial survey data from OWF sites to be translated into demographic consequences at population level and provides integration of information on the turnover of individuals using the area with the fate of individual birds. The model was tested for three different sized fictional OWFs at varying distances from breeding colonies for all SPA colonies in Forth and Tay region (Buchan Ness, Fowlsheugh, Forth Islands, St Abbs Head). Tests were also run for cumulative effects.

Results in Searle *et al.* (2018) showed that the magnitude of effects resulting from OWFs depended on the size and shape of the site, proximity to SPA colonies and the species in question, which is in accordance with theory and past work. For any particular OWF scenario, SPA and species, the impacts on displacement and barrier effects on productivity and adult survival varied with assumed prey levels. Therefore, Searle *et al.* (2018) recommended:

1. Those using the model for impact assessment identify the range of prey levels that constitute moderate conditions.as determined from empirical data on adult body condition at the end of the season; and
2. A series of matched pairs of model runs at different prey levels within that range are undertaken to obtain the estimated range of potential effects under moderate conditions.

The 'test' run of the model for black legged kittiwake displayed that different breeding colonies responded differently to the construction of single or multiple OWFs. Importance of cumulative effects varied between different SPA colonies, with birds from the Forth Islands experiencing a greater effect during construction of multiple developments, whereas birds from St Abbs head experienced similar effects during construction of both one and three OWF developments. For the birds from the Forth Islands, the majority of birds suffered from both barrier and displacement effects or barrier effects only. Adult mortality was largest when birds were affected by both displacement and barrier effects. It was thought that barrier effects caused the greatest increase in mortality as the birds experiencing barrier effects exclusively were also affected much more than those that were only displaced.

3.2 Operation and maintenance

3.2.1 Collision risk birds

Bowgen and Cook (2018) analysed data collected on seabird collision and avoidance rates at an operational wind farm (referenced as the Bird Collision Avoidance (BCA) study). The study revealed that data regarding empirical avoidance rates may not be directly comparable to the avoidance rates that are currently used in collision risk models (e.g. the Band model). Bowgen and Cook (2018) aimed to consider how best to use the data from the BCA study in order to inform pre-construction assessments of collision risk at OWFs. They deduced that suitable empirical avoidance rates for use in the deterministic Band Collision Risk Models

[6] *It is noted that the impacts from Vallejo et al. (2017) cover all phases of offshore wind development, however this article fits best within construction and therefore is mentioned above to avoid unnecessary repetition.*

were; 0.995 for large gulls and gannets and 0.990 for black-legged kittiwakes for option 1 of the Band model and 0.993 for large gulls and 0.980 for black-legged kittiwake in relation to option 3 of the Band model.

Bowgen and Cook (2018) also noted that assumptions made in relation to the Band model and the data used in the model can have a significant effect on predicted collision rates particular in relation to flight height and speed. A concern is noted in relation to speed as this is used twice in the model and reported flight speeds are significantly lower than those typically used in existing guidance for the band model.

Vallejo *et al.,* (2017) reported that displacement of guillemot across Robin Rigg offshore wind farm was very low. Whilst relative guillemot abundance changes were detected in some areas, the number of guillemot per segment of the OWF remained comparable through each phase of development. In addition to this, very few guillemots were recorded flying through the footprint of the OWF throughout operational monitoring, with the majority of these birds (c.98%) flying below the rotor-swept area. Thus, potential collision risk is very low (Walls, Pendlebury, *et al*., 2013). Vallejo *et al.,* (2017) note that information between OWF is variable and therefore further evidence regarding the magnitude of effect is needed.

Seasonal differences

Wind farms are constructed in areas with high wind yield which also happen to be important corridors for migratory birds (Schuster *et al.* 2015). Bird migration takes place year round, with peaks during spring and autumn. However, mass migration events take place on only a few occasions and seem to be mostly at night (Schuster *et al.* 2015, Hill *et al*. 2014). Hill *et al*. (2014) confirmed high rates of bird calls predominantly after midnight, especially during spring and autumn migration. Thus, effects of offshore wind on birds can also vary throughout the year and depend on the season (Schuster *et al.* 2015).

In recent years, there have been several studies invested in creating enhanced models to estimate collision rates. Results have shown that species that were previously thought to be at high risk, such as large gull species and gannets, display meso- and micro- avoidance behaviours that significantly reduce their risk of collision rates (Fox and Peterson, 2019). An example of this is demonstrated by Furness *et al*. (2018) who used data from tracking studies to derive evidence-based correction factors for nocturnal flight activity of adult gannets during the breeding and nonbreeding seasons, and of immature gannets during the summer prospecting phase.

Various studies of breeding gannets in multiple years and locations demonstrate that immature and mature gannets show minimal levels of flight and diving activity at night, including during astronomical and nautical twilight during both the breeding and nonbreeding seasons. Based on a systematic review of the literature, Furness *et al*. (2018) recommends that precautionary values of the nocturnal flight activity for estimating collision risk should be 8% of daytime flight activity during the breeding season and 3% of daytime flight activity during the nonbreeding season. In Furness *et al*. (2018) it is proposed that using these correction factors will be beneficial in reducing the uncertainty of collision risk models.

Flight height and foraging behaviour

Several new studies published after 2014 investigate the flight altitude of different bird species in relation to offshore wind. Flight height greatly influences the collision risk. Studies on bird flight height have been limited to boat surveys and/or radar observations. New technological developments, however, have made it possible to retrieve this information using GPS. GPS can provide more detailed information of the flight path of individual birds over a larger area. The flight altitude of birds can differ depending on the time of day, location and weather conditions. Birds migrating over the sea are more likely to collide with turbines in poor weather, when individuals are more likely to fly at altitudes swept by turbine blades and visibility is reduced (Shamoun-Baranes *et al*. 2017).

According to a multiyear study using vertically rotating marine radar the highest bird flight activity appears to be below 200m over all seasons (Schuster *et al*. (2015); Hill *et al*. (2014)).

Results from Zydelis *et al*. (2015) in Koppel and Schuster (2015) indicate that flight altitudes of common cranes at sea can range from a few meters to more than a 1,000m (at the initiation of the crossing after which they descend whilst travelling over water). During headwind and tailwinds of >10m/s and poor visibility cranes fly lower while during sunny and calm tailwind conditions common cranes fly higher. About 80% of migrating cranes fly at potential rotor height of offshore wind farms in the middle of the Arkona Basin.

Ross-Smith *et al*. (2016) determined flight height of lesser black-backed gull and great skua using GPS. To accommodate for GPS error they developed an analytical solution using Bayesian State-space models to describe flight height distribution throughout the season. Lesser black-backed gulls flew lower by night than by day, indicating that this species would be less likely to encounter turbine blades at night, when birds' ability to detect and avoid them might be reduced. Gulls flew highest over land (22- 1ms above ground) and lowest near the coast (6-7 meter above ground level). The flight height offshore was between 12-8 meter above sea level 50% of the time (Ross-Smith *et al*., 2016) For great skuas, no significant relationship was found between flight height, time of day and location. Ross-Smith *et al*. (2016) concluded that lesser black-backed gulls are at greater risk of collision than great skuas especially during the day.

In earlier studies Thaxter *et al*. (2015) and Wade *et al*. (2014) studied the movements of lesser-black backed gulls and greater skua to better understand the interaction between OWF Areas (OWFAs) and breeding areas for these two species. Thaxter *et al*. (2015) studied the movements of 25 lesser black-backed gulls from the Alde–Ore Special Protection Area (SPA), UK between 2010 and 2012, using telemetry. The results show that behaviour of this species can be highly variable within seasons and between years, as well as between individuals and sexes (Thaxter *et al*. 2015). During the breeding season, the gulls foraged in marine habitats close to the colony. The amount of time spent at sea was shorter when incubation commenced and increased again during the early chick-rearing period. During the chick rearing period the birds also used the OWFAs. There was a lot of individual variation. It also seemed that later in the breeding season males used OWFAs significantly more than females. In 2014 Ross-Smith *et al*. (2016) tagged a further 25 gulls at Skokholm Island in Pembrokeshire and Skomer (SPA) and 25 at South Walney in Cumbria (part of Morecambe Bay SPA). Birds breeding at Skokholm spent most time out at sea and made the longest foraging trips. At South Walney 13 of 25 birds showed spatial overlap with the proposed OWFAs. These birds spent a great proportion of time in the OWFA although primarily commuting rather than foraging there.

Wade *et al*. (2014) used GPS tracking devices to study movements of Great skua breeding in Scotland in relation to marine renewable energy developments including offshore wind in Scotland. The results show that the overlap of great skuas with leased and proposed offshore wind sites was low. Failed breeders overlapped with larger areas of offshore wind developments than breeding birds but the overall overlap with core areas used remained low. Wade *et al*. (2014) compared results with historical data from 2011 which indicates that distances travelled by great skuas have likely increased over recent decades.

Grecian *et al*. (2018) compared foraging behaviour of immature and adult gannets using GPS loggers. Immature gannets spent more time at sea (average 43 hours per foraging trip) than adult gannets (average 24 hours per foraging trip). Immature gannets also had a wider foraging distribution when compared to adult gannets. Adults show a stronger response to frontal activity (where two water masses meet) than immature birds and are more likely to commence foraging behaviour as frontal intensity increases.

Cleasby (2015) used data from GPS-loggers and barometric pressure loggers to track three-dimensional movements of northern gannets rearing chicks at a large colony in south-east Scotland (Bass Rock), located <50km from several major wind farm developments with recent planning consent. The results showed that the gannets foraged in and around planned OWFAs (Cleasby 2015). The probability of flying at collision-risk height was low during commuting between colonies and foraging areas (median height 12m) but was greater during periods of active foraging (median height 27 m), Cleasby (2015) estimated that ~1,500 breeding adults from Bass Rock could be killed annually by collision with wind turbines at two planned sites in the Firth of Forth region.

3.2.2 Collision risk bats

As set out in Degraer *et al.* (2018), several bat species are known to migrate long distances between summer and winter roosts. During this migration, a part of the population crosses the North Sea. The development of OWFs in the North Sea could therefore be a risk for migrating bats. The activity of bats at sea at turbine rotor height is unknown. Brabant *et al.* as reported in Degraer *et al.* (2018) attached eight acoustic bat detectors to four turbines in the BPNS. Four were installed on the platform of the transition piece (17m above mean sea level (AMSL) and four were installed on the nacelle of the turbines in the centre of the rotor swept area (94 m AMSL). A total of 98 recordings of bats was made by all eight Batcorders during 19 different nights during the entire study period (from the end of August 2017 until the end of November 2017). The detections at nacelle height were around 10% of the detections made at low altitude. The observations made by the detectors at nacelle height give an indication of the activity of bats at that altitude, but do not allow to make sound conclusions about the collision risk for bats, especially not in the lower part of the rotor swept zone.

Langeveld *et al*. (2015) as reported in Koppel and Schuster (2015), conducted bat surveys in 2012, 2013, and 2014 to assess the presence of bats over the North Sea. Bat activity was monitored at three locations: the meteorological mast at the Offshore Wind Farm Egmond aan Zee (OWEZ), a wind turbine at the Princess Amalia Wind Farm (PAWP), and the IJmuiden meteorological mast, respectively 15, 23, and 75km from shore. The results from Langeveld *et al*. (2015) recorded bat activity at all four monitoring stations, suggesting that bats are regularly found offshore especially during migration season.

Most bat activity was observed during late August and throughout September. The number of bats detected during spring was low. Outside of the migration season (in July) only one bat was detected at OWEZ. According to Langeveld *et al*. (2015) bat activity is strongly associated with the weather conditions; virtually all bats were only recorded during nights with low or moderate wind speeds, no precipitation, and a high ambient pressure. Four different bat species were identified of which the Nathusius' pipistrelle (*Pipistrellus nathusii*) was the most commonly recorded species. Noctules (*Nyctalus noctula*) and Particoloured Bats (*Vespertilio murinus*) were recorded occasionally and the Common Pipistrelle *(Pipistrellus pipistrellus)* was recorded only once. According to the pattern of occurrence it is most likely that the Nathusius' pipistrelle were migrating animals. The Nyctaloid species were either migrating or they were residents from the mainland which use the wind farms as foraging areas. There were no observations of roosting individuals.

Building on this research, exploratory research into the occurrence of bats at the Dutch North Sea as reported in Lagerveld *et al., (*2017a) has shown that there is regular seasonal migration over sea of at least nathusius' pipistrelle *Pipistrellus nathusii* but perhaps also of parti-coloured bat *Vespertilio murinus* and common Noctule *Nyctalus noctule*.

Lagerveld *et al.,* (2017a) reported on behaviour and collision risk of bats to estimate the migratory population of nathusius' pipistrelle over the southern North Sea and the size of its source population. As the data was highly fragmented and incomplete, involving high uncertainty levels it has been used as a first step towards an estimate of the number of individuals migrating over the southern North Sea. Lagerveld *et al.* (2017d) estimated that the relevant summer population consists of approximately 275,000 individuals of which 40,000 individuals may migrate over the southern North Sea to the UK from mainland Europe, in autumn..

A secondary study investigated how bat behaviour can be studied near offshore wind turbines. A stereoscopic setup consisting of two thermal cameras was devised and used to collect footage of bats in August and September 2016 (Lagerveld *et al.,* 2017c),. The cameras were positioned in such a way that the overlapping field of view in both cameras could be used to determine 3D bat paths at distances of 80m around a single wind turbine. In addition, acoustic bat activity was measured with a 12 channel bat detector at 3 different heights with microphones in each wind direction. This allowed for bat flight trajectories to be measured in 3D and to study the effects of wind turbines on bat mortality and bat flight behaviour.

Lagerveld *et al.* (2017b) found that the used stereo configuration and analysis methods are promising but need further improvement so that reliable 3D paths can be derived automatically. The next step is to build a prototype with multiple stereo cameras (which can cover the entire rotor swept area) on land and prove the feasibility for a configuration on sea which can be used for birds as well.

In 2016 a bat monitoring campaign was conducted at OWF Gemini, windfarm Buitengaats and Wageningen Marine Research executed a bat monitoring program at Wintershall platform P6-A and offshore research station FINO3 in the same year (Lagerveld *et al.,* 2017c). Lagerveld *et al.,* (2017c) reported that the occurrence of bats at sea is highly seasonal which indicates that individuals recorded at sea are on migration. The peak period runs from late August until the end of September. After that it levels off throughout October. Spring migration is much less pronounced but the duration seems to be quite extensive; from late March until the end of June.

Lagerveld *et al.,* (2017c) found that factors that impact bat presence at the coast and at sea include higher temperatures seeing higher abundances as well as changes in abundance related to wind direction. In addition to this moonlight and rain also impact abundance.

Lagerveld *et al.* (2017c) recommends continuing monitoring offshore to increase the number of observations in the dataset. The model can furthermore be improved by monitoring in a denser grid to reveal spatial patterns and include information on the availability of insects. Telemetry can be successfully applied to study migratory movements of bats over land and over sea and individual bat behaviour near and in offshore windfarms (Lagerveld *et al*., 2017d).

The study reported on in Limpens *et al.* (2017) aims to develop a prototype estimator for migrating populations of bats. This is based on data, or estimates, regarding the size and bandwidth of source populations, population dynamical factors defining such populations, and factors defining migration fluxes. Acknowledging the rareness of such data, a flow model is constructed targeting a preliminary estimate for the southern North Sea. The model produced a preliminary estimate for bats crossing the southern North Sea of roughly 40,000 individuals with a bandwidth between 100 and 1,000,000 individuals. The accuracy of this outcome can (and must) be improved through assessment of (more accurate) data and/or estimates per country/region to improve the different factor components per country, to define the now generic factor components as components per county and to incorporate mortality during migration.

3.2.3 Avoidance and Attraction

Avoidance

Avoidance of OWFs by birds can occur at three scales, which were defined by Cook *et al.* (2014) and further updated by Skov *et al*. (2018). Overall avoidance rates are a combination of the different types of avoidance recorded. The types of avoidance are:

- Macro-avoidance – total avoidance of the wind farm footprint and in some cases a buffer of upto 3km.
- Meso-avoidance – any responses to turbines within the windfarm site e.g. flying between rows or within a specific buffer around the rotor swept zone
- Micro-avoidance – 'last-minute' action to avoid collision with blades within a defined buffer.

Micro-avoidance

In 2010, a purpose-built fixed pencil-beam radar (BirdScan) was installed on the research platform FINO1 near the Alpha Ventus OWF in the German North Sea (Coppack *et al*. (2015) in Koppel and Schuster 2015). BirdScan automatically detected birds in elevations of up to 3,400m and enabled the calculation of migration rates for different species groups based on specific wing-beat patterns. Migration rates were measured over seven successive migration seasons within the wind farm and were compared with values from an adjacent reference area outside the wind farm.

In five of seven seasons, significantly higher migration rates were detected inside the wind farm within the lowest 200 meters. In autumn 2012, significantly higher migration rates were found outside the wind farm, where as in autumn 2013, no differences were seen. The majority of detected signals were classified as night-migrating songbirds. In addition to BirdScan, an infra-red sensitive camera system (Visual Automatic Recording System (VARS)) was deployed on the nacelle of a wind turbine to quantify the number of birds passing through the rotor swept zone. Around 82% of all observed flights through the rotor-swept area occurred at night. Lower numbers of birds were detected within the rotor-swept area when the turbine was running, indicating significant micro-avoidance (avoidance of the rotor-swept area). The ratio of events determined with VARS and migration rates measured with BirdScan at relevant elevations yielded nocturnal micro-avoidance rates that ranged from 95.62% to 98.03%. The micro avoidance rate decreased to 40.73% when the turbine was inactive.

Hill *et al*. (2014) in Schuster *et al*. (2015) investigated bird distribution at the German Alpha Ventus OWF during nights and found that migration intensity can be considerably higher inside than outside the wind farm. However, bird distribution varied at night possibly due to wind conditions/visibility or the operational status of the OWF. No birds were recorded within the rotor swept zone of the wind turbine AV 4. Nevertheless, migration intensity was higher inside compared to outside the OWF. Hill *et al*. (2014) hypothesized that this possibly indicated micro-avoidance of the turbine connected to the blade movement. However, since only one turbine was investigated, collision events at other turbines could not be ruled out due to turbine specific collision risk Higher flight altitudes at night were also reported by. This suggests avoidance can be assumed to be higher at nights.

Thaxter *et al.* (2018) used GPS telemetry to collect fine-scale movements of lesser black-backed gulls *Larus fuscus* from a breeding colony around nearby OWFs. Use of the areas within OWFs varied among the birds studied, with 15 of 24 birds visiting the OWFs equating to 1.3% of the time budget across all birds. Two birds frequently visited OWF sites and although flights were recorded at turbine blade height, overlap with the spherical 3-dimensional rotor swept volume was significantly lower than random distribution. These preliminary results suggest no macro-scale avoidance for *L. fuscus.* However meso-scale avoidance was stipulated.

Attraction

As reported in Degaer *et al.* (2017), there is currently little information available on the behaviour of large gulls inside OWF areas, and it remains unclear whether these birds visit the wind farms because of enhanced foraging conditions or simply for roosting. As reported in Degraer *et al*. 2017, a study was undertaken at the Thornton Bank OWF to report on the attraction of large gulls to OWFs. At the Thornton Bank OWF, roosting possibilities are particularly numerous as 48 out of 54 turbines are built on jacket foundations which offer easy access to the intertidal fouling communities during low tide.

In order to unravel part of the remaining knowledge gaps, as reported in Degraer *et al.* (2017), Vanermen *et al.* studied the occurrence and behaviour of large gull species in the Thornton Bank wind farm area using (i) the results of dedicated ship-based seabird counts, (ii) GPS tracking data and (iii) observational data through a fixed camera installed on one of the turbines.

While the limited number of data collected up to date does not allow any definite conclusions to be drawn, first results indicate that the time spent resting was higher inside the OWF when compared to outside the OWF. Based on transect count data, almost 80% of the great black-backed gulls observed inside the OWF were associated with the turbine foundations. Tracking data of lesser black-backed gulls showed that birds entering the OWF spend about 50% of their time roosting on the jacket foundations.

Turbine foundations were mainly used for roosting, but during a short time period around low tide, small numbers of birds were observed foraging on mussels growing on the lower reaches of the foundations. In total, 9% of the large gulls observed on the jacket foundations within viewing range of the fixed camera were actively foraging. Herring gull in particular seemed to favour this temporary but daily available food source.

The findings reported by Vanermen *et al*. raised concerns on the number of expected collision victims. When considering the upcoming large scale exploitation of offshore wind in the North Sea, collision mortality might even affect these species on a population level (Brabant *et al.* 2015).

As reported in Degraer *et al.* (2018), Vanermen *et al.* undertook analysis of GPS data of lesser black-backed gulls (*Larus fuscus*) caught and tagged in colonies at Ostend and Zeebrugge. After exploring general patterns in at-sea presence and behaviour, Vanermen *et al.* performed three modelling exercises to study the response of lesser black-backed gulls towards the C-Power turbines at the Thornton Bank OWF in more detail. These exercises confirmed that much more time was spent roosting on outer than on inner turbines.

It was also found that there was a significant and gradual increase in the number of logs of flying birds going from the centre of the OWF up to 2,000m from the OWF edge, beyond which the response seemed to stabilise. For non-flying birds, the model also predicted a minimum number of logs in the centre of the OWF again stabilising at about 2,000m, yet with a highly increased presence right at the wind farm's edge, representing birds roosting on the outer turbine foundations.

The final model used by Vanermen *et al.*, aimed to assess temporal variation in the presence of lesser black-backed gulls in and around the Thornton Bank OWF. This showed that the birds were increasingly wary of entering the wind farm during times of strong winds with fast moving rotor blades. The results of this study illustrate that the response of lesser black-backed gulls towards OWFs can be subject to both temporal and (within-OWF) spatial variation. This can be of high value in refining collision risk modelling.

As reported in Degraer *et al.* (2017), the Thornton Bank OWF attracted great black-backed gulls, this species having increased in numbers by a factor 6.6. Sandwich tern too appeared to be attracted to the OWF, this effect being significant for the buffer zone[7] only. Again, these results are highly similar to the results in Vanermen *et al*. 2016. For herring gull there was a shift in the estimated wind farm effect. While the OWF coefficient for herring gull was estimated to be close to zero after three years of monitoring, it now showed a borderline significant increase in numbers by a factor 2.9. A significant decrease in numbers of herring gull was observed in the buffer zone. Great black-backed gulls further seemed to prefer the outer turbines, suggesting a partial barrier effect.

It is important to note that those species not avoiding wind farms are confronted with the risk of colliding with turbines, which may affect populations, in particular gulls (Dierschke *et al.* 2016, Leopold *et al*., 2014; Brabant *et al*., 2015).

Birds that migrate nocturnally, such as songbirds and waders, seem to be attracted to illuminated structures. This has been observed for offshore gas production and research platforms, lighthouses, and offshore wind turbines (Schuster *et al* 2015, Aumüller *et al*. 2011; Hill *et al*. 2014; van de Laar 2007). This behaviour has also been observed in other types of birds. Welcker & Nehls 2016 observed that two gull species (lesser and great black-backed gull), were attracted to an OWF. The abundance of these two species was 79-100% higher inside the windfarm than in neighbouring areas.

As reported in Schuster *et al*. (2015) abundance of common gull (*Larus canus*) and herring gull (*Larus argentatus*) clusters were not affected by OWFs. Recent studies suggest that these two gull species are attracted to offshore wind farms (Petersen *et al*. 2006, Vanermen *et al*. 2013, 2015). As also set out above, it is possible that gulls benefit from foraging opportunities on hard substrate benthic species and fish species

[7] *A 3km area surrounding the offshore wind farm to define the "impact area", being the zone where effects of the wind farm on the presence of seabirds could be expected.*

known to increase substantially within OWFs (Lindeboom *et al*. 2011, Reubens *et al*. 2013, Stenberg *et al*. 2015).

Dierschke *et al*. 2016 found that several gull species and red-breasted merganser also showed weak attraction, while great cormorant and European shag showed strong attraction to OWFs. Responses in other species are low. Attraction of cormorants relates at least in part to their use of structures for roosting and for drying plumage, but increases in food availability at OWFs appears to be an important influence for several species.

Building on the above research Fox and Peterson (2019) reports that species such as the larger *Larus* gull species and cormorants are undoubtedly attracted to the superstructure of turbines, meteorological masts and transformer stations (Fox and Peterson, 2019). With regards to the behaviour of large gulls and cormorants inside OWFs, this paper reiterated that a study undertaken in the Thornton Bank OWF determined that 89% of roosting great cormorants were found to be roosting on the turbine foundations, with a clear preference for outer rather than inner turbines (Petersen *et al*. 2006 in Perrow, 2019a).

3.2.4 Displacement / barrier effect / habitat loss

As reported in Schuster *et al*. (2015) there is evidence across studies that auks, gannets and particularly divers are displaced by OWFs. However, estimated response distances that are observed vary between species and between studies. Avoidance distances vary from zero (no displacement) to 13km (Percival 2013, Petersen *et al*. 2014). It seems likely that discrepancies of this magnitude are, at least partly, due to differences in study designs and data analyses, as well as the confounding effect of spatiotemporal variation in seabird populations at sea. For example, Petersen *et al*. (2014) found lower abundance of divers post- versus pre-construction at the 'Horns Rev II' OWF and a displacement distance of 13km. The authors, however, concluded that a response distance of this magnitude was unrealistic and likely related to factors other than the OWF (Petersen *et al*. 2014).

There is considerable uncertainty on the response of tern species to OWFs. Webb *et al.* (2015) observed an estimated response distance of divers in the Lincs OWF of 2–6km avoidance and Petersen *et al*. (2014) found a similar response distance 5-6km in Hors Rev II. Whereas Pervial (2014) observed an estimated response distance for divers of 1km in the Kentish Flats OWF (however no statistical effect was found). Webb *et al*. (2015) observed an avoidance of gannets in the Lincs OWF. Vanermen *et al*. (2013) & (2015) observed an avoidance of gannets of 3km in Thornton Bank and Bligh Bank. Auks show 4km avoidance in Lincs (Webb *et al*. 2015) and 3km avoidance (significant negative effect for common guillemots and razorbills) in Bligh bank (Vanermen *et al*. 2015). Other birds specifically little gulls, herring gull, great black gull, kittiwake and terns show no response to the OWFs (Webb *et al*. 2015, Vanermen *et al* 2013 & 2015). However, in Bligh Bank great black gulls, little gulls and herring gulls did show attraction to the OWF (Vanermen *et al* 2015).

Dierschke *et al*. (2016) reviewed post-construction studies of seabirds at 20 OWFs in European waters to extract and classify evidence for displacement or attraction of 33 different species. Divers and northern gannets showed consistent and strong avoidance behaviour/displacement. This may also be the case for great crested grebe and northern fulmar. Longtailed duck, common scoter, Manx shearwater, razorbill, common guillemot, little gull and sandwich tern showed less consistent displacement by OWFs. Other species showed either weak or strong attraction or no response. Displacement seems to be mainly due to bird responses to OWF structures and appears stronger when turbines are rotating, though this could in part be due to boat traffic to and from OWFs.

Welcker & Nehls (2016) undertook an extensive survey program aimed at determining the effects on seabirds of the first German OWF, Alpha Ventus. Data was collected by line transect surveys during the first three years of operation. Significant displacement of five species was found. The densities inside the windfarm were 75−92% lower than outside the wind farm. For three species, the response distance to the outermost turbines was estimated to exceed 1km. There was also evidence of displacement of divers, gannets, little gulls, terns and auks from the wind farm. The abundance was, on average, 90% (divers), 79% (gannet), 92% (little gull), 76% (terns) and 75% (auks) lower inside compared to outside the wind farm. None of the species showed complete displacement; the proportion of birds displaced varied between 75 and 90%. The disturbance effect extended to a distance between approximately 1.5 and 2.5km beyond the outermost turbines of the wind farm.

As reported in Koppel and Schuster (2015), Perrow *et al*. confirmed avoidance behaviour of constructed and operational turbines by tracking seabirds. Prior to operation, 98.8% of tracks heading towards the OWF entered while only 65.8% of tracks entered the OWF during operation. Of the 49.4% of birds passing within 50m of a turbine base and thus falling within potential span of the rotors prior to construction, just 4.7% did so afterwards. The flight height distribution shifted downwards meaning that the proportion of birds at risk collision height declined by more than half. A model starting with passage rate derived from boat-based data and incorporating a number of steps measured from tracks, orientation of operational turbines relative to the main SW-NE flight axis from the colony and the industry standard collision risk model to estimate the probability of a tern colliding with a rotor, predicted that approximately 1 in every 10,000 passages would result in collision.

As reported in Degraer *et al.* (2017), after four years of post-impact monitoring at the Thornton Bank OWF, the impact area appeared to be avoided by four species: northern gannet, little gull, black-legged kittiwake and common guillemot. In the OWF footprint area, these species dropped in numbers by 97%, 89%, 75% and 69% respectively. These results are highly similar to those reported in the latest monitoring report (Vanermen *et al*. 2016). At the Bligh Bank, a significant decrease in numbers of northern gannet and common guillemot was also observed, while for the latter site, results for little gull and black-legged kittiwake remained inconclusive.

There is an additional energetic cost associated with OWF avoidance. In the case of migratory seabirds where wind farm avoidance may only occur twice a year, the impacts on their energetic costs may be trivial (e.g. in Masden *et al*. 2010). However, in the case of breeding birds commuting between offshore foraging grounds and a breeding colony several times a day this would result in energetic costs of avoidance which may be considerably greater (Fox and Peterson, 2019). Consequently, this could affect survival and reproductive success and have long-term impacts on overall population size. The degree of energetic cost is highest for species with high wing loadings such as cormorants, or species such as terns that commute frequently between offshore feeding grounds and their nesting colonies (Masden *et al*. 2010).

Responses can be variable, even within species, Fox and Peterson (2019) references findings from Lindeboom *et al*. (2011) who observed that in the Netherlands, red-throated divers were not detected between turbines at one site but were at another Dutch windfarm. Whilst Mendel *et al.* (2019) reported on before and after distributions of red-throated divers in the German Bight which suggest major displacement effects from newly constructed windfarms out to at least 16km and reductions in bird densities of more than 60% in an area within 10km of the turbines (Mendel *et al.* 2019).

3.2.5 Change in prey resource

As reported in Schuster *et al.* (2015), seabirds of different foraging guilds were found to feed inside offshore wind farms, though detailed reports about foraging mode and prey are still rare. Foraging around the foundations is reported for herring gull (May 2008), with lesser black-backed gulls reported to feed on the epifauna of foundations after potential prey organisms had settled there (Vanermen *et al*., 2013a, 2013c, 2015a). Diving for epibenthic prey e.g. by common eiders has not been detected but diving by great cormorants was observed (May, 2008).

Other species reported to fish inside OWFs are red throated divers and gannets – both exceptionally owing to their general avoidance of OWFs – and more often European shag, sandwich tern, little tern and common guillemot (e.g. Krijgsveld *et al*., 2010, 2011; Leopold and Camphuysen, 2008; Perrow *et al*., 2006; Petersen *et al*., 2006; Walls *et al*., 2008). Diving for bivalves was reported explicitly only for common scoters in Horns

Rev 1 and 2 (Petersen and Fox, 2007; Petersen *et al*., 2014), but this certainly also applies to common scoters and long-tailed ducks seen in other OWFs, especially in the Baltic Sea. An increase in numbers of observations of auks and northern gannets within an OWF following avoidance during the beginning of the operational phase was attributed to increasing fish stocks (Krijgsveld *et al*., 2011; Vanermen *et al*., 2011).

3.3 Cumulative Impacts ornithology

As reported in Koppel and Schuster (2015), serial development of OWFs are an important consideration in determining the potential cumulative effect of these developments on populations, but the extent to which both offshore and onshore wind farms occur along migration routes has received relatively little attention (Rees *et al*. 2015). Satellite-tracking of Whooper Swan and Barnacle Goose migration in relation to wind farm development therefore was undertaken in 2006–2010, and more recently Bewick's Swans fitted with GPS/GSM loggers were tracked in spring 2014, to determine the frequency of movement across offshore and onshore wind farm footprints during a single migratory flight. Each species followed different migration routes from the UK, to breeding grounds in Iceland, Svalbard and arctic Russia, respectively. The preliminary results from the study show that the migration routes of all three species of geese pass over many offshore and onshore wind farm sites and/or were within ≤5km from the flight-lines. Of the tracked Barnacle Geese, 19% of individuals passed across a wind farm footprint once, 9.5% twice, 5% on three occasions, 33% four times, 14% five times and 19% on six or more occasions. The results emphasise the importance of ensuring that the full range of wind farms encountered during the annual cycle are taken in to account on undertaking risk assessments for the development of wind farms along migration routes.

3.4 Mitigation

In some countries, standing still procedures are a permit requirement of OWF to reduce collision risk. Coppack *et al*. (2015) studied the nocturnal micro-avoidance rates at Alpha Ventus OWF. The results showed that during operation the nocturnal micro-avoidance rates ranged from 95.62% to 98.03%. However, when the turbine was standing still the micro-avoidance rate decreased to 40.73%.

Further to this Fox and Peterson (2019) noted that wind farms should not be constructed in areas where migrant birds of any kind are concentrated by coastal topography because the number of birds migrating from these areas will be high as they funnel out and disperse. Avoiding the construction of turbines in these areas will mitigate the risk of collision mortality

Shutdown of turbines during key migration periods, when birds are observed nearby or during weather conditions that increase collision risk is also likely to be highly effective in preventing collisions, as stationary turbines provide much less of a risk than rotating blades (Perrow *et al.,* 2019).

Other mitigation measures to reduce collision risk are for example fewer, larger, turbines which generate the same energy as a greater number of small and more densely packed turbines (Barrios and Rodriguez 2004; Johnston *et al*. 2014; Everaert 2014, Schamoun-Barnes *et al.* 2017, Perrow *et al.* 2019). Although larger turbines may be more dangerous for bats (Barclay *et al*. 2007). Schamoun-Barnes *et al*. (2017) suggest that "Micro-siting" can also be effective, whereby particular turbines that cause high levels of mortality are removed (de Lucas *et al*. 2012; May *et al*. 2015). Perrow *et al.* 2019 suggests this could also increase permeability of the site and thereby reduce barrier effects or collision risk.

Schamoun-Barnes *et al.* (2017) suggests that measures can also be taken to make the wind farm less attractive to animals, or more conspicuous in the case of enhancing avoidance. Such techniques include altering the paint colour, lighting regime, using lasers, electromagnetic fields and acoustic deterrents (Cook *et al*. 2011; Nicholls and Racey 2007). However, care must be taken that birds do not habituate to these measures, as has been noted in collision mitigation measures implemented on aerodromes (MacKinnon *et al*. 2004), and it is difficult to find an effective way to discourage all vulnerable species (May *et al*. 2015).

Further to this, painting one turbine blade black or all blades with a UV paint has been suggested to reduce the risk of collisions (May *et al*., 2017; Perrow *et al*., 2019b). However, results of studies using these methods have been varied as different species have different sensitivities to UV light (May, 2017). Furthermore, any painting is not likely to be effective if the bird is looking downwards whilst searching for roosting sites or food (Martin & Shaw, 2010)

Other mitigation measures that have been proposed include:

- The direct and indirect disturbance caused during the construction phase of OWFs may be mitigated by limiting the number and size of vessels and by careful planning of the timing, routes and frequency of vessel movements Perrow (2019b).
- The application of noise-mitigation methods during piling may help to minimise any indirect impacts on birds by reducing the effects on their fish prey. Methods used to reduce underwater noise using noise-mitigating systems include modifications of the piling hammer, impulse prolongation, and the use of hydro-sound dampers, bubble curtains, casings and cofferdams (Perrow, 2019b).
- Gulls are well known for being attracted to fishing vessels. By limiting fishing vessel activity within the OWFs or preventing waste being released from fishing vessels, attraction of gulls to OWFs can be reduced (Perrow, 2019b).
- To reduce the number of birds perching on structures within a windfarm site, ‘decoy’ structures can be placed some distance away from the site as well as anti-perching devices on the turbines themselves (Perrow, 2019b). This method has not been deployed at a windfarm site to date.

3.5 Knowledge gaps

The information provided above on impacts from offshore wind development on ornithological and bat receptors also identify a number of knowledge gaps or recommendations. For clarify these have been pulled out and summarised below:

3.5.1 Birds

- As reported in Degaer *et al.* (2017), there is currently little information available on the behaviour of large gulls inside OWF areas, and it remains unclear whether these birds visit the wind farms because of enhanced foraging conditions or simply for roosting.
- There is considerable uncertainty on the response of tern species to OWFs.
- As reported in Schuster *et al.* (2015), seabirds of different foraging guilds were found to feed inside OWFs, though detailed reports about foraging mode and prey are still rare.
- The OSPAR offshore region encompasses a large area where few or no studies relating to the environmental impacts of OWFs on birds have been undertaken. As is to be expected with the current locations where development of OWF has taken place the majority of the literature focusses on the North Sea with other areas under represented.
- There is accumulating evidence for widespread avoidance of offshore turbines by large-bodied birds at macro-, meso- and micro- scales, but knowledge of smaller birds is still less adequate (Fox and Petersen 2019).
- It is assumed that the cumulative impacts from multiple wind farm developments are greater than from individual developments, however, there are very few studies that aim to assess the impacts on seabird populations from multiple wind farm developments. Therefore, it is currently difficult to make conclusive decisions on the impacts of multiple developments, and cumulative assessments remain one of the greatest knowledge gaps with regards to OWF effects on bird populations (Fox and Peterson 2019).

- At present there is only one study regarding the displacement of terns post-construction and general conclusions cannot be drawn from one study Perrow (2019a).
- An important source of uncertainty is the quantification of displacement impacts and the lack of knowledge on the carrying capacity of seabird populations. It is hypothesised that in a population close to carrying capacity, habitat loss due to displacement could lead to birds being unable to find alternative foraging habitat that is not already fully occupied Perrow (2019a).
- There is a wide variation in the proportion of birds thought to be affected by barrier effects and displacement (Searle *et al.,* 2018).
- There is a huge variation between species among studies (Searle *et al.,* 2018)
- There is a lack of quantitative data on how birds navigate around OWFs to access foraging grounds and select new foraging locations (Searle *et al.,* 2018).
- Further investigation is required to verify the findings at Robin Rigg OWF, including further modelling of GPS altitude measurements to account for error sources, and separation of foraging and commuting flights (Thaxter *et al.,* 2018).
- A study by Skov *et al.* (2018) used bird collision risk models to estimate and quantify bird collisions at OWF's. However, there is uncertainty of the scale of collision impacts due to the limited studies that have gathered empirical evidence on bird collisions at OWF's. Therefore, there is a knowledge gap for monitoring studies at OWF's that gather actual evidence of seabird collisions which can be used to inform collision risk models.

3.5.2 Bats

- It is essential that offshore bat migrations and feeding behaviours are further investigated to adequately inform impact assessments in relation to bats and OWF developments (Schuster *et al*., 2015)
- Inventories across the entire European continent to access the summer population and territorial male roosts per country/region, and intensive survey of a sample of sites can be used to model larger geographical areas (Lagerveld *et al*., 2017a);
- Continue monitoring offshore to increase the number of bat observations in the data set. Models can be further improved by monitoring in a denser grid to reveal spatial patterns and include information on the availability of insects (Lagerveld *et al*., 2017c);
- Monitoring data from higher altitudes of bat migration are urgently needed (Lagerveld *et al*., 2017c);
- Need surveys from a wider range of countries for a more complete estimate of bat migrations, by population size and should be done in the form of per country/landscape of the southern North Sea (Limpens *et al*., 2017).
- Limpens *et al.* (2017) and Lagerveld *et al.,* (2017a) recommend further studies to understand the percentage of males, females and juveniles participating in migratory movements and migration directions and the role of guiding landscape features near the coast and offshore and occurrence, distribution and abundance of relevant species, their different roost types and the – average – numbers in such roost types.

4 Benthic Ecology

4.1 Construction[8]

4.1.1 Habitat Disturbance

Activities related to the construction of OWFs, in particular gravity-based foundations (GBFs), are mainly associated to dredging, causing direct effects to the macrofauna in the seabed. Coates *et al*. (2015) undertook a study on the sediment characteristics and macrofauna before and after construction (2005–2010) of six GBFs in an OWF in the BPNS. They distinguished natural from anthropogenic-related fluctuations in macrofaunal communities by analysing a long-term dataset (1980–2012).

The analysed sandbanks were characterised by sandy substrates and a community with low species abundance (180–812 ind m^{-2}) and diversity (6–15 species per 0.1 m^2). Strong temporal variations were observed possibly related to variable weather conditions in the area. Significant differences in community composition were observed due to the installation of six GBFs in the construction year of the OWF followed by a rapid recovery a year later, this was confirmed by the benthic ecosystem quality index BEQI. Even though the construction of GBFs creates a physical disturbance to the seabed, the macrobenthic community of these sediments have illustrated a fast recovery potential.

4.1.2 Increased Suspended Sediment Concentrations (SSC)

The literature provided did not include information on this potential impact of offshore wind development on this particular receptor. The increase of SSC has the potential to lead to smothering and scouring effects on benthic fauna. This may cause a change in species diversity, abundance and biomass.

4.1.3 Deterioration in water quality due to resuspended contaminated sediments

The literature provided did not include additional information on this potential impact of offshore wind development on this particular receptor.

4.1.4 Underwater Noise

As set out in Degraer *et al.* (2017), Hawkins and Popper (2016) demonstrated that the cumulative sound exposure level (SELcum) used in marine mammal assessments is not suitable for fish and invertebrates. They propose characterising the emitted sound using the sound exposure level of a single stroke (SELss) combined with total time of piling and the total number of strokes.

Roberts *et al*. (2015) specifically studied the sensitivity of mussels (*Mytilus edulis*) to anthropogenically generated noise. The sensitivity of the mussel to substrate-borne vibration was quantified by exposure to vibration under controlled conditions (Roberts et al, 2015). Sinusoidal excitation through signals with frequencies ranging from 5 to 410 Hz were applied. Clear behavioural responses were observed in response to the vibration stimulus, where valve closure was used as the behavioural indicator of reception and response.

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[8] *Comments received on this document identified further topics that could be included. Such as sandwave clearance for cable installation which involves large volumes of dredging, physical disturbance from cable installation, grapnel runs, boulder clearance, UXO clearance and cable installation.*

Whilst these topics were not covered in the papers identified for this literature review, it is recommended these topics are specifically looked at for inclusion in future updates.

The closure of valves can have costly consequences such as respiratory and heart rate disruption and impaired excretion ability. The responses recorded during this experiment showed that vibrations measured are likely to impact the overall fitness of both individuals and mussel beds, as it disrupts the natural valve periodicity, which may have ecosystem and commercial implications, eventually leading to population effects. The greatest sensitivity to vibration was measured at 10 Hz with a decrease in sensitivity at 210 Hz. Sensitivity to vibration decreased with the size, hence the weight of the mussel.

As the levels of vibration produced through man made operations vary depending on environmental parameters, the actual detection of vibrations will be scenario-specific. Impulsive signals such as pile driving and seismic surveys additionally produce water-borne particle motion and a sound pressure component, which were not included in this study.

Vibration sensitivity is important within the context of marine noise pollution due to the prevalence of activities contacting the seabed. By comparing sensitivities to field measurements, the data in this study demonstrate that *Mytilus edulis* is likely to detect such vibrations and is likely to exhibit behavioural changes at levels produced by operations.

4.2 Operation and maintenance

4.2.1 Habitat Loss

The literature provided did not include information on this potential impact of offshore wind development on this receptor.

4.2.2 Introduction of New Substrate/altered substrate[9]

Since 2005, the Institute for Agricultural and Fisheries Research (ILVO) has been performing beam trawl monitoring aimed at evaluating the potential effects of wind farms on the soft sediment epibenthos and fish in between turbines (as reported in Degraer *et al*. 2017 and 2018). The study effort is concentrated on the Thornton and Bligh Bank OWFs (54 turbines, 325 MW and 55 turbines, 165 MW respectively). It is worth noting that the observations from the studies and the conclusions drawn should also consider that all fishing activity is prohibited from the OWF area.

The following conclusions were drawn:

1) Soft sediment epibenthos and fish assemblages in between the turbines (at distance > 200 m) have not really changed 6 years after the construction of the wind turbines. The species originally inhabiting the sandy bottom are still in place and dominant. This is in line with other studies, e.g., Bergström *et al*. (2013) and Stenberg *et al*. An exception is plaice (*Pleuronectes platessa)* which has seen densities increase following construction, indicating an attraction effect due to increased food availability and/or fisheries exclusion. Overall fish assemblages did not change though in some species feeding habits changed from targeting only sandy bottom prey species to including species typically associated with hard substrates (Derweduwen *et al*. 2016b).
2) Species assemblages within the OWFs seem to be mainly structured by temporal variability at larger spatial scales such as yearly temperature fluctuations, hydrodynamic changes, or plankton blooms. For future analyses, it would be worthwhile to include environmental variables to gain a better insight in the observed patterns.
3) The post-construction "overshoot" of epibenthos density and biomass caused by an increase in opportunistic, scavenging species, was a temporary phenomenon lasting only 2 years post-

[9]Comments received on this document identified that Forster (2018) and its references provide information on the effects of Cable Installation, Protection, Mitigation and Habitat Recoverability.

construction. This shows that the previously observed wind farm effect (Vandendriessche *et al*. 2013; Derweduwen *et al*. 2016) was probably only a temporary phenomenon.

4) No effect of fisheries exclusion has been observed in soft sediment epibenthos and fish between turbines. Near the turbines, “refugium” effects have been observed for fish (Reubens *et al*. 2013; Stenberg *et al*. 2015), but in the current post construction phase of the wind farms, such a refugium effect has not been observed at greater distances from the turbines possibly excluding plaice as mentioned above. Up till now, no changes in macrobenthos related to fisheries exclusion have been observed (Reubens *et al*. 2016). As such, a related change in epibenthos and fish assemblage is also not to be expected yet.
5) Monitoring effort should be increased with a higher number of replicate samples per survey to increase the statistical power of the analyses.
6) Epifaunal communities appear to differ in composition between foundation types. For example, a 1m mussel zone (*Mytilus edulis*) has developed on gravity based foundations, while this zone is only 0.5m on monopiles and jacket foundations are fully covered with mussels. Consideration should be given to the different phases of succession of each site as the monopiles have only been operational since 2011 with the jackets being in place since 2013 (Degraer *et al*. 2016).
7) In 2017, respectively 6 and 7 years after construction Thornton Bank and Bligh Bank, no direct wind farm (‘reef’) effect, nor indirect fisheries exclusion effect, as yet observed for the soft-bottom epibenthos and demersal-benthopelagic fish assemblage in 2017. Species composition, species number, density and biomass (for epibenthos only) of the soft-bottom assemblage inside the OWFs were very similar compared to the assemblage in reference locations outside the OWFs. The species, originally inhabiting the soft sediments of both OWFs, remain to be dominant. Remarkable was that two epifaunal animals, i.e., *Mytilus edulis* and *Anthozoa sp*., known to be fouling on the foundations, were quite abundant in the C-Power OWF soft sediment samples, and totally absent or only present in much lower densities in the reference locations outside the OWF. This could indicate that the ‘reef’ effect is starting to expand beyond the direct vicinity of the turbines. However, detailed follow-up is needed to validate whether this is a one-off observation or a real wind farm effect reflected with time after construction possibly because of increasing epifaunal biomass on the foundations.

A study was undertaken to investigate the effect of turbine presence on macrobenthic community structure and if an effect was identified how this differs between different types of foundations. Samples were taken at two distances from the turbines: far (350-500m) and close (50m). The results of this study were reported in Lefaible *et al.* in Degraer *et al*. (2018) and indicate that the installation of offshore wind turbines can induce changes in the macrobenthos.

This is mainly seen at the Thornton Bank, where communities of the far sites differ significantly from the close sites. These community changes occurred independently of the abiotic environment (measured variables: grain size, total organic matter and sediment fractions above 2mm), for which no differences were detected linked to turbine presence. The community shifted from low species richness (5-7 species) and abundance (190- 402 ind. m^2) to high species richness (10-30 species) and abundance (1390-18583 ind./m^2). These changes were mainly observed in close vicinity of the turbines (less than 50m)

In contrast to the Thornton Bank, the Bligh Bank demonstrated a higher organic matter content further from the turbines although this did not result in differences between communities near and far from the turbines. This is in agreement with findings from Leonhard & Pedersen (2005) looking at a Danish wind farm with monopiles, where no differences were found in benthic communities between sites at different distances.

Sediment type and food supply are two of the main natural factors that structure macrobenthic communities. Grain size distribution can change in the immediate vicinity of an offshore wind turbine, inducing an important impact on the associated soft-sediment macrofauna, up to 50m distance from the turbines (Leonhard &

Pedersen 2005; Coates *et al*. 2014a). A significant refinement of the grain size close to (15-50m) a gravity based turbine on the Thornton Bank (Coates *et al*. 2014a) and a tendency to finer sand close to monopiles in a Danish OWF (5-25m) (Leonhard & Pedersen 2005) have been observed. In line with the study of Reubens *et al*. (2016), Degraer *et al.* (2017) did not observe such a refinement at 50m from the turbines. This suggests that such refinement effects remain highly local in the immediate proximity of turbines, and do not extend beyond a maximum of a few tens of meters, 50m being the limit of detection for changes in sediment granulometry.

No differences were observed for both the abiotic and the biotic variables between jacket and gravity based foundations. Alternatively, the effect of turbine presence and foundation type might manifest itself within close vicinity of the turbines (< 50m) and as such has not been identified through this study. Coates *et al*. (2014a) suggests this may be the case. To tackle this, it is recommended to perform a targeted monitoring study to investigate potential changes in sedimentology and organic enrichment in the close vicinity (7-100 m) of the three turbine types present in the BPNS (jacket, gravity bases and monopiles).

The results from Degraer *et al*. (2017) lead to a follow up study where the sampling strategy was adjusted by comparing far with very close locations (37.5m) from the foundation (Lafaible *et al.* in Degraer *et al.* 2018). The results confirm turbine-related effects at very close distances around jacket- based foundations at the Thornton Bank. Within very close samples, fining and enrichment of the sediment was detected together with higher macrofaunal densities, diversity and shifts in communities. In contrast, effects around monopile-based foundations at the Bligh Bank were less pronounced and a significant difference in community composition only was found between both distances. Degraer *et al*. (2018) suggest that these contrasting results might be due to a combination of site-specific dispersive capacities and structural differences between foundation types (jackets vs. monopiles) and their associated epifouling communities. Consequently, Degraer *et al*. (2018) recommend performing a targeted monitoring study comparing the three different turbine foundation types (monopiles, jackets and gravity-based foundations) used in the BPNS.

Research was undertaken to establish the differences between natural hard substrates (in this case gravel beds at the Westhinder sandbank) and artificial hard substrates (in this case monopile foundations and scour protection at an offshore wind farm on the Bligh Bank). This was reported on Kerckhof *et al.* (2012) in Degraer *et al.* (2017). Both habitats were found to harbour a rich species diversity and share a number of species. However, initial results show that natural hard substrata harbour a much higher number of species and also more unique species and that there are also some differences in life traits. Therefore, it seems that artificial hard substrata cannot act as alternatives to the loss of natural hard substrata. This confirms the findings in Bulleri & Chapman (2010).

Both natural hard substrata and the scour protection are situated in a very dynamic environment, influenced by the movements of strong sand waves that sometimes cover the stones completely. It is unclear why deposit feeders and predators/scavengers are more numerous on the natural hard substrata than on the artificial hard substrates.

Two limitations of the study were found. The first being a lack of data gathered from large stones and boulders which will likely further increase the species diversity for the natural hard substrates with the second being the short amount of time (two years) that the scour protection has been available for colonisation (Degraer *et al*. 2017).

Species diversity, biomass and abundance

Jak and Glorius (2017) conducted a literature review of OWF monitoring programmes focussing on the hard and soft substrate benthic fauna in the European Economic Zone (EEZ). OWFs with more than five wind turbines were prioritised for analysis since changes in benthic species compositions of this kind are more likely than in smaller wind farms that are likely to be operational for less time. Results were categorised by infauna, epifauna and hard substrate for each study. The following conclusions were drawn:

1) A general pattern of rapid colonisation of fouling communities was found, with studies displaying an increasing number of species, density and biomass over time in wind farm sites compared to their reference sites. This pattern was found for Belwind and Thornton Bank in Belgium (de Mesel *et al*. 2015; Degraer *et al*. 2013 and Krone *et al*. 2015), Horns Rev 1 OWF in Denmark (Leonhard & Pederson 2006) and Egmond aan Zee (Bouma and Lengkeek 2009; Bouma and Lengkeek 2012). Of note was that 10 non indigenous species were found on hard substrate at Thornton Bank OWF.
2) Increases in epifaunal biomass were found at Belwind (Vandendriessche *et al*. 2013; 2015) and Thornton Bank (Vandendriessche *et al*. 2013; 2015) in Belgium and Egmond aan Zee (Tien *et al.* 2014 referenced in Jak & Glorius, 2017) in Netherlands. However, there was a recorded decrease at Alpha Ventus in Germany (Gutow *et al*. 2014), where the highly abundant bristle worm *Spiophanes bombyx* and sea urchin *Echinocardium cordatum* played major roles in total abundance and biomass respectively. These variations were within the range of ambient variations of the infauna on fine sand sediments in the German bight.
3) No clear responses of infaunal benthic communities to presence of wind turbines were detected in any of the wind farms studied. Effects were generally small or subtle and therefore statistical correlations with technical aspects of the wind farms and environmental variables could not be made. Species richness in infaunal communities was generally found to increase closer to the turbine foundation[10].

A study by Coolen *et al.* (2018a) aimed to evaluate potential biodiversity enhancement by artificial structures across three different hard substrates: an old offshore oil and gas platform (age 15-40 years), a wind farm (5 years in operation) and a natural reef on the Dutch continental shelf. The effects of depth, age, disturbance by marine growth removal, season, substrate type and presence of potential key stone species on species richness and composition was investigated. The study resulted in the following:

1) Depth, sampling date, abundance of *Mytilus edulis*, *Psammechinus miliaris*, *Metridium dianthus*, and the presence of Tubulariidae and substrate (rock or steel) all correlated with species richness. Rather than age of structure influencing species richness, short-term variation (i.e. seasonality) may be much more important. Results showed a slight decrease from April followed by an increase in richness from July to October, although data outside this range were missing from analysis. Contrary to Degreaer *et al* (2017), Coolen *et al.* (2018a) did not find a positive pattern in species richness between different substrate types (rocky substrate versus straight steel surfaces).
2) There was no strong differentiation between the natural and artificial substrates, in contrast to earlier studies which showed communities on these substrates differing significantly (Page *et al*., 2007; Wilhelmsson and Malm, 2008). Non-indigenous species percentage was higher in the intertidal zones of offshore wind turbines (intertidal structures), which is in line with observations by De Mesel *et al* (2015). However, this is in contrast to the general belief that the fouling fauna from artificial hard substrate are predominantly poor and more opportunistic species when compared to natural hard substrate (Kerckhof, 2017).
3) In order to provide habitat to epibenthic species which would normally inhabit natural rocky reefs, scour protection should be made up of various sizes around the structure to increase local habitat complexity. To minimise non-indigenous species, it is advised that 'renewables to reefs' projects should remove the intertidal zone from abandoned installations to reduce the presence of intertidal species at offshore locations, cutting them well below the water surface.

A study by Coolen *et al* (2019) considered upscaling the positive effects on benthic macrofauna and associated fish species of scour protection in OWFs. Their research posed the question 'when 5,000 wind turbines are installed in the Dutch Sea, each with 2,000m^2 scour protection, would this significantly change

[10] *Comments received on this document identified that this is fully in contrast with Coates et al 2014, and Lefaible et al 2018. This should be investigated in future updates.*

the benthic communities? And to what extent are benthic species' populations on OWF turbine foundations interconnected?'.

1) Modelling results suggested that epibenthic biomass in an area covered by scour protection directly around a turbine increases 24-fold. Their research concluded that connectivity between populations of benthic species increases after the construction of OWFs however being able to quantify this is difficult due to differences in larval durations and paucity of reported travel distances. Interconnectivity is also species dependent, as some species are found in every location for example the marine amphipod, *Jassa herdmani*, however other species such as blue mussel are common on offshore platforms but are rare on subtidal reefs (Coolen *et al.* 2018b).
2) The interconnected populations of mussels on offshore installations can be attributed to their long pelagic larval stages (70 days) (Coolen *et al*. 2018b; Henry *et al*. 2017). Species with shorter larval stages are generally isolated or are absent from offshore installations, such as the European flat oyster (10 days) (Dannheim *et al*. 2018; Kamermans *et al*. 2018). These findings imply that these species in particular would benefit from restoration projects in offshore wind farms.
3) It was also found that data availability of scour protection species was low. Biomass data was only available from 5 locations across operational wind farms and only a single fish dataset. It is important to note that this quick scan investigation ignored negative impacts and infaunal benthic species environmental differences and therefore results must be treated with caution.

A five-year study by Bicknell *et al* (2009) investigated baited remote underwater video systems (BRUVs) as a technique to monitor diversity, abundance and assemblage composition data to evaluate MREDs on mobile epi benthic species. The aim was to demonstrate how annual natural variation (time) and survey design (spatial scale and power) are important factors in the ability to robustly detect change in common ecological metrics of benthic and bentho pelagic ecosystems of the north east Atlantic. The study took place off the north coast of Cornwall between 2011 and 2015 and the study area was located within and adjacent to a wave hub development zone. Depth was variable (20 – 53m) and data was pooled by habitat (rocky reef, large sediment, medium, gravel, fine sediment).

Bicknell *et al.* (2009) found there were consistent changes across years with increases in relative abundance of pollack and saithe around cable infrastructure, which suggests that the addition of scour protection on cabling provides suitable conditions. This builds on previous evidence that these fish species use rocky reef and hard substrate habitat as nursery grounds (Seitz *et al*. 2014). Greater abundances of cuckoo wrasse *Labrus mixtus* in the same survey area were also attributed to presence of hard substrate for cable protection (Sheehan *et al*. 2013). There was no distinct evidence trawling exclusion impacts in the wave hub zone, potentially due to low fishing effort in the area before (Bicknell *et al.* 2009).

Leewis *et al* (2018) assessed benthic development in and around OWF Prinses Amalia Wind Park near Dutch coastal zone before and after construction (2003-2017). Their focus was on the soft bottom fauna and how it had changed after 10 years of exclusion of fisheries in the wind farm area. Baseline data from 2003 was compared to data in 2012, 2013 and 2017.

1) Clear temporal effects on the species composition of the OWF was found, reflected by the number of species, abundance and diversity indices. Sampling year offered the greatest significance in comparison to other environmental factors, i.e. there was a strong temporal effect on the species composition. 2003 was distinctly different from other years, coinciding with high fishing intensities, however it was not possible to prove a causal relationship between fishing intensity and community composition. Other variables such as depth, grain size and organic matter content also played a role in the diversity of samples, which was also found by de Jong *et al.* (2015), where medium fine sands and high organic matter were correlated with highest species richness and biomass.

2) Leewis *et al.* (2018) speculated whether the temporal effects could be cased by yearly fluctuations in temperature and climatic conditions. Also they questioned whether 10 years after construction of the OWF was sufficient to capture recovery of the benthos. A further sampling campaign should measure and analyse additional environmental variables such as sediment characteristics (Leewis *et al.*, 2012) and shear stress (de Jong *et al*. 2015). Further analysis of the data based on species traits may elucidate greater understanding of the functioning of the ecosystem (Glorius *et al.* 2016) and mechanisms for recovery.

Vertical mixing, stratification and primary production

Floetar *et al* (2017) investigated pelagic effects of OWF foundations and it was the first time empirical bio-physical data has been gathered from the BARD 1 OWF in Germany. The study followed up previous theoretical modelling investigations and considered the impact on ambient hydrography, local nutrient concentrations, light availability and primary production and zooplankton and pelagic fish distribution.

1) As tidal currents flow past OWF foundation structures, a turbulent wake is generated which is expected to contribute to mixing of the stratification and a subsequent transport of nutrients into the surface mixed layer (Cazenave *et al*. 2016; Carpenter *et al*. 2016). Results suggest that OWF foundations are responsible for at least part of the observed increase in vertical mixing (also discussed in section 2), which are also being enhanced by local tide-bathymetry interactions. However, the exact separation of natural and anthropogenic causes requires more knowledge of the stratification variability in undisturbed conditions and requires further investigation. Data from Video Plankton Recorder images revealed zooplankton densities that were group specific, demonstrating distinct distribution patterns in relation to the OWF.
2) At a certain scale, median pelagic fish densities were found to be higher within the OWFs and to the northwest of the OWFs. However, variability was high and high densities were found in other areas as well, therefore this did not give rise to any statistically significant differences, though there is a possibility that the vertical echosounder may not have detected fish close to the turbine foundations (Floetar *et al*. 2017). The results of this study demonstrate the difficulty in fully separating anthropogenic impacts from natural variability. Being able to discern OWF induced cause-effect relationships from natural variability remains a crucial challenge.

Cause-effect paths

Dannheim *et al* (2019) conducted a literature review of 233 publications on benthic effects of offshore renewables. Their study defines a set of scientifically argued cause-effect relationships, describing interactions between marine renewable energy devices (MREDs) and benthos. Dannhem *et al* (2019) established conceptual cause-effect diagrams which are then scored to identify areas of high priority and further work.

They found that in general, paths linked to the artificial reef effect had the highest scores on temporal and spatial scale, as well as the highest magnitude of the effect (sensitivity). The results provided further evidence that benthic sensitivity to offshore renewable effects is higher than previously indicated. Their approach identified prominent knowledge gaps and research needs on:

- hydrodynamic changes possibly resulting in altered primary production with potential consequences for filter feeders,
- the introduction and range expansion of non-native species (through stepping stone effects) and
- noise and vibration effects on benthic organisms,

Knowledge on changes of ecological functioning through cascading effects is limited and requires distinct hypothesis-driven research combined with integrative ecological modelling. Following the methodology applied in this study, suggestions for future research are included in the knowledge gap section

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All these cause–effect relationships have the potential to change the benthic system over large spatial scales and for a long term.

Invasive species

Past research has suggested that MREDS may offer pathways or act as ‘stepping stones’ for invasive species to reach further offshore (Miller *et al*. 2013) or indeed for species that are usually restricted in their distribution to more coastal regions of the North Sea. Indeed ten non indigenous species were found on hard substrate at Thornton Bank OWF (Jak and Glorius 2017).

Further research has demonstrated invasion and range expansion by MREDS (De Mesel *et al*. 2015; Coolen *et al*. 2016). However, caution is advised on the potential threat of invasive species in subtidal regions due to species already known to inhabit existing habitats (Dannheim *et al* (2019). The expansion of intertidal species is however likely to be more prevalent as MREDS will represent a new habitat offshore (Kerckhof *et al*., 2016). It is suggested that future modelling and field studies should target the level of risk of invasions posed by MREDS for intertidal and subtidal species.

4.2.3 Increased Suspended Sediment Concentrations (SSC)

4.2.4 The literature provided did not include information on this potential impact of offshore wind development on this particular receptor[11]. Disturbance due to maintenance activities

The literature provided did not include information on this potential impact of offshore wind development on this particular receptor.

4.2.5 Operational Noise

The emission of energy into the marine environment, principally noise or vibration has been shown to potentially affect local fish populations (Gill *et al.*, 2012; De Backer and Hostens, 2017). Fitness and the occurrence of bioturbation has also been shown to be affected in noise experimental studies (Pratt *et al.*, 2014; Debusschere *et al.*, 2016). The comprehensive literature review by Dannheim *et al* (2019) highlights that our understanding of the impact of sound on epibenthos is limited (Edmonds *et al.*, 2016; Roberts and Elliott, 2017).

Studies have investigated the sensitivity of crustacean to noise (Solan *et al*., 2016) and the impact this has on their behaviour. An example of this is a study on bioirrigation in *Nephrops norvegicus* (Solan *et al*. 2016). Dannheim *et al* (2019) highlight that many invertebrates are sessile and not able to escape and may therefore experience a higher risk of damage from noise pollution and therefore further research is required investigating causal underwater sound parameters such as particle motion and sound pressure and their subsequent effects on benthic fauna. There is still a lack of understanding of the causal underwater sound parameters and their effect on marine fauna.

4.2.6 Electromagnetic Frequencies

The literature provided did not include information on this potential impact of offshore wind development on this particular receptor[12].

See **Section 5.2.4** for further information on effects from electromagnetic frequencies on shellfish.

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[11] *Comments received on this document identified further papers that could be included in future updates including, Baeye & Fettweis (2015) and Forster (2018) and its references. It is recommended this is included in future updates.*
[12] *Comments received on this document identified further papers that could be included in future updates including, Thomsen et al. (2015). It is recommended this is included in future updates*

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4.2.7 Survey Design and Statistical Power

Many of the papers reviewed in the 2019 update reached the same conclusion in respect of sampling design, gear types and the implications this has on statistical power, and ultimately, being able to distinguish between natural variability and discernible wind farm effects. The use of BRUVs are useful in temperate high energy environments, however, can be subject to poor weather, logistical and technical issues which then increases the required sampling effort to ensure sufficient statistical power to detect change on benthic systems (Bicknell *et al.* 2009). This must be considered with EIAs if associated findings are used to justify positive or negative effects. There were spatial differences in the ability to detect change in species richness and relative abundance as well as yearly (Bicknell *et al.* 2009). More studies need to report post-hoc statistical power to prevent reanalysis of original data. This re-analysis recommended for future comprehensive studies. Jack & Glorius (2017) acknowledge this is possible for some OWFs but not all due to data ownership. Distinguishing between poor sampling design could be overcome by continuing monitoring in existing wind farms. Dutch wind farms Egmond aan Zee and Prinses Amalia are good candidates given their relatively comprehensive sampling programme (Jak and Glorius 2017).

4.3 Decommissioning

4.3.1 Habitat Loss

A study by Fowler *et al* (2019) considered research on oil and gas platforms on the basis that they can be indicators of the potential impacts of habitat loss for OWFs when they reach their decommissioning phase. The current policy preference is for complete removal, reflected by OSPARs 93/3 decision which seeks to ensure safe access to and use of the seabed for all users, limiting risks of offshore chemical pollution and minimising long term liabilities for the state. There are however numerous partial removal options where some sections of the structure are left in the marine environment and the remainder is transported to shore for recycling. Examples include topping where the top section is removed and deployed *in situ* beside the base or toppling the whole structure *in situ* (Fowler *et al.* 2019). A more flexible case-by-case system would adhere to the adaptive management approach to protection of the marine environment articulated within OSPAR's Northeast Atlantic Environment Strategy (OSPAR Agreement 2010-03). Further study of these options is required to help inform EIAs. The study by Fowler *et al* (2019) recommends the temporary suspension of obligatory removal of offshore infrastructure and advises that this approach should be applied to decommissioning in OWFs.

4.4 Knowledge gaps

The information provided above on impacts from offshore wind development on benthic receptors also identify a number of knowledge gaps or recommendations. For clarify these have been pulled out and summarised below:

- Going forward there is also a need for more research and standardisation from bio-acousticians in the development of behavioural response thresholds for other receptors such as fish and invertebrates (Hawkins and Popper, 2016).
- Species assemblages within the OWFs seem to be mainly structured by temporal variability at larger spatial scales such as yearly temperature fluctuations, hydrodynamic changes, or plankton blooms. For future analyses, it would be worthwhile to include environmental variables to gain a better insight in the observed patterns.
- Monitoring effort should be increased with a higher number of replicate samples per survey to increase the statistical power of the analyses.

- *Mytilus edulis* and *Anthozoa sp* found further from foundations in soft sediment - This could indicate that the 'reef' effect is starting to expand beyond the direct vicinity of the turbines. However, detailed follow-up is needed to validate whether this is a one-off observation or a real wind farm effect reflected with time after construction possibly because of increasing epifaunal biomass on the foundations.
- No differences were observed for both the abiotic and the biotic variables between jacket and gravity based foundations. Alternatively, the effect of turbine presence and foundation type might manifest itself within close vicinity of the turbines (< 50m) and as such has not been identified through this study. Coates *et al.* (2014a) suggests this may be the case. To tackle this, it is recommended to perform a targeted monitoring study to investigate potential changes in sedimentology and organic enrichment in the close vicinity (7-100 m) of the three turbine types present in the BPNS (jacket, gravity bases and monopiles).
- Degraer *et al.* (2018) recommend performing a targeted monitoring study comparing the three different turbine foundation types (monopiles, jackets and gravity-based foundations) used in the BPNS
- Degraer *et al.* 2017 mentions two limitations of the studies done on the difference between natural hard substrates and artificial hard substrates in de BPNS. The first being a lack of data gathered from large stones and boulders which will likely further emphasize that the species diversity for the natural hard substrates is higher than artificial hard substrates. The second being the short amount of time (two years) that the scour protection has been available for colonisation. Long term effects of artificial hard substrates on species diversity are unknown.
- Jak & Glorius (2017) highlighted the trend in Dutch waters of wind farms being planned and developed increasingly offshore and in deeper waters, thereby reducing the applicability of existing research and exacerbating current knowledge gaps. If this trend continues for other European nations, then addressing current knowledge gaps becomes even more pertinent. The papers reviewed as part of the 2019 update provide the following recommendations for future research to address current knowledge gaps:
    - Future studies should aim to quantify wind wake effects on the regional ecosystem scale and in multiple disciplines given that many more OWFs will be in full operation in the near future. There should be greater focus on cumulative effects of OWF clusters and on the trophic transfer of any increases in production (Floetar *et al*. 2017).
    - Research into the impacts of newly introduced substrate should consider studying natural reefs in close proximity to artificial reefs to reduce the variability caused by geographical separation and associated environmental variables (Coolen *et al*. 2018).
    - Even with limited knowledge and significant statistical evidence being available, clear changes are being found in the benthos affected by infrastructure associated with offshore wind farms (Dannheim *et al*. 2019). Dannheim *et al*. 2019 recommend including more hypothesis driven questions by targeted field studies to support our understanding of ecological processes and patterns at local scales.
    - Upscaling hypothesis-driven research at smaller scales with modelling approaches in order to define and understand large scale ecological effects (Dannheim *et al*. 2019). Modelling approaches may assist in determining likelihood of effects and project potential ecological cascading effects which may lead to unknown changes. This is also suggested by Coolen *et al* (2019) i.e. future monitoring should focus on enhancing our understanding of species ecology and system ecology, for example starting a broad study of impact on the wider ecosystem and food web.

- Provide further, more detailed knowledge of the natural variability of the benthic system in space and time, as this is a prerequisite to distinguish potential changes induced by offshore wind farm infrastructure from the natural variability. We can then better understand the structure and dynamics of benthic ecosystems. Cooperation between studies groups and locations could enhance our ability to determine the factors affecting variability (Dannheim *et al*. 2019).
- 'Standby time' of vessels traditionally commissioned by industry should be accessed by researchers for minimal additional cost to industry. In return researchers could provide analysis of data back to industry for use in EIAs. An example of this would be to study epifouling communities on offshore structures, which may include many smaller more cryptic species than is detectable using video (Fowler *et al*. 2019).
- Videos and stills gathered by industry when examining structural integrity of installations should be better utilised. Resolution can be poor but it is often good enough for dominant species to be identified (van der Stap *et al.* 2016; Coolen *et al.* 2018a). Operators typically inspect installations every 2-3 years, therefore this is a rare opportunity to build long term data sets on offshore ecosystems (Macreadie *et al*. 2018; Fowler *et al*. 2019).
- Industry personnel could be trained to collect basic data (Fowler *et al.* 2019) as it has been found previously that staff with an interest in marine ecology are often willing to participate in scientific investigations while working offshore as it is conducive to good team morale (Gates *et al*. 2017).
- Incentivise energy developers for joint research funding opportunities such as Neptune Energy in the Netherlands which facilitated Coolen *et al* (2016, 2018a). A good example in the UK of this is INSITE. INSITE encourages stakeholder cooperation to address knowledge gaps. Between 2015 and 2017 the magnitude of effects of manmade structures compared with spatial and temporal variability was investigated via the award of 9 research contracts. Further studies should investigate to what extent the structures represent a large inter connected hard substrate system (Fowler *et al*. 2019).
- Pilot projects should be established to provide the opportunity to examine ecological risks of various decommissioning options, which can then help inform policy. Five considerations often not considered at this phase but are pivotal include: provision of reef habitat, productivity of offshore ecosystems, enhancement of biodiversity, protection of seabed from trawling and enhancement of connectivity. Research in these areas will encourage collaboration between the offshore energy industry and independent researchers (Fowler *et al*. 2019).
- More field data is required on epibenthic fauna and fish on scour protection and connectivity between locations (Coolen *et al*. 2019).
- Larval dispersal models have used tidal currents and weather patterns from previous years to investigate settlement from origin location for blue mussel *Mytilis edulis*, amphipod *Jassa herdmani*,, European flat oyster *Ostrea edulis*, common limpet *Patella vulgata*, dead man's fingers *Alcyonium digitatum*, edible sea urchin *Echinus esculentus*, plumose anemone *Metridium senile*, slipper limpet *Crepidula fornicate* and sponges porifera. Further research could investigate why some species are never observed far offshore while others are common, and which locations are connected and which aren't. Studies could also consider which species use locations in between as stepping stones to reach locations further offshore to assess the impact of when a structure is removed (Coolen *et al*. 2019).

- The introduction of three-dimensional artificial structures will modify the hydrodynamic conditions. These newly added structures will determine settlement success and species occurrences in the natural surrounding habitats and may change the food availability to filter-feeders. This highlight the importance for studies on ecosystem effects (see also section 8).;[13]

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5 Fish and Shellfish Ecology

5.1 Construction

5.1.1 Habitat Disturbance

The literature provided did not include information on this potential impact of offshore wind development on this particular receptor.

5.1.2 Deterioration in water quality due to resuspended contaminated sediments

The literature provided did not include information on this potential impact of offshore wind development on this particular receptor.

5.1.3 Increased Suspended Sediment Concentrations (SSC)

The literature provided did not include information on this potential impact of offshore wind development on this particular receptor.

5.1.4 Underwater noise

Fish

OWF construction activities, such as pile driving, generate sound (both sound and particle motion). Sound is used for communication between fishes, mating behaviour, the detection of prey and predators, orientation and migration and habitat selection. Thus, anything that interferes with the ability of a fish to detect and respond to biologically relevant sounds can decrease survival and fitness (Popper & Hawkins, 2019).

In view of the rapid increase in OWFs in the North Sea, and in order to further determine sound thresholds to be used in international guidelines, research was undertaken to gain more knowledge on the effects of pile driving on fish health (Degraer *et al*. 2017). Halvorsen *et al.* (2012a) showed that the severity of injuries is not only owing to the total energy level of exposure (SELcum); the energy level of exposure of one single impulse (SELss), and the number of impulses are as important.

Taking the above in to consideration, a field experiment was undertaken in the summer of 2016 in the Nobelwind OWF in the BPNS to determine the direct effect of pile driving on the health status of Atlantic cod (*Gadus morhua*). Large netted cages, each holding 9 to 12 cod individuals (avg. size 31cm), were submerged at 8m under the water surface. The cages were placed at increasing distances (75m, 400m, 1,400m and 1,700m) from the sound source, exposing the cod to one piling event.

Average single strike sound exposure levels (SELss) decreased from 175 dB re 1μPa²s at 400m distance to 168 dB re 1μPa²s at 1,700 m distance (Degraer *et al*., 2017). Ambient sound pressure levels (SPL) varied between 114 and 138 dB re 1μPa. Overall, 11% cod were retrieved dead, most probably due to handling

[13] *Comments received on this document identified further knowledge gaps as follows:*

1. *Significance of colonisation of cable protection - Results from the Crown Estate EB10 report found that there is little or no information on the effects of cable protection either on the seabed or on associated benthic ecology communities (e.g. colonisation of installed protection measures); and*
2. *Impacts of sandwave clearance and recovery of benthos from cable installation.*

stress, as no direct relation could be found with distance to the sound source (Degraer *et al*., 2017). A steep increase in swim bladder barotrauma was detected with decreasing distance to the pile driving source: no swim bladders were ruptured at 1700m nor at the control sites, 20% were ruptured at 1400m distance, 40% at 400m distance and up to 90% of the swim bladders were ruptured at 75m distance. Although most fish in the cages in the direct vicinity of the piling source (100m distance) did survive this short term experiment, they all showed many multiple instances of internal bleeding and a high degree of abnormal swimming behaviour, indicating a reduced long term survival rate. However, these immediate detrimental effects seem to only occur close to the high impulsive sound source. Results of this in situ experiment provide valuable information to scientifically evaluate current “critical sound limits”. It should be noted that this experiment provides a worst case scenario where the cod were unable to swim away from the noise source to which they were exposed.

Results indicate that with the current sound limits, swim bladder barotrauma can occur in physoclistous fish (fish with a swim bladder) like Atlantic cod when they are within a radius of 750m distance around the sound source during pile driving. This is, however, a small-scale effect, and it seems unlikely to cause significant effects at the population level. Nevertheless, in order to investigate what the observed effect means on a wider scale, the individual impact can provide the basis for a population impact assessment.

This experiment proved that it should be repeated to answer further research questions relating inner ear injuries, long-term survival rate, etc.; this time, however, with small, autonomous digital hydrophones (e.g. icListen HF-X2) that can be deployed together with the cages. Ideally, particle motion is also measured, since this is an important second component of sound, and its role in the effects of impulsive sound on fish needs further investigation.

Bolle *et al*. (2015) in Koppel and Schuster (2015), examined lethal effects of exposure to pile-driving sound in different larval stages of 3 fish species (common sole *Solea solea*, European sea bass *Dicentrarchus labrax* and herring *Clupea harengus*), representing different swim bladder developments (no, open, and closed swim bladder). Furthermore, Bolle *et al*. (2014) examined lethal effects, injuries, and recovery from injuries in European sea bass juveniles. Recorded pile-driving sounds could be reproduced at zero-to-peak levels up to 210 dB re 1 μPa^2 (zero to peak pressures up to 32 kPa) and single pulse sound exposure levels up to 186 dB re 1 μPa^{2}s. The highest cumulative sound exposure level (SELcum) applied was 216 dB re 1 μPa^{2}s (999 strikes). Survival was monitored during a 7 to 13 day period. For European sea bass juveniles, injuries were assessed directly after treatment and potential recovery from injuries was examined 13 days after treatment. The results of the larval studies showed no significant differences in mortality between the control group and the exposure groups (at SELcum up to 216 dB re 1 μPa2s) for any of the species or larval stages, suggesting that lethal effects of pile-driving might only occur at small range (<100m).

In a later study Bolle *et al.* (2017) limited to lethal effects on the larvae of common sole, experiments were carried in which different development stages were exposed to various levels and durations of piling sound. The initial series of experiments indicated that an effect of sound pressure exposure may occur, but the differences were not statistically significant, possibly due to sample size. Results of this study cannot be extrapolated to fish larvae in general, as interspecific difference in vulnerability to sound exposure may occur. However, this study does indicate that the previous assumptions and criteria may need to be revised.

Such as, the interim cumulative SEL criterion defined by the US Fisheries Hydro-acoustic Working Group (FHWG) for non-auditory tissue damage in fish <2g is 183 dB re 1 u Pa2 s^{-1} (Oestman *et al.,* 2009). The highest cumulative SEL used in the present study (206 dB) was much higher than this norm, but no significant effects on the survival of common sole larvae were observed. Initially, the FHWG proposed single-strike thresholds at 187 dB SEL and 208 dB peak pressure for the onset of injury from pile driving (Popper *et al.* 2006), based on an evaluation of the available information (Hastings & Popper 2005). Later these criteria were updated: the SEL norm of 187 dB was proposed for cumulative SEL instead of single-strike SEL (Woodbury & Stadler 2008), the SEL norm was reduced to 183 dB for small fish (Stadler & Woodbury, 2009), and the peak pressure norm was reduced to 206 dB (Stadler & Woodbury 2009). Stadler and Woodbury (2009) reported in Bolle *et al.* (2019) stated that these thresholds represent the initial onset of injury, not the levels at which fishes will be severely injured or killed.

Debusschere *et al*. studied the impact of pile-driving on post-larval and juvenile European sea bass which was reported on in Koppel and Schuster (2015). Fish (<2 grams) were exposed to strikes with a high single strike sound exposure level between 181 and 188 dB re 1μPa²s. The number of strikes ranged from 1,739 to 3,067, resulting in a cumulative sound exposure level ranging from 215 to 222dB re 1μPa²s. The immediate and long-term survival of the exposed groups was high and similar to the control groups. During the sound exposure the fish showed a decreased respiration during the sound exposure, indicating an elevated stress level.

During the study fish behaviour and physiology was also observed in a laboratory setup (Debusschere *et al*. 2015). Single strike sound levels reached 162 dB re 1 μPa²s and 2400 strikes led to a cumulative sound exposure level of 196 dB re 1 μPa²s were reached in the aquaria. Under these conditions, normal behaviour was disturbed, with an increase in startle responses and stationary behaviour at the beginning of the sound exposure, but was re-established shortly after the cessation of the sound. Feeding and respiration were not affected. The specific growth rate, however, was significantly different between treatments, indicating that food assimilation was decreased due to increased stress levels after exposure. These results indicate that short-term exposure to impulsive sound creates sound pressure levels at the sound source that are below the lethal sound threshold for fish, but above the stress sound threshold, at least for sea bass smaller than 2 g. Furthermore, the sound levels at a wider range can disturb fish behaviour. This disturbance, however, was short-lived and little impact on growth and condition was seen in the conducted experiments.

Hawkins *et al.* (2014) in Popper & Hawkins (2019) observed European sprat (*Sprattus sprattus*) is sensitive to sound pressure, while Atlantic mackerel (*Scomber scombrus*) is likely to be sensitive only to particle motion. The fish were exposed to short sequences of repeated impulsive sounds, simulating the strikes from a pile driver at different sound levels. Results showed that incidence of behavioural responses increased with increasing sound level. However, the responses of European sprat at night were very different to those shown during the day. European sprat schools break up at night and the individual fish did not respond to the playback of pile driving sounds.

Despite extensive academic literature and survey work, and their use in EIAs, uncertainty remains on both the accuracy of the fish spawning information currently available and the level/significance of impacts from piling activity on fish species (Boyle & New, 2018). Data was consolidated and reviewed to define UK populations, key spawning areas and key spawning periods for herring (*Clupea harengus*), to identify any gaps in our understanding of herring (Boyle & New, 2018). The study suggests that there is an ability to identify areas within the historical mapping where spawning activity is focused within more defined spawning grounds. Even from larval data with drift that hasn't been back-calculated to a specific location, it is possible to demonstrate that there are specific locations where spawning activity is focused within these historical spawning areas (Boyle & New, 2018). As there are perceived impacts of piling on herring related to underwater sound pressure and particle motion it is important to identify locations of spawning of herring in relation to the offshore wind construction site. In addition to established sound thresholds for fish, thresholds need to be established in terms of particle motion.

Shellfish

Andersson *et al.* (2017) strongly concurred with the idea that future guidelines for fishes must also be in terms of particle motion and must also consider signals from the substrate. Pile driving produces radiating particle motion that could impact bottom-dwelling animals. Roberts *et al.* (2015) reported in Weilgart (2018) found clear behavioural change to the behaviour in mussels, mainly valve closures. The thresholds of mussel response were within the range of vibrations measured near pile driving. Vibration is likely to impact overall mussel health and reproduction in both individuals and whole mussel beds, because valve closure, which is an energetically and otherwise costly behaviour, disrupting breathing, heart rate and excretion

(Weilgart, 2018). Therefore, water-borne particle motion and acoustic pressure needs to be considered when looking at the effects of bottom dwellers.

5.2 Operation and maintenance

5.2.1 Habitat Loss

The literature provided did not include information on this potential impact of offshore wind development on this particular receptor.

5.2.2 Introduction of New Substrate and Changes to Fishing Activity[14]

Artificial hard substrata are known to attract many marine species, among which several highly mobile species. The species composition and uniqueness of the fish fauna around offshore wind turbine foundations in Belgian waters has therefore been studied as reported in Degraer *et al*. (2018). These offshore structures provide shelter, suitable habitat and a source of food for several fish species. Kerckhof *et al.* in Degraer *et al.* (2018) observed a total of 25 fish species around the turbine foundations, 15 of which are also known to dwell around wrecks in the same area. Four species, the Tadpole Fish (*Raniceps raninus*), the Tompot Blenny (*Parablennius gattorugine*) and the Longspined Bullhead (*Taurulus bulbalis*) were previously rarely or, in the case of the Ballan Wrasse (*Labrys bergylta*), only once reported from Belgian waters. This, however, does not necessarily mean that they are rare. Kerckhof *et al.* show that, in order to obtain a good insight into the fish fauna, the use of a suite of varied sampling techniques is necessary. Most of the obligate hard substrata fish species that were observed are frequently recorded in the oyster beds and boulder fields of the nearby Eastern Scheldt estuary. It is expected that hard substrata- frequenting fish species will increasingly benefit from the continued expansion of OWFs in the Southern North Sea.

Various publications have shown that substantial populations of edible crab can occur near monopiles. Based on the population increase in OWF's in the German Bight combined with the density data in the Dutch part of the North sea an increase in the population density of *C.pagarus* is expected in the Dutch OWF, Prinses Amalis park, which consists of 60 monopiles and covers a total area of 14.2km^2. These findings along with reproductive and behaviour traits of the crab, such as migrations patterns of female crabs and burrowing of females with eggs demonstrate the potential for successful colonisation in offshore windfarms and the development of *C.pagarus* exploitation (Tonk & Rozemeijer, 2019). However, there are uncertainties concerning local carrying capacity and ecosystem indicators if the crab population increases substantially.

Tallack (2002) in Tonk & Rozemeijer (2019) studied a dynamic energy budget (DEB) model on European lobster (*Homarus gammarus*) production on OWF and found that 1 lobster per monopile can reach marketable size (85mm carapace length (CL) in Dutch waters) after 3 years when stocked at a 50 mm carapace length. Without restocking (release of cultured juvenile stock into depleted wild populations) it takes about 6 years for lobster to reach 87mm Cl. It takes about 4 years for edible crabs to reach marketable size (130mm CL) with restocking. Lobsters occur at monopiles to a less extent than crabs, or not at all (Krone *et al.,* 2011, 2015, 2017).

The local maximum production capacity of edible crab will depend on the background population, the colonisation success (including migration patterns and specific interactions between monopiles and different life stage of brown crab), growth rate and local carrying capacity. It poses questions about how much food is required to support an edible crab population at a monopile (Rozemeijer & van de Wolfshaar, 2019).

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[14] Comments received on this document identified further papers that could be included in future updates including, Barbut et al. (2019) on changes in recruitment of flatfish. It is recommended this information is included in future updates.

The proposed function of monopiles acting as larvae collectors may also benefit local population densities. However, little is known about the early settlement of juvenile *C.pagarus* and how this interaction takes place (Tonk & Rozemeijer, 2019).

We are only beginning to understand the role that decapods play in marine ecosystems, and how exploitation or large-scale addition of substrate in the form of monopiles might modify this role (Boudreau and Worm, 2012). The available evidence suggests that large decapods can play important roles in structuring benthic communities. The limited information currently available regarding constraints and opportunities of decapod fisheries in OWF's demonstrate the need for further research into the ecological and socio-economic issues surrounding fishery co-location potential (Hooper & Austen, 2014).

In the German Bight the addition of another 5,000 monopiles in the future is suggested to provide new artificial reef habitat for another estimated 320% brown crabs. However, it is unclear how the increased amount of crabs at monopiles in the German Bight will affect the carrying capacity and whether the available food supply will sustain sufficient growth of these crabs. The study by Krone *et al.* (2017) illustrates a potential system shift towards a future North Sea fauna, which display a more important role of certain reef animals than in the current state of the North Sea. Nonetheless, these findings show huge potential for the envisioned crab fisheries in Dutch OWF's further south in North Sea. However, it is not known how the extraordinary amounts of brown crab associated to monopiles in the German Bight infer to the OWF's in the more southernly North Sea since natural crab densities in the German Bight are higher. Therefore, extrapolation of this data needs to be treated as a very rough indication and more accurate densities of brown crabs are needed to provide a better insight.

5.2.3 Increased Suspended Sediment Concentrations (SSC)

The literature provided did not include information on this potential impact of offshore wind development on this particular receptor.

5.2.4 Electromagnetic Frequencies

OWFs will be connected to land by subsea power cables that transport the generated energy to shore. These cables generate electromagnetic fields (EMFs) and induced electric fields (iEFs) in the marine environment. Much of the current understanding is based on theoretical or trial with exaggerated experimental EMF strengths. Determining impacts of realistic EMFs on species is therefore a key priority. Snoek *et al.* (2016) identified four main potential effects due to EMFs in literature. These effects are: disturbance of behavioural responses and movement (attraction, avoidance); disturbance of navigation and migratory behaviour; disturbance of predator / prey interactions and distribution of prey; and, disturbance of embryonic and cellular development. Studies should focus on the four effect categories.

Invertebrates

Species from the Mollusca phylum tend to react on a changed magnetic field by changing their activity pattern. However, to induce this behavioural change, the intensity of the magnetic field has to increase substantially (Snoek *et al.*, 2016). In mussels *Mytilus edulis,* EMFs can lead to a decrease in hydration and amine nitrogen values at >5mT (Snoek *et al.,* 2016).

Scott *et al*. (2018) studied the effects of simulated electromagnetic fields (EMF), emitted from sub-sea power cables, on the commercially important decapod edible crab (*Cancer pagurus*). Crabs were kept in 1000L flow through tanks with a natural photoperiod. Crabs were exposed for 24-hours to static EMFs at strengths of 2.8mT and 40mT to correspond with the expected, although highly variable levels on the surface of a sub-sea power cable and correspond to those in previous studies. The EMF was produced by electric solenoid magnets (24V) placed underneath the experimental tanks. Stress related physiological parameters were measures (L-Lactate, D-Glucose, Haemocyanin and respiration rate) along with behavioural and response parameters. Exposure to EMF had significant physiological effects on de edible crab and changed their behaviour. Crabs showed a clear attraction to EMF exposed shelter (69%) compared to control shelter (9%) and significantly reduced their time spent roaming by 21%. This suggests that the natural roaming behaviour, where individuals will actively seek food and/or mates has been overridden by an attraction to the source of the EMF. These results predict that in benthic areas surrounding Marine Renewable Energy Devices (MREDs), where there is increased EMFs, there will be an increase in abundance of *C.pagurus* present. Melatonin levels in several species have been found to be affected by EMF exposure (Naylor *et al.* 1997; Shields & Payne, 2014). This suggests that EMF exposure could affect crustaceans on a hormonal level. The potential aggregation is cause for concern. Given this species' proven attraction to EMF sources, incubation of the eggs may take place around areas with increased EMF emissions. Scott *et al.*, 2018 suggests long terms studies are needed to investigate the effects of chronic EMF exposure along with the effects of EMF on egg development, hatching success and larval fitness.

Bony Fish

Bony fish are known to detect EMFs and electricity fields for navigation, long distance migration, homing, etc. For example, diadromous fish species can use the Earth's magnetic field for orientation and direction during migration (Snoek *et al.,* 2016). Boemre (2011) in Snoek *et al.* (2016) found that a potential effect of EMFs on fish for a subsea power cable depend upon the sensory capabilities of a species, the life functions of which it's magnetic or sensory systems support and the natural history characteristics of the species.

The number of studies specifically addressing North Sea marine life are scarce, especially field based studies and studies that address magnetic fields within the range 5-300 uT or iE fields of 0.5-5 mV/m. Snoek *et al*. (2016) collected and presented relevant or recent studies that report species from the North Sea (**Table 5.1**). Based on this Table it is concluded that the available information on effect of EMFs on species that inhabit the North Sea is too limited to draw conclusions on the potential impact of EMFs generated by subsea power cables.

To create more knowledge on species and eventually populations, research has to focus on priority species (groups) and – life stages and specifically on field sites and field strengths that are in the same range as those emitted by subsea cables (Snoek *et al,* 2016).

Table 5.1 Overview of relevant studies addressing North Sea species. Source: Snoek et al., 2016.

Source / Type of study	North Sea species	Type Fields tested	Conclusion	Discussion
Orpwood *et al.,* 2015. Laboratory experiment. Movement (passing through a oil) of a migratory species.	European eel (*Anguilla Anguilla*) silver eel stage	AC MF of 9.6 uT	No evidence for different movement	Small sample size, nocturnal behaviour not included, low field strength
Gill *et al.,* 2009. Mesocosm experiment in shallow water. Behaviour near powered and unpowered buried cables in Scotland.	Ray (*Raja clavate*), Spurdog (*Squalus acanthias*) and Lesser-spotted Dogfish (*Scyliorhinus canicular*)	Maximum of 100A current, 8 uT and 2.2 mV/m	Dogfish is nearer to the cable when powered. Reactions of individuals to EMFs vary widely	No evidence from the present study to suggest any positive or negative effect on elasmobranchs of the EMF encountered
Vattenfall 2006. Field study of Nysted cable (Baltic Sea) using quadri	Fish fauna: including Atlantic cod, Baltic herring, flounder (*Paralichthys flesus*) and European eel	No measurements of EMF field strengths	European eels appeared to depart from, cod appeared to accumulate close to the cable and plaice	Baseline data missing, set up with high complexity and many difficulties, other factors can confine results

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Source / Type of study	North Sea species	Type Fields tested	Conclusion	Discussion
directional fykes and mark recapture of eel			and flounder most likely to cross the cable during periods of low power production	
Bocher & Zetler 2004; 2006. Laboratory study of Baltic sea specimen exposed to artificial static magnetic fields	Flounder, Blue mussel, North Sea praw (*Crangon crangon*), Round crab (*Rhithropanopeus harrisii*).	Static 3.7 mT field (long term), 2.7 mT (short term)	No difference between experimental animals	High field strength
Kalmijn 1971. Laboratoryexperiment. Feeding response to prey and fields emitted by electrodes	Lesser spotted dog fish, *R.clavata*	4 uA	At short range, electro fields act as a much stronger directive force than do the visual and chemical stimuli. (electrodes preferred over fish smell)	Only low magnitude Electric Fields (in range of emitted) by prey tested

Elasmobranchs

Studies on the effects of EMFs on elasmobranch species that inhabit the North Sea region are rare (**Table 5.1**). Attraction to elevated EMF field strengths has been observed in several species of sharks and rays in multiple studies. However, studies of field magnitudes within the range emitted by subsea cables, let alone field studies, are scarce and inconclusive. Furthermore, response differences amongst individuals and habituation have been observed. Since electrosensory primary neurons react on electric fields of 1- 10 Hz, reactions outside this bandwidth (i.e. subsea cables of 50Hz) are expected to be only evoked with much stronger field intensities.

A COWRIE-sponsored mesocosm study was designed to examine behaviour of electro-sensitive species confined in the vicinity of powered and unpowered buried cables in Scotland (Gill, *et al.* 2009). This study showed that the two species of benthic elasmobranchs studied, did respond by being attracted to the EMF emitted, albeit with high variability among individual fish (Boemre, 2011). The results however did not allow for an assessment of the impact on the fish or fish populations.

Also dogfish showed attraction to elevated field strengths with a preference for AC cables. No general assumptions can be made as elasmobranch species tend to react different even among individuals. Furthermore, learning and habituation has been observed in shark species, indicating that they can adapt to anthropogenic electric fields on a local scale. To gain more knowledge on species and eventually on impact at population level, research has to focus on specific sites, species and specifically on the range of field strengths that are generated by subsea power cables.

Field type, strength and configuration will determine species' detectability of anthropogenic fields Electromagnetic sensitive organisms in the marine environment can detect both local and larger-scale uniform EMFs; these are the predominant type of fields associated with subsea power cables (Gill *et al.*, 2005). Species are more likely to detect EMFs generated by DC cables compared to AC cables due to the higher EMF strength for DC cables. Also, species detection depends on the cable configuration since EMFs can be enforced or cancelled out depending on the distance between cables. Lower EMF strengths, are not necessarily associated with less impact. Moreover, weak EMFs can have an important ecological function, such as the little variations in the geomagnetic field used for navigation during migration and the weak fields induced by prey.

5.2.5 Operational Noise

Continuous operation of an offshore wind turbine may change the acoustic environment. Consequently, critical aspects of fish behaviour could be interfered with respect by the presence of long-term sounds that mask a fish's ability to detect sound of biological importance (Popper & Hawkins, 2019). For example, anthropogenic sounds may interfere with foraging behaviour either by masking the relevant sounds or by resembling the sound that the prey may generate (Purser & Radford, 2011).

Pine *et al.* (2012) in Weilgart (2018) found that noise from wind turbines discourage larval settlement and delayed metamorphosis in two crab species. This is due to noise masking important natural acoustic settlement cues.

Many fish migrate and use a variety of cues to orientate and navigate (Popper & Hawkins, 2019). High level sounds may result in avoidance responses. Sounds are also important for many fish species for spawning. Casaretto *et al.* (2015) in Popper & Hawkins (2019) showed that male haddock (*Melanogrammus aeglefinus*) are territorial and visits to their territories by females are induced by the sounds of males, triggered courtship behaviour, leading to spawning embrace. It has been suggested by de Jong *et al.* (2018) that acoustic communication may play a crucial role in reproductive interaction and they point out over 800 species of fish have been to communicate acoustically. Further research needs to be undertaken to review the long-term effects of continuous exposure to anthropogenic sound, particularly examining the behaviour of wild fishes under more natural conditions.

5.2.6 Changes to Fishing Activity

As reported in Koppel and Schuster (2015), Winter *et al*. (2015) studied the demersal and pelagic fish community in the OWF Egmond aan Zee and two reference areas before (T0), and after construction (T1, T5) using trawling surveys and acoustic surveys. Potential ecological consequences for fish were hypothesized to be linked to the introduction of new habitat, i.e. the monopiles and the scour protection surrounding them, disturbance by the operation of the wind farm (e.g. noise), and the exclusion of fisheries in the wind farm and its surrounding safety zone. In addition, species composition was studied in the vicinity of the monopiles in three seasons during the T5 monitoring period. Behaviour of individual fish in and around the wind farm was studied by a tagging and telemetry study for which sole (*Solea solea*) and cod (*Gadus morhua*) were selected to represent both sand and hard substrate dwelling species. The results show that the presence of wind farms seems to have a limited effect on the fish community in the Dutch coastal zone. For a few species local benefits occurred possibly due to a combination of creation of new hard substrate habitats and exclusion of fisheries. Differences were observed between the new artificial hard-substrate habitat and sandy substrate. Large aggregations of fish were observed near the monopiles mainly in summer. Furthermore, a significantly higher abundance of cod, bib (*Trisopterus luscus*), bullrout (*Myoxocephalus scorpius*), sea scorpion (*Taurulus bubalis*), and common dragonet (*Callionymus lyra*) was observed on the scour protection near the monopiles. Lower abundance was observed for flatfish species, sole, dab (*Limanda limanda*) and plaice (*Pleuronectes platessa*) and also for whiting (*Merlangius merlangus*). For some species, higher abundance near the monopiles may lead to protection from fisheries and a potential positive effect on their populations. However, on a larger scale (when comparing to the entire Dutch Coastal Zone) no significant differences in fish abundance were found in the wind farm compared to the reference sites.

5.2.7 Management and Mitigation

Weilgart (2018) suggested certain management and mitigation measures in respect to pile driving. (1) All noise sources should avoid biologically important areas and times of the year, such as spawning. Dawn or dusk fish choruses should be avoided. (2) Reduce pile driving or construction noise through the water and vibration through the seabed. Alternative foundation such as suction caissons or gravity-based foundations may effectively eliminate noise during construction. Quieter, new installation methods such as BLUE Piling which do not require a hammer and have no moving parts, should be explored and promoted. (3) Thorough EIAs need to be completed for all noise activities having the potential to cause impacts. Analyses of the impacts on fish and invertebrates need to be included. (4) Acoustic refuges of still-quiet biologically important areas for noise-sensitive marine life should be safeguarded and protected from noise.

A total of 19 OWF have been identified to date as having herring restrictions or other mitigation requirements for this species associated with marine licences – reason that piling restrictions are applied is due to the potential effect of piling on spawning adult herring and / or their behaviour. Limited range of noise levels is considered to pose little if any risk to eggs or larvae (Boyle & New, 2018). It would appear that spawning herring have not been a concern for OWF development in non-UK countries to date, with the main concern being related to the effects of underwater noise on marine mammals. There is no specific guidance or regulations in place specifically to address herring in non-UK waters. In the UK, there are some general regulations and guidance that relate to spawning fish populations as well as to sound exposure criteria and thresholds (Boyle & New, 2018). In addition, the UK has a Marine Policy Statement in place, which sets out process for UK countries to form and adopt National and Regional Marine Plans. In Scotland, herring is listed as a priority marine feature (PMF) and therefore its conservation needs to be considered during the decision-making process.

Scott *et al.* (2018) mentions that the impact of EMF on crustaceans must be considered when planning MREDs.

Tonk & Rozemeijer (2019) suggest monitoring the age at which *C.apagrus* become fertile at proposed OWF sites is required. DEB modelling is recommended in combination with planned monitoring in OWF Prinses Amalia to quantify local production potential. The designation of closed / no take areas is suggested to address the potential low densities of large male *C.pagarus* in the Dutch OWFs.

5.3 Knowledge gaps

The information provided above on impacts from offshore wind development on fish and shellfish ecology receptors also identify a number of knowledge gaps or recommendations. For clarity these have been pulled out and summarised below:

- Farcas *et al*. 2015 identified an important knowledge gap. Current models applied in EIAs consider only the sound pressure component of sound, which is the means by which mammals hear. However, the primary mechanism by which fish and invertebrate species detect sound is through particle motion (Popper and Fay, 2011; Morley *et al*., 2014). Levels of sound pressure and particle motion can deviate substantially in the region close to noise sources and in shallow water (Hawkins, 1986), and so techniques to specifically model this component of sound are needed to better predict the potential impact of noise-generating activities on these animal groups.
- There are still knowledge gaps on the effects of underwater noise from piling related to inner ear injuries and long-term survival rate. Future studies should studying impacts on fish survival should use small, autonomous digital hydrophones (e.g. icListen HF-X2) that can be deployed together with the cages. In addition it is unclear how particle motion associated with piling and under water noise impacts fish. Ideally, particle motion is also measured, since this is an important second component of sound, and its role in the effects of impulsive sound on fish needs further investigation.
- Popper & Hawkins (2019) suggests that further research of underwater noise to fish needs to have a representative set of species of fish types (e.g. with no, open and closed swimbladders).
- Further studies of how particle motion associated with piling and underwater noise impacts fish and this then needs to be managed and mitigated (Bolle *et al*., 2017).
- Need to examine the behaviour of wild fishes under more natural conditions, as most previous studies have been under laboratory conditions and captive animals (Popper & Hawkins, 2019).

- There need to be long term studies to investigate the effects of chronic EMF exposure along with the effects of EMF on egg development, hatching success and larval fitness. Impact of EMF on crustaceans must be considered when planning MREDs (Scott *et al.,* 2018). There is also a strong knowledge gap on the actual electromagnetic field strength that can be expected for the various cable designs, voltages and outputs of OWFs.
- DEB modelling is recommended in combination with planned monitoring of OWF to quantify local production potential. Designation of closed/no take areas is suggested to address the potential low densities of large males in the Dutch OWF's (Tonk & Rozemeijer, 2019).

6 Marine Mammals

6.1 Construction

6.1.1 Disturbance due to human activities

Brandt *et al*. 2018 investigated the disturbance impact of the first seven German offshore windfarms under construction with and without noise mitigation measures. Whilst undertaking this study it was also observed that harbour porpoise detections in the vicinity of the construction site started to decline several hours prior to piling commencing, although not to the extent found during piling. A likely explanation of this decline is an increase in construction-related activities, such as an increase in shipping traffic in combination with enhanced sound transmission during the calm weather conditions during which piling activities occur (Degraer *et al*. 2017 and Dragon *et al*. 2016). Increased shipping traffic could contribute to harbour porpoise deterrence, and a recent study suggests that harbour porpoise may react to shipping activity at distances over 1km (Dyndo *et al*. 2015). Brandt *et al*. 2018 also observed that the duration of the disturbance effect in the vicinity of piling tended to be longer for piling events with noise mitigation system(s) (NMS) than for piling events without NMS. This could be related to more shipping activity associated with noise-mitigated piling events when NMS have to be installed and uninstalled. This poses the question as to how much of the effect duration after piling is really due to ongoing deterrence effects from piling noise and how much may be caused by other construction - and weather-related noise characteristics. It also poses the question if by using NMS, one trades a smaller effect radius and a smaller effect strength for a longer effect duration in the vicinity of the construction site.

An alternative explanation is offered by Haelters *et al.* (2016) where consecutive pile driving events which prevent the stabilisation of porpoise densities are considered. However, this may also be due to seasonal fluctuations in porpoise densities with decreasing numbers in function of time at the start of the construction period (Haelters *et al.* 2016).

6.1.2 Underwater noise

Behavioural response and displacement

Russel *et al*. (2016) undertook a study to establish if seal distribution impacted by piling is restricted to piling activities or has a longer temporal impact. It was found that there was no significant displacement of harbour seal during construction as a whole. However, during piling, seal usage (abundance) was significantly reduced up to 25km from the piling activity; within 25km of the centre of the wind farm, there was a 19 to 83% (95% confidence intervals) decrease in usage compared to during breaks in piling. This amounts to significant displacement starting from predicted received levels of between 166 and 178 dB re 1 lPa(p-p). Displacement was limited to piling activity; within 2h of cessation of pile driving, seals were distributed as per the non-piling scenario.

Hastie *et al*. (2016) conducted a study on harbour seals during construction of an offshore wind farm in southeast England. 25 harbour seals were tagged with a GPS system which provided data on distribution and activity. The closest range of the individual seals to piling varied from 6.65km to 46.1km. In addition, the maximum predicted received noise levels for each individual seal varied between 146.9 and 169 dB re 1 µPa peak to peak

Observed displacement of harbour porpoise might also be a result of the use of deterrent devices if applied (Dähne *et al*. 2013). A study carried out at Alpha Ventus showed temporal displacement within 20km from the piling site, with detection rates increasing with distance from the construction site. The detection rate at 25 and 50km distance showed a positive correlation during pile driving, indicating that displaced harbour porpoise moved toward this area (Dähne *et al*. 2013). The significance of displacement as well as of recovery might be strongly dependent on conditions within the surrounding area, such as habitat quality, prey availability, competition, and vessel activity (Scheidat 2012).

Tougaard *et al*. (2012) and Dähne *et al*. (2014b) as set out in Schuster (2015), emphasized that even single incidences where species behaviour is interrupted (e.g. to mate, feed, or interact) could have an effect on the population in the long term. It was however noted that this effect is virtually impossible to quantify (Dähne *et al*. 2014b).

Rumes *et al.* as set out in Degraer *et al.* (2017) looked at the long-term impact of pile driving events on harbour porpoise distribution. From May to September 2016, pile driving was taking place at the Nobelwind OWF located on the Bligh Bank in Belgium. In this period, harbour porpoise activity was recorded using passive acoustic monitoring (PAM) using Continuous Porpoise Detectors (C-PoDs), at various distances from the construction site (1 – > 55km). In this study, harbour porpoise detections before, during and after pile driving were compared. During piling, porpoise detections decreased at stations located up to 20km from the location of the piling event. At greater distances (20-55km), harbour porpoise detections either remained the same or increased slightly during piling events, which may be due to displaced individuals entering the area. Underwater sound levels were extrapolated for the different locations. Pile driving sound levels at the furthest distance where reductions in harbour porpoise detections were observed were ~159 dB re 1µPa (pile driving sound level Lz-p)/ 136 dB 1µPa^{2}s (sound exposure level (SEL_{ss}), which is close to the threshold level for major disturbance for harbour porpoise as proposed in literature.

With increasing distance from the pile driving event it is expected that changes in porpoise detections will be less pronounced, start later, and last shorter (as in Diederichs *et al.* 2010;2011; 2016). However, while this appears to be correct for the stations at 15-20 km distance, further stations (25-55 km distance) do not follow this trend (Degraer *et al*. 2017). As argued in Tougaard *et al*., (2009), this may be due to limited data availability.

In order to more accurately assess the spatial and temporal extent of pile-driving induced deterrence of harbour porpoise the consequences of repeated piling events needs to be understood (Degraer *et al*., 2017). Although Thompson *et al*. (2010) suggested that the distance over which cetaceans are disturbed becomes larger with each successive piling event, no such effect was observed in the German Bight (Brandt *et al*. 2016).

Graham *et al.* (2019) undertook a study to identify the response of harbour porpoise to the construction of OWF. Using echolocation detectors and noise recorders they investigated behavioural responses to piling noise during the 10-month foundation installation of a North Sea windfarm. Current UK guidance assumes total displacement within 26km of pile driving. It was found that the number of detection positive hours fluctuated during the year but there was no evidence of a negative temporal trend in occurrence as a result of piling. The scale of response by the local population of porpoises declined over time, highlighting that previous assessments of disturbance impacts of long-term piling programmes may be conservative. The study suggest that response distances are unlikely to exceed 20km and provides a dataset that can be incorporated into available population modelling frameworks to undertake more detailed cost–benefit analyses of potential noise reduction methodologies. Based upon an average density of porpoises in the Moray Firth study area of 0.274km^{-2} (Hammond *et a*l., 2013) the JNCC guidance predicts displacement of 582 individuals. In comparison, 160 (95% CI = 120–202) and 102 (95% CI = 75–133) individuals are predicted to be disturbed based upon the behavioural response function developed by Graham *et al.* (2019) for the first and last piling events, which is 28% and 18% respectively of the total estimate of individuals if using the current JNCC guidance. The use of ADDs and vessel presence within 1km were significant covariates in the models and further work is required to better understand the relative contribution of pile driving, ADD noise and vessel activity to observed responses of cetaceans to offshore construction.

Hearing threshold values

As set out by Hastie *et al.* (2015) a number of different threshold criteria have been developed in recent years for marine mammals (e.g. Southall *et al*., 2007, 2019; NOAA, 2013, 2015) and fish (e.g. Popper *et al*., 2014).

Lucke *et al* (2016) found that to date, hearing studies on captive animals have shown that harbour seals have an acute sense of hearing in air and underwater (Bullock *et al.* 1971; Terhune 1991; Kastak and Schusterman 1998; Wolski *et al*. 2003; Reichmuth *et al*. 2013) with functional hearing ranging from at least 100Hz up to 33kHz in air and 51kHz underwater (Reichmuth *et al*. 2013; see Cunningham and Reichmuth 2016 for high-frequency sensitivity). These hearing studies have all been undertaken in captivity. Therefore, Lucke *et al*. (2016) studied hearing sensitivity in wild seals. Hearing thresholds were measured for the target frequencies of 1.4, 2.0, and 2.8kHz in (18) free-ranging seals in The Wash (in the UK) in 2012 and in six of the ten animals tested in captivity in 2013. The study concluded that hearing thresholds in the captive environment were comparable to those in the wild.

Southall *et al*. (2019) undertook a review of current literature to update the findings of Southall *et al*. (2007) using peer reviewed data. Southall *et al*. (2007) defined sound sources as “pulses” or “non-pulses” based on their characteristics at the source using a simple, measurement based approach proposed by Harris (1998), but the respective exposure criteria (impulsive or non-impulsive) should be applied based on signal features likely to be received by animals rather than by signal features at the sound source. The same dual exposure metrics used by Southall *et al*. (2007) are used for impulsive noise criteria: (1) *frequency- weighted sound exposure level (*SEL*),* and (2) *unweighted peak sound pressure level* (hereafter peak SPL). These two metrics are applied under the condition that exceeding either threshold by the specified level is sufficient to result in the predicted TTS or PTS onset.

The different exposure metrics are required to account for different aspects of exposure level and duration: SEL is a measure of sound energy of exposure accumulated over time and over multiple exposures, whereas SPL is a measure of absolute maximum exposure. For impulsive exposures (e.g. pile driving and seismic airguns), both criteria are defined for all marine mammal groups. For non-impulsive exposures (e.g. vessel/aircraft passes; drilling; many construction or other industrial operations), only frequency-weighted SEL criteria are given replacing the dual exposure metric approach proposed by Southall *et al.* (2007).

To estimate PTS-onset criteria for non-impulsive noise in terms of SEL, an exposure level of 20 dB above the TTS-onset level (6dB TTS) was used for each marine mammal group. This assumes the same growth rate (1.6dB TTS/ dB noise) from the point of TTS onset (6dB TTS) to estimated PTS onset (40 dB TTS) used in Southall *et al.* (2007); this growth rate is now supported with limited empirical data on TTS growth for a few marine mammal species (reviewed in Finneran, 2015). The associated non-impulsive SEL TTS- and PTS-onset criteria for all marine mammal hearing groups are given in **Error! Reference source not found.**.

Table 2 TTS- and PTS-onset thresholds for marine mammals exposed to non-impulsive noise: SEL thresholds in dB re 1 µPa2s under water and dB re (20 µPa)2s in air (groups PCA and OCA only)

Marine mammal hearing group	TTS onset: SEL (weighted)	PTS onset: SEL (weighted)
Low-frequency cetaceans (LF; e.g. baleen whales)	179	199
High-frequency	178	198

Cetaceans (HF; e.g. dolphins)		
Very High-frequency Cetaceans (VHF: e.g. porpoise)	153	173
Sirenians (SI)	186	206
Phocid carnivores in water (PCW)	181	201
Other marine carnivores in water (OCW)	199	219
Phocid carnivores in air (PCA)	134	154
Other marine carnivores in air (OCA)	157	177

As in Southall *et al*. (2007), a dual metric approach is retained for impulsive stimuli, and the weighted SEL threshold is used in conjunction with an unweighted peak SPL threshold. Few TTS studies have been conducted in marine mammals using representative impulsive noise sources such as pile driving and airgun signals (see Finneran, 2015), in part given the extensive challenges in successfully generating impulsive stimuli in laboratory conditions that approximate exposure conditions for such sources with free-ranging animals. The associated impulsive SEL and peak SPL TTS- and PTS-onset criteria were calculated, and the resulting exposure criteria are presented in Table 2.

Table 3. TTS- and PTS-onset thresholds for marine mammals exposed to impulsive noise: SEL thresholds in dB re 1 μPa2s under water and dB re (20 μPa)2s in air (groups PCA and OCA only); and peak SPL thresholds in dB re 1 μPa under water and dB re 20 μPa in air (groups PCA and OCA only).

Marine mammal hearing group	TTS onset: SEL(weighted)	TTS onset: Peak SPL(unweighted)	PTS onset: SEL(weighted)	PTS onset: Peak SPL(unweighted)
LF	168	213	183	219
HF	170	224	185	230
VHF	140	196	155	202
SI	175	220	190	226
PCW	170	212	185	218
OCW	188	226	203	232
PCA	123	138	138	144
OCA	146	161	161	167

Underwater noise modelling

To predict the noise exposure of marine animals during activities, noise prorogation models are used. According to Farcas *et al*. (2015) the study of sound propagation is well established and understood, and doesn't need to present a significant level of uncertainty if carried out according to best practice (Farcas *et al.* 2015). For piling, sophisticated physical and numerical models to describe the sources have been developed (e.g. Reinhall and Dahl, 2011; Zampolli *et al*., 2013; Lippert and von Estorff, 2014; Fricke and Rolfes, 2015). Farcas *et al*. (2015) did identify a few improvements which are mentioned in the Knowledge Gaps section.

Auditory damage

A behavioural study during the construction of a wind farm using tags on 24 harbour seals was undertaken by Hastie *et al.* (2015). Pile driving data and acoustic propagation models, together with seal movement and dive data, allowed the prediction of auditory damage in each seal. TTS and PTS were predicted for cumulative sound exposure levels and pulsed sounds. The closest distance of each seal to pile driving varied from 4.7 to 40.5km, and predicted maximum M-weighted cumulative sound exposure levels (cSELs(Mpw)) ranged from 170.7 to 195.3 dB re 1lPa2-s for individual seals. Comparison to exposure criteria suggests that half of the seals exceeded estimated permanent auditory damage thresholds.

Kastelein *et al.* (2018) investigated the TTS of two harbour seals at 4 and 8kHz (frequencies of the highest TTS) after exposure to playbacks of broadband pile-driving sounds with a psychoacoustic technique. Pile-driving strikes may be audible to harbour seals at distances of over 100km from the pile driving site, depending on the circumstances (Kastelein *et al*., 2013); therefore, many seals in areas where pile driving occurs are exposed to multiple pile-driving sounds (at various received SEL_{ss} and SEL_{cum}). If a harbour seal is exposed to a normal pile driving sequence with a SEL_{cum} of 190 dB re 1 lPa^2s (i.e., 8280 pile-driving strikes in 3h at an average received SEL_{ss} of 151 dB re 1 lPa^2s), no significant TTS occurs at 4 or 8 kHz. A small TTS (2–4 dB) may occur at both frequencies if a harbour seal is exposed to the same sounds for 6h (SEL_{cum} of 193 dB re 1 lPa^2s). In practice, the SEL_{cum} during pile driving can be considerably higher than 190 dB re 1 lPa^2s, depending on the distance of the seal to the piling site and the propagation conditions. The pile-driving sounds used in the present study may resemble those at about 10km from the piling site (depending on the propagation conditions). In modern practice, deterring devices are used in an attempt to move harbour seals away from piling sites before piling begins, in order to prevent PTS due to the first strike. It takes only 2–3h to complete the placement of a monopile foundation for a wind turbine depending on the pile diameter and sea bed composition (Norro *et al*., 2013). However, the governments of several countries around the North Sea have plans to construct many wind parks over the coming decade. It is likely that piling operations at different construction sites will overlap in time, so that the 6 h exposures of the present study, or longer exposures without quiet periods, may become realistic scenarios for seals in the North Sea.

6.1.3 Collision Risk

The literature provided did not include information on this potential impact of offshore wind development on this particular receptor.

6.1.4 Changes in Prey Resource

Foundations of OWFs have provided substrate for artificial reefs, resulting in localised increases in fish and crustacean density. Russel *et al*. (2014) researched two seal species, harbour seal (*Phoca vitulina*) and grey seal (*Halichoerus grypus*), to understand whether these species show behavioural adaptations due to these potentially scattered local increases of food sources. Individual seals were deployed with GPS tracking devices. The study shows that seals do exploit the windfarms and clearly showed a grid like movement in windfarms. At individual structures the foraging behaviour increased significantly. What the ecological consequences are is still not well understood.

6.2 Operation and maintenance

6.2.1 Displacement

Russell *et al*. (2016) found that within an operational wind farm, there was a close-to-significant increase in seal usage compared to prior to wind farm development. However, the wind farm was at the edge of a large area of increased usage, so the presence of the wind farm was unlikely to be the cause. Avoidance/ displacement of wind farms by harbour seals is thus limited to pile driving activities.

6.2.2 Underwater noise

The literature provided did not include information on this potential impact of offshore wind development on this particular receptor.

6.2.3 Collision Risk

The literature provided did not include information on this potential impact of offshore wind development on this particular receptor.

6.2.4 Electromagnetic Fields (EMF)

The literature provided did not include information on this potential impact of offshore wind development on this particular receptor.

6.2.5 Physical Barrier

The literature provided did not include information on this potential impact of offshore wind development on this particular receptor.

6.2.6 Changes in Habitat and Prey Resource

See changes in prey resource in Section 7.1

6.3 Information relevant for spatial planning

Jones *et al*. 2015 analysed two decades of at sea movement data and terrestrial count data from harbour seal and grey seal species to produce high resolution, broad-scale maps of distribution and associated uncertainty to inform conservation and management. Even though the grey seal and harbour seal have a similar taxonomy their distribution can be different. The results showed that grey seal use offshore areas connected to their haul-out sites by prominent corridors, and harbour seal primarily stay within 50 km of the coastline. Both species show fine-scale offshore spatial segregation off the east coast of Britain and broad-scale partitioning off western Scotland. These results illustrate that, for broad-scale marine spatial planning, the conservation needs of harbour seals (primarily inshore, the exception being selected offshore usage areas) are different from those of grey seals (up to 100km offshore and corridors connecting these areas to haul-out sites).

Jones *et al.* (2017) developed a high resolution distribution map for harbour seal in northern Scotland and Orkney. High-resolution usage maps can be integrated within IBMs to produce a powerful analytical framework to predict change in species distributions to assess the impact of direct and indirect anthropogenic activities on protected species

Hawkins and Popper (2016) confirms the 20km circle radius of behavioural disturbance for harbour porpoise (*Phocoena phocoena*), the radius of 16km that was already proposed by Norro *et al*. (2013) and confirmed by Haelters *et al*. (2015) for the major behavioural disturbance zone.

Considering the area over which noise propagates through water a cross-border strategy on cumulative sound emissions needs to be encouraged should a reduction of excessive underwater sound be strived for in the near future (Norro 2017 in Degraer *et al*. 2017

6.4 Mitigation

Several recent studies investigated the effectiveness of mitigation measures such as NMS, deterrent devices or other measures. The results of each study are presented below

6.4.1 Alternatives to percussive piling

To mitigate potential negative impacts of percussive piling, alternatives such as vibration piling are encouraged. However, there is limited information on the effectivity of these alternatives compared to percussive piling. Graham *et al.* (2017) studied the impact of vibration piling on bottlenose dolphins and harbour porpoise during harbour construction work in northeast Scotland. The comparative study was executed using PAM devices to record cetacean activity and noise recorders to measure and predict received noise levels. The noise levels of both techniques were measured. For percussive piling the median peak-to-peak source level estimated was 240 dB re 1 lPa (single-pulse sound exposure level [SEL] 198 dB re 1 lPa^2 s). For vibration piling the root mean square (r.m.s.) source level was 192 dB re 1 lPa. The predicted received broadband SEL values 812m from the piling site were markedly lower due to high propagation loss: 133.4 dB re 1 lPa^2 s (impact) and 128.9 dB re 1 lPa^2 s (vibration). Bottlenose dolphins and harbour porpoise were not excluded/completely displaced from sites near percussive piling or vibration piling; nevertheless, some small effects were detected. Bottlenose dolphins spent a reduced period of time in the vicinity of construction works during both percussive and vibration piling. The probability of occurrence of both cetacean species was also slightly less during periods of vibration piling (Graham *et al*. 2017).

6.4.2 Noise mitigation systems

Brandt *et al.* (2018) investigated the disturbance of OWF construction with and without NMS on harbour porpoise using acoustic porpoise monitoring data and noise measurements during construction of the first seven large-scale OWFs in the German Bight between 2010 and 2013. At six wind farms, active NMSs were applied during most piling events, and one was constructed without. The number of harbour porpoise declines significantly in the vicinity of the windfarms after piling. The declines were found at sound levels exceeding 143 dB re 1 μPa^2s and up to 17km from the piling location. For the windfarms with NMSs the maximum effect distance was 14km. The number of harbour porpoise also declined more strongly, compared to 24−48 hours before piling, during unmitigated piling events at all distances. At 10−15km from the piling event declines were around 50% during piling without NMS, but only 17% when NMS were applied. Within the vicinity (up to about 2km) of the construction site, harbour porpoise detections declined several hours before the start of piling and were reduced for about 1−2 days after piling, while at the maximum effect distance, avoidance was only found during the hours of piling. The application of first generation NMS thus reduced the effect range of pile driving and led to a lower decline of harbour porpoise detections over all distances. However, NMS were still under development and did not always work with equal efficiency. As NMS have further developed since, future investigations are expected to show additional reduction of disturbance effects (Brandt *et al*. 2018).

Following up to the study by Brandt *et al* (2018), Rose *et al*. (2019) analysed the impact of the construction of eleven OWFs and offshore converter platforms built in the German North Sea and adjacent Dutch waters in the period 2014-2016 on harbour porpoises. It was expected that the improved noise-mitigation technologies, which reduce under water noise levels significantly, would reduce the duration and range of displacement of harbour porpoises accordingly. This was not the case, the effect range regarding porpoise detection rates during mitigated pile driving from all projects was at 17km, and the effect duration in close range lasted from 28 hours before until 48 hours after stop of pile driving. These values were similar to those obtained in the study by Brandt *et al* (2018), and thus no reduced displacement effect could be shown even with a considerable noise reduction achieved (noise reduction from on average 167dB to 158dB SEL_{05}). On a larger spatial and temporal scale, the regional harbour porpoise population was not negatively affected even though the range and duration of displacement was still significant. The construction works of the Rentel OWF off the Belgian coast were monitored for the emission of energy into the sea by means of underwater sound (pressure). The results were presented in Degrear *et al.* (2018). Thirteen complete piling events were monitored, covering the driving to full depth of 13 steel monopiles of 7.8m diameter using a hydraulic hammer with a maximum power of 4,000kJ. Sound mitigation in the form of a single big bubble curtain (BBC) was used. The results show that even with an optimised BBC, the maximum reduction that the NMS system can obtain is 17 dB re 1µPa and remains insufficient to reduce Lz-p below 185 dB re 1µPa at 750m distance (Belgium noise noise threshold)(Degraer *et al.* 2018).

The results from Degraer *et al.* (2018) demonstrate that, when it is required to install XL or XXL monopiles by pile driving, it will be necessary to use a combination of at least two sound mitigation measures in order to comply with Belgium national Marine Strategy Framework Directive regulations (185 dB re 1µPa), as had also had been predicted by Rumes *et al*. (2017).

Degraer *et al.* 2018 used the interim Population Consequences of Disturbance model (iPCOD; Harwood & King 2014) to quantify how differences in regulatory regimes with regards to OWF construction impact a simulated harbour porpoise population. Degraer *et al.* (2018) modelled the likely construction schedules for the Rentel, Norther and Seastar OWFs and tested 17 scenarios with and without various mitigating measures. The results of this study are indicative rather than absolute outcomes. Nevertheless, the results indicate that the impact of pile driving on the harbour porpoise population is strongly influenced by the timing of the activities, but that this effect is reduced when effective noise mitigation measures, i.e. BBC and/or NMS, are used. The combination of a seasonal pile driving restriction and an acoustic deterrent device (ADD) was not enough to lower the impact on the harbour porpoise population to acceptable values. The results also show that building an OWF every year affected the harbour porpoise population more than building two OWFs at the same time within the Belgium EEZ.

As set out in Köppel & Schuster (2015), Schubert *et al*. (2015) investigated the effectiveness of noise mitigation tools (such as the BBC) during the construction process of three German offshore windfarms (Borkum West II, Global Tech 1, and DanTysk). The behaviour of harbour porpoise was investigated using up to 26 passive acoustic dataloggers (C-PODs) placed at different distances from the construction area. The results show applying noise mitigation techniques like a bubble curtain can reduce the spatial scale of harbour porpoise avoidance behaviour by up to 90%. Reducing impact zones of sound emission during pile driving may be the most successful way to mitigate negative effects of offshore construction on marine mammals.

A review was undertaken by Scottish Natural Heritage (Verfuss *et al.*, 2019) of NMS and their applicability for pile-driving operations for OWF construction in Scottish waters.

The BBC, the IHC Noise Mitigation Screen and the Hydrosound damper (HSD) have frequently been used for mitigating sound during OWF construction (installation of monopiles (BBC, IHC Noise Mitigation Screen and HSD) and jacket foundations (BBC only)) in German waters. There are two kinds of NMS that have been applied on projects with water depths of up to 45m; this included BBC and vibrohammers (VH) or vibration piling. There is still the question of the effectiveness of these measures in waters deeper than 40m. BBC may remain challenging due to the need for an increasing number of compressors to form a suitable bubble curtain at higher hydrostatic pressures, and to counteract against the drift of the bubbles on their path to the water surface. VH is currently mostly used in connection with a conventional piling hammer, which at least retains some impact caused by this conventional method (although over a shorter period of time) but the VH emits a different kind of noise that may need further assessment to ensure that this method indeed reduces the impact on marine mammals.

Casings (Noise Mitigation Screen and HydroNAS) and resonators (Hydrosound damper and AdBm Noise Abatement System) maybe of future use but currently lack field experience or are only in use for water depths less than 50m. The BLUE Hammer, an impact hammer with less noise emission compared to a conventional hydraulic hammer, is also a promising system that has undergone its first full-scale test and will be improved based on the test results.

With the BBC, IHC Noise Mitigation Screen and HSD, broadband sound levels can be reduced by a at least 10dB (for both, $L_{pk,\ flat}$ and SEL_{ss}) and reductions have been demonstrated of up to 20dB and more for the SEL when combining two NMS. The BLUE Hammer resulted in a noise reduction of around 20dB in SEL_{ss} in its first full-scale trial, with the caveat that full validation of the technology is still pending. The NMS are generally more effective at reducing the risk of noise impact on marine mammals and fish sensitive to higher frequencies than for fish that are only sensitive to frequencies below 100Hz.

Field experience with the deployment of all NMS in OWF-projects at water depth beyond 45m is lacking, however, most NMS are applicable in theory. The application of the systems in deeper water may be more challenging. Also, experience with the deployment of NMS during the installation of piles with a diameter greater than 8m is lacking.

Project-specific assessment are recommended to be conducted to ensure the most suitable NMS option and configuration is chosen, considering the environmental conditions of the OWF site, and the specification of the planned installation vessel and method.

6.4.3 Mitigation using deterrent devices

As set out by Köppel & Schuster (2015), Brandt *et al.* conducted two investigations on the effects of the Lofitech seal scarer on harbour porpoise and showed that during a near shore visual study harbour porpoise avoided the seal scarer at noise levels above 118 dB re 1 μPa²s, which in these shallow waters was reached at about 2.6 km. A study in deeper offshore waters using acoustic monitoring of harbour porpoise revealed less harbour porpoise echolocation activity at noise levels above 113 dB re 1 μPa²s, which was reached at 7.5km distance.

However, complete deterrence was only achieved with noise levels at and above 122 dB re 1 μPa²s (Köppel & Schuster 2015). Differences between these two studies are mainly due to different sound transmissions in the area, and may also be caused by a greater variation in sound levels at great distances in deeper water and with the different monitoring techniques applied. At the time, it was assumed that seal scarers provide an appropriate tool to deter harbour porpoise from offshore construction sites because danger zones, where animals may suffer from TTS of their hearing system, reached up to about 2.5km. Since then, noise mitigation techniques have come a long way and during installation of OWFs in German waters in 2014, danger zones for harbour porpoise usually did not exceed a radius of 750m from the construction site.

A seal scarer may reach far beyond the needed deterrence distance and may cause unnecessary disturbance that affects an even larger area than pile driving itself. Therefore, seal scarers no longer seem to be an appropriate mitigation tool during wind farm construction, on the other hand the application of three pingers with deterrence radii of about 200m is not sufficient.

A specific porpoise deterrent device, the FaunaGuard (porpoise module) was developed as mitigation measures for the construction phase of the Eneco Luchterduinen Wind Farm in the Dutch North Sea. The FaunaGuard is meant to deter harbour porpoise during piling activities to avoid hearing damage. As set out by Köppel & Schuster (2015), van der Meij *et al*. tested the effectiveness of the FaunaGuard on harbour porpoise. The number of respirations differed significantly between control and test sessions at mean received levels of ≥104 dB re 1 μPa. The porpoise's distance to the transducer was significantly greater during test sessions than during control sessions when mean received levels in sessions were ≥86 dB re 1μPa.

To calculate the effective range of the FaunaGuard at sea, information on its Source SPL and the established behavioural threshold SPL were combined with sound propagation modelling, for the signals of the FaunaGuard. By doing this the calculated effective distance was sufficient to prevent PTS in harbour porpoise due to pile driving sound (Köppel & Schuster, 2015).

6.5 Knowledge Gaps

The information provided above on impacts from offshore wind development on marine mammal ecology receptors also identify a number of knowledge gaps or recommendations. For clarify these have been pulled out and summarised below:

- Most offshore wind impact studies focus on harbour porpoise and seals. Since, harbour porpoise and seals are considered particularly responsive to anthropogenic disturbance. Thus, impacts on other marine mammal receptor species remains unclear.

- Noise emission from rock dumping for scour protection during construction and also from geotechnical surveys, carried out before construction to exploit the suitability of the seabed, needs to be further considered

- Noise modelling can be further improved to predict propagation of sound in the time domain. Current models used in EIAs are based on modelling the overall sound energy as it spreads away from the noise source. However, the risk of acute auditory injury is closely linked with the temporal structure of sound, and in particular the sharpness of peaks in sound pressure caused by impulsive sources (e.g. impact pile driving or seismic airguns). As these pulses propagate away from the source, the sharp peaks in sound level become more dispersed, and present less of a risk of auditory injury relative to the sound energy contained within them (Farcas *et al*., 2015).

- Harbour porpoise numbers decrease several hours prior to the piling event. This poses the question as to how much of the effect duration after piling is due to ongoing deterrence effects from piling noise and how much may be caused by other construction - and weather-related noise characteristics. It also poses the question if by using NMS, one trades a smaller effect radius and a smaller effect strength for a longer effect duration in the vicinity of the construction site. This should be further investigated.

- In order to more accurately assess the spatial and temporal extent of pile-driving induced deterrence of harbour porpoise the consequences of repeated piling events needs to be understood (Degraer *et al*., 2017). Although Thompson *et al*. (2010) suggested that the distance over which cetaceans are disturbed becomes larger with each successive piling event, no such effect was observed in the German Bight (Brandt *et al*. 2016).

- One of the studies shows that seals do exploit the windfarms and clearly showed a grid like movement in windfarms. At individual structures, the foraging behaviour increased significantly. However, the ecological consequences are still not well understood.

- Considering the area over which noise propagates through water a cross-border strategy on cumulative sound emissions needs to be encouraged should a reduction of excessive underwater sound be strived for in the near future (Norro 2017 in Degraer *et al*. 2017)
- Implementation of NMS system has proven to effectively reduce underwater noise. However the study of Rose *et al*. (2019) hoped to show additional reduction of disturbance effects (Brandt *et al*. 2018) and address how effective relatively new NMS systems are in reduction of disturbance effects. However, in the continuation of the possible positive effects of improved NMS might have been counteracted by the presence of more service vessels in the area, due to a tighter pile-driving schedule and the fact that often more than one NMS was applied. Further research is required to identify any reduction in disturbance and the effectiveness of new NMS systems.
- Graham *et al.* (2019) results highlight the need to consider trade-offs between efforts to reduce far-field behavioural disturbance and near-field injury through ADD use. The use of ADDs and vessel presence within 1km were significant covariates in the models and further work is required to better understand the relative contribution of pile driving, ADD noise and vessel activity to observed responses of cetaceans to offshore construction. There are still areas that need further research such as the effect of different sources of noise on CPOD detection probability to optimize the design of studies which might disentangle the role of different noise sources in shaping observed responses which was previously raised.

- Separate criteria are needed to evaluate behavioural responses and broader-scale auditory effects (e.g., auditory masking) and physiological effects (e.g., stress responses) (Southall *et al*., 2019). These will necessarily involve different approaches but should consider integrating some aspects of the current criteria (e.g., weighting functions).

- More research is needed to determine whether the dynamic range of a species plays a role in its susceptibility to TTS and PTS (Kastelein *et al.*, 2018)
- Further investigations are needed into existing and new noise mitigating technologies to assess the effectiveness in a wider range of environments. VH emits continuous low-level noise that may need further assessment to ensure that this method indeed reduces impact on marine mammals.
- There is a lack of full knowledge and experience on the drivability and bearing capacity of piles driven with VH and BLUE Hammer technologies and with commercial deployment of NMS OWF projects in waters deeper than 45m in general. Also, experience with the deployment of NMS during the installation of piles with a diameter greater than 8m is lacking (Verfuss *et al.*, 2019).

7 Other receptors

In the articles reviewed two additional receptor species were identified which did not fall in to any of the above mentioned receptor groups. These are marine insects and turtles.

7.1 Marine insects

Large assemblages of insects have been noted anecdotally on offshore wind farms around the UK, however very little is known about these communities; what species inhabit offshore structures, their abundances, and origin (Bloxsom *et al.*, 2015 as set out in Köppel & Schuster *et al.* 2015). Reports on the potential for offshore wind turbines to increase the movement of organisms and spread non-indigenous species make it vital to investigate any colonisation of offshore structures. Bloxsom *et al* .(2015) conducted a study which provides an initial look into the communities of marine insects inhabiting offshore. A questionnaire showed that communities of insects are present on offshore wind farms around the UK. Through field sampling six different families of insect were identified on offshore structures including offshore wind. Bloxsom *et al.* (2015) discussed the different taxa along with differences in abundance and species richness of insect communities between offshore and coastal man-made structures.

7.2 Turtles

Turtles are known to be sensitive to magnetic fields and are believed to use natural magnetic fields in migration. A review by Normandeau *et al*. (2011) concluded that turtles can probably detect magnetic fields from sub-sea cabling. It was suggested that at short range, magnetic fields from sub-sea cabling may cause turtles to deviate from migration cues. However, turtles should be able to correct their course using other natural cues (Cefas, 2014).

7.3 Knowledge Gaps

As set out above, very little is known about insect communities; what species inhabit offshore structures, their abundances, and origin (Bloxsom *et al.*, 2015). Reports on the potential for offshore wind turbines to increase the movement of organisms and spread non-indigenous species make it vital to investigate any colonisation of offshore structures.

Other than the papers referenced above, no further information has been found on the impacts that OWF developments might have on turtles. The lack of information on this receptor is a data gap that requires additional information particularly as developments move in to areas more frequently visited by turtles.

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8 Ecosystem Effects

In 2018 the literature provided did not include information on the possible ecosystem effects of OWF. During the 2019 update articles did include information on ecosystem effects. The findings have been split across each phase of development and where appropriate have been further split to impact level.

8.1 Construction

The literature provided did not include information on the potential impact of offshore wind development on this particular phase..

8.2 Operation and maintenance

8.2.1 Nutrients

In a recent survey in a German OWF, high-resolution CTD (Conductivity, Temperature, Depth) data were collected, together with data on oxygen and chlorophyll-a (Floeter *et al*., 2017) around various OWFs in the German Bight, southern North Sea. These data provided empirical evidence that vertical mixing is indeed enhanced within OWFs in the summer- stratified North Sea. This leads to a “doming” effect on the thermocline and increased transport of nutrients from the deeper layers into the surface mixed layer.

8.2.2 Changes to primary production and impacts on higher trophic levels

Zooplankton

Changes to sea surface temperature (SST) related to changes in meteorological conditions, mixing and stratification as set out above affect the onset of growth, abundance and composition of zooplankton along with changes to primary production (i.e. phytoplankton). Total food availability, but also the quality (through phytoplankton composition) has been shown to have a major influence on zooplankton growth (Suchy, 2014).

In a desk study it is suggested that there is potential for increased competition between zooplankton and zoobenthos (e.g. newly established shellfish or other filter-feeding organisms) and therefore a reduction of available food (algae) due to filtering by epifauna on wind farm foundations. Whilst not directly related to offshore wind farms it has been found that overgrazing by shellfish in the Oosterschelde is the main cause for the decrease of primary production (Smaal *et al.*, 2013), this may also limit the growth of zooplankton. Slavik *et al.* (2018) modelled a significant decrease in phytoplankton around offshore wind farms based on mussel biomass and filtration rates on the wind farm foundations which may lead to a decrease in zooplankton (Deltares 2018).

As set out in Section **Error! Reference source not found.** changes to wave height, currents and vertical mixing may impact the water composition at OWF sites (e.g. changes to suspended particulate matter (SPM), Region of Freshwater Influence (ROF), destratification, nutrient concentrations etc.) (Deltares, 2018).

These changes may affect the distribution of nutrients into the surface (light) layer, as well as the access of benthic filter feeders to phytoplankton, and therefore non-linearly change the primary production and the food web.

Feeding activities from epistructural fauna on the offshore wind farm foundations may significantly decrease phytoplankton densities around wind farms affecting in turn zooplankton densities, as well as nutrient regeneration and primary production (Deltares 2018).

Further to the above, tidal currents are one of the most important transport mechanisms in the North Sea. Changes in these current (due to large OWF) can significantly alter the bed shear stress and, consequently, erosion/deposition processes influencing nutrient transport and affecting ecosystem dynamics (Deltares 2018).

Furthermore, the stratification and turbulent mixing is known to be important for carbon fixation, biomass distribution, and dissolved oxygen concentrations. For example in both mixed and stratified waters, particulate matter in the lower water layer, especially the fines, may be transported upwards potentially influencing nutrient transport (Deltares 2018).

8.2.3 Changes in zooplankton and benthos affect higher trophic levels

Changes to a system at the level of primary and secondary trophic levels are likely to influence higher trophic levels, i.e. fish, marine mammals and birds. The direction and magnitude of these effects are very hard to assess as the direction and magnitude of the effects on the lower trophic levels are uncertain. Furthermore, there may be direct effects of physical and chemical ecosystem changes to fish, marine mammals and birds. For example, changes in SPM loads may affect feeding success of diving birds that hunt by sight (Baptist and Leopold, 2010).

Knock-on effects of zooplankton changes to higher trophic levels can be expected. Failing recruitment of herring was analysed in Hufnagl *et al.*, 2017 and Payne *et al.*, 2008 showing a correlation between decreased availability of important larval herring prey copepod species and recruitment. Arnott and Ruxton (2002) found comparable relationships between sandeel recruitment and the (NAO-forced) temperature and density of *Calanus sp.*Since both herring and sandeel are important stock species for other fish and marine mammals (Gilles *et al.*, 2016) as well as for several seabird species, any changes in their abundance and distribution has the potential to affect higher trophic levels (Deltares 2018).

Degraer *et al.* (2012) showed differences in flatfish feeding patterns within and outside wind farms. In a more recent study (Degraer *et al.,* 2016), such patterns were also found for the lesser weever and dab, linking their feeding habits to prey species typical for wind farms hard substrates. Whether the availability and ingestion of local prey species will provide benefits for these species and lead to a higher survival of the individuals living around wind farms has not been established. Bergström *et al.* (2013) found increases in piscivorous fish near the piles in an offshore Swedish wind farm in the Baltic Sea. Within the Dutch wind farm OWEZ, increased densities in sole, whiting, and striped red mullet were found compared to outside the wind farm (Lindeboom *et al.*, 2011). The upscaling of wind farms in the southern North Sea will provide more feeding opportunities for fish, but whether this will lead to higher survival rates is unknown (Deltares 2018).

An increase in fish densities within OWFs may lead to increased presence of marine mammals. Russell *et al.*, 2014 reported seals within an OWF. They were however unable to conclude that there was a structural increase in the presence of seals within OWFs.

Cormorants have been found to actively forage within Dutch OWFs, using the platforms for drying their wings (Hartman *et al.*, 2012). Other birds, such as gannets, avoid the wind farms and are thus not likely to profit, they may even lose habitat by avoiding OWF. Any changes in the distribution of fish may lead to changes in the distribution of their predators. Large-scale presence of wind farms in the southern North Sea therefor has the potential to change the large-scale distribution of marine mammals and birds. Whether marine mammals and birds profit from an increased presence of fish and shellfish remains to be studied (Deltares 2018).

8.2.4 Stepping stone effect

The stepping stone effects of OWFs may lead to genetic homogenisation and to the spread of species beyond their natural boundaries. The many structures currently present in the North Sea (buoys, platforms, but also vessels) already contribute to these processes. In contrast to OWFs these have no intertidal zone platforms (Van Duren *et al*., 2016). Furthermore, for subtidal species, additional hard substrate in offshore wind farms may provide stepping stones that tip the balance (Deltares 2018).

Studies in the North Sea on the growth and diversity of epifaunal organisms on OWFs and platforms have been conducted by Vanagt *et al.* (2013), Krone *et al.* (2013), and Mesel *et al.* (2015). These studies show that biodiversity is substantially enhanced in sandy areas where previously no hard substrate was found. Such fouling organisms are also present on buoys, and the many wrecks littered throughout the North Sea. The construction of offshore platforms and OWFs has contributed to an increase in their distributions and numbers; species on the intertidal and subtidal hard substrate add up to around 80 unique species. The construction of OWFs introduces a number of new species, typical for intertidal environments, including a number of non-indigenous species (NIS) (Coolen *et al.*, 2015).

The distribution of these organisms is mainly mediated through the regional and local hydrography; larvae are transported through water currents from source to sink. The speed of transport and duration of the larval phase are important parameters in the (hydrographic) distance between two connected populations of a species. Coolen *et al.* (2017) studied the role of hard structures offshore such as wind farms and oil and gas exploitation platforms in the North Sea. The role these structures play in the distribution of hard substrate species is termed the stepping-stone effect: each structure can act as a sink and source of these species and with decreasing distance between the structures the spatial distribution of species can be facilitated. They found a clear stepping-stone effect of these structures in the North Sea. Any additional wind farm will enhance this stepping-stone effect, which may lead to more comparable species compositions and a lower species genetic diversity. When offshore wind farms are placed near locations where species' distribution is hindered by hydrodynamic boundaries, this could lead to an additional spread of non-endemic species (Adams *et al.*, 2014).

8.2.5 Coastal food web sensitivity

Raoux *et. al* (2019) applied a combination of modelling tools to simulate the impacts of the future Courseulles-sur-mer OWF in the Bay of Seine, English Channel on ecosystem structure and functioning. They considered the added substrate (reef effect), fishing restriction (reserve effect), and their combined effect caused by the presence of the OWF. The analyses suggests that after the installation of the OWF, the ecosystem is expected to be more mature (according to Odum 1969, 1971) while still in a healthy state (according to Mukherjee *et al.*, 2015). Moreover, the study suggested that the small size of the fisheries restriction area would not have any important impact on the ecosystem structure and functioning.

8.3 Knowledge gaps

Deltares (2018) found that the cumulative effect of all marine and coastal human activities is a topic that requires further study and is currently lacking in the literature.

Raoux *et. al* (2019) concluded that as marine ecosystems face many natural and anthropogenic perturbations, there is an urgent need to understand how multiple perturbations interact to influence each other and their consequences on ecosystem functioning and stability (Raoux *et al.*, 2018). Thus, a natural next step would be to develop a holistic view of cumulated impacts within the OWF (Raoux *et al*, 2018).

9 References

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A1 List of references provided by client in 2018

Behind each reference it is mentioned whether or not the paper is included in the report.

1) Physical Processes
    a) No specific papers provided.
2) Ornithology
    a) Cleasby *et al.* 2015 – Three-dimensional tracking of a wide-ranging marine predator: flight heights and vulnerability to offshore wind farms; → **included**
    b) Koppel & Schuster 2015 - Book of Abstracts. Conference on Wind energy and Wildlife impacts; → **included**
    c) Dierschke *et al.* 2016 – Seabirds and offshore wind farms in European waters: Avoidance and attraction; → **included**
    d) Grecian *et al.* 2018 – Understanding the ontogeny of foraging behaviour: insights from combining marine predator bio-logging with satellite-derived oceanography in hidden Markov models; → **included**
    e) Ross-Smith *et al.* 2016a – GPS telemetry reveals differences in the foraging ecology of breeding Lesser Black-backed Gulls between three Special Protection Area colonies; → **included**
    f) Ross-Smith *et al.* 2016b – Modelling flight heights of lesser black-backed gulls and great skuas from GPS: a Bayesian approach; → **included**
    g) Schamoun-Baranes *et al*. 2017 – Sharing the Aerosphere: Conflicts and Potential Solutions; → **included**
    h) Thaxter *et al.* 2013 – Connectivity between seabird features of protected sites and offshore wind farms: Lesser Black-backed Gulls and Great Skuas through the breeding, migration and non-breeding seasons; → **included**
    i) Thaxter *et al.* 2014 - A trial of three harness attachment methods and their suitability for long-term use on Lesser Black-backed Gulls and Great Skuas, Ringing & Migration; → **included**
    j) Thaxter *et al.* 2015 - Seabird–wind farm interactions during the breeding season vary within and between years: A case study of lesser black-backed gull Larus fuscus in the UK; → **included**
    k) Thaxter *et al.* 2018 – Dodging the blades: new insights into three-dimensional space use of offshore wind farms by lesser black-backed gulls *Larus fuscus*; → **included**
    l) Wade *et al.* 2014 – Great skua (*Stercorarius skua*) movements at sea in relation to marine renewable energy developments; → **included**
    m) Wakefield *et al.* 2013 – Space Partitioning Without Territoriality in Gannets; and → **not included as not within scope**
    n) Welcker & Nehls 2016 - Displacement of seabirds by an offshore wind farm in the North Sea. → **included**
3) Bats
    a) No specific papers provided.
4) Benthic Ecology
    a) Coates *et al*. 2015 - Rapid macrobenthic recovery after dredging activities in an offshore wind farm in the Belgian part of the North Sea (BPNS); → **paper added by RHDHV**

b) Gafeira *et al*. 2012 - Semi-automated characterisation of seabed pockmarks in the central North Sea; → **not included as not within scope**

c) Hastie *et al*. 2009 - Cephalopods in the North-Eastern Atlantic: species, biogeography, ecology, exploitation and conservation; → **not included as not within scope**

d) Howell *et al*. 2010 - Identifying deepsea megafaunal epibenthic assemblages for use in habitat mapping and marine protected area network design; → **not included as not within scope**

e) Roberts *et al.* 2015 - Sensitivity of the mussel *Mytilus edulis* to substrate-borne vibration in relation to anthropogenically-generated noise;→ **paper added by RHDHV**

f) Wasson and de Blauwe 2014 - Two new records of cheilostome Bryozoa from British waters → **not included as not within scope**

5) Fish and Shellfish Ecology

   a) No specific papers provided

6) Marine Mammals

   a) Brandt *et al*. 2018 – Disturbance of harbour porpoises during construction of the first seven offshore wind farms in Germany; → **included**

   b) Cheney *et al*. 2014 – Long-term trends in the use of a protected area by small cetaceans in relation to changes in population status→ **not included as not within scope**

   c) Farcas *et al*. 2016 – Underwater noise modelling for environmental impact assessment; → **included**

   d) Graham *et al* 2017 – Responses of bottlenose dolphins and harbour porpoises to impact and vibration piling noise during harbour construction; → **included**

   e) Hastie *et al*. 2015 – Sound exposure in harbour seals during the installation of an offshore wind farm: predictions of auditory damage; → **included**

   f) Hastie *et al*. 2016 – Multiple-Pulse Sounds and Seals: Results of a Harbour Seal (*Phoca vitulina*) Telemetry Study During Wind Farm Construction; → **included**

   g) Jones *et al*. 2015 – Patterns of space use in sympatric marine colonial predators reveal scales of spatial partitioning; → **included**

   h) Jones *et al*. 2017 – Fine-scale harbour seal usage for informed marine spatial planning; → **included**

   i) Lucke *et al*. 2016 – Aerial low-frequency hearing in captive and free-ranging harbour seals (*Phoca vitulina*) measured using auditory brainstem responses; → **included**

   j) McClintock *et al.* 2013 – Combining individual animal movement and ancillary biotelemetry data to investigate population-level activity budgets; → **not included as not within scope**

   k) Russell *et al*. 2013 – Uncovering the links between foraging and breeding regions in a highly mobile mammal→ **not included as not within scope**

   l) Russell *et al*. 2014 – Marine mammals trace anthropogenic structures at sea; → **included**

   m) Russell *et al*. 2015 – Intrinsic and extrinsic drivers of activity budgets in sympatric grey and harbour seals→ **not included as not within scope**

   n) Russell *et al*. 2016 – Avoidance of wind farms by harbour seals is limited to pile driving activities; → **included**

   o) Silva *et al* 2014 - Assessing Performance of Bayesian State-Space Models Fit to Argos Satellite Telemetry Locations Processed with Kalman Filtering→ **not included as not within scope**

7) Multiple topics

   a) Degraer *et al.* 2017 - Environmental impacts of offshore wind farms in the Belgian part of the North Sea: A continued move towards integration and quantification; → **included**

   b) Degraer *et al.* 2018 - Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Assessing and Managing Effect Spheres of Influence; and→ **included**

   c) Schuster *et al.* 2015 - Consolidating the State of Knowledge: A Synoptical Review of Wind Energy's Wildlife Effects. → **included**