Hornsea Project Four

Gannet Displacement and Mortality Evidence Review

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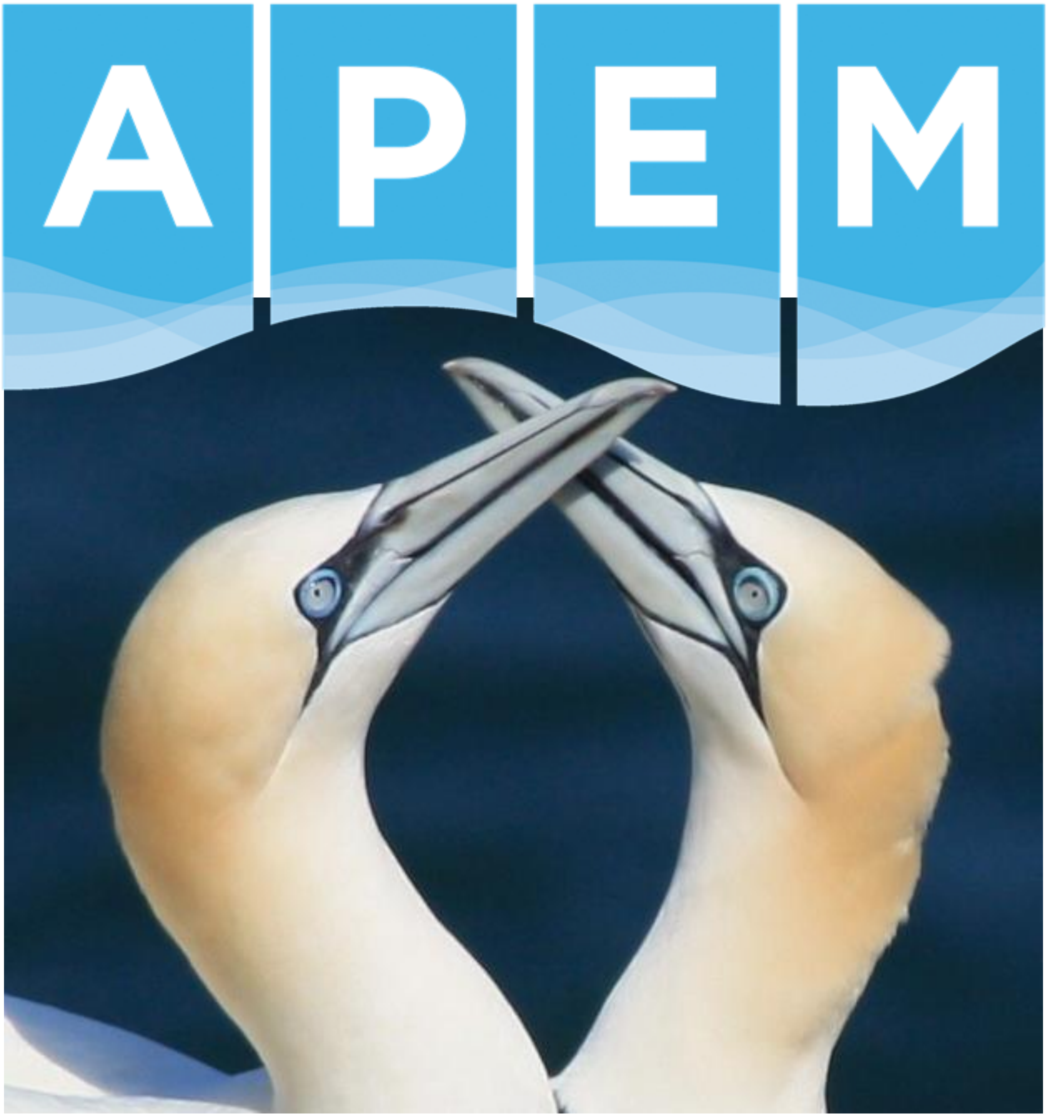

Gannet Displacement and Mortality Evidence Review

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1.1	10/03/2022	All	All	Internal review	SS
1.2	21/03/2022	All	All	Issue to Client	SS
2.0	25/03/2022	All	All	Amendments following Client Review	SS

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1. Executive Summary

1.1.1.1 This technical report presents a review of the latest evidence available and meta-analysis, focussed on gannet (*Morus bassanus*), to determine gannet displacement and associated mortality rates for use in the Hornsea Four Environmental Impact Assessment (EIA) and Habitat Regulations Assessment (HRA) reporting. Evidence has been collated from multiple sources, including offshore wind farm (OWF) technical monitoring reports, published research papers and grey literature study reports that provide data on displacement effects and mortality associated with gannet.

1.1.1.2 Avoidance behaviours observed by birds to OWFs are reported to have various impacts, which include displacement effects from the OWF footprint and surrounding area, avoidance effects to wind turbine generators (WTGs) (macro-, meso- and micro-) and barrier effects. Different methodologies can be used or combined to study these effects, for example at-sea transect surveys are used to study displacement effects via changes in abundance and distribution and various types of tracking studies or density gradient analyses are used to assess WTG avoidance, whereas a combination of these methods can be used for barrier effect determination. This review has focussed on displacement effect and macro-avoidance, which refers to avoidance to the presence of an OWF and not individual WTGs resulting in re-distribution of birds inside and outside of the OWF.

1.1.1.3 The report is the most comprehensive to date, having collated and critically appraised studies from 25 OWFs encompassing 34 years of combined data from 30 reports and publications. Gannet displacement effects varied from no evidence of avoidance to strong avoidance, however, reported effects would either show; a) inferred macro-avoidance or a displacement rate of 60% or higher or b) imply a lack of evidence for macro-avoidance or displacement. The lack of reported displacement rates under 60% should not necessarily be interpreted as avoidance behaviours not occurring at these OWFs, as consideration should be given to the sensitivity of the analysis.

1.1.1.4 This report has identified that OWFs fall into other displacement rate categories aside from than the 60-80% range currently advocated by Statutory Nature Conservation Bodies (SNCBs) for impact assessment for gannet. Although 26% of OWFs in this review fall into the 60-80% range, 32% are reported as rates of >80% and 42% reported or inferred as rates of <60% displacement. However, the report highlights that consideration must be made to the quality of the data used in the assessment and the standard of analysis. Using a critical appraisal approach each study was graded on the confidence of the reported displacement effect as poor, moderate, or good. Only one study was considered to reach a confidence of ‘good’, the majority of studies reporting displacement rates of 60-80% and >80% were of a moderate confidence and the majority of studies reporting displacement rates of <60% were of a low confidence and consisted of UK OWF studies only.

1.1.1.5 The compilation of study data and OWF design metrics from this report has provided the opportunity to determine which variables are associated with displacement effects in the non-breeding season. Fourteen variables were tested for differences in pairwise comparisons between OWFs grouped according to whether a high displacement effect (>75%) was shown or inferred and those suggested to have displacement effects of ≤75%. Four variables were shown to be significantly different between groups inferring an association with high displacement effect and avoidance behaviours, these variables were: density (WTGs/km^2), OWF area, distance between WTGs and distance from shore. Area

and distance between WTGs negatively corelated with displacement rate, whereas density and distance from shore positively correlated with displacement rate.

1.1.1.6 The results imply that high displacement effects (>75%) during the non-breeding season are due to increased avoidance responses when thresholds are reached in relation to the following; an OWF's size (<25 km^2), WTG density (>2.7 WTGs/km^2), perceived access through WTG corridors (distance between WTG rows <900 m) and the further from shore (>19 km), which all contribute to high avoidance behaviour.

1.1.1.7 The data set displays a seasonal difference in the rate of displacement with a significantly lower displacement rate in the breeding season compared to the non-breeding season across the data. Displacement rates for the breeding season in general ranged from 40-60%, with the lower assigned rate being precautionary. For the non-breeding season the displacement rate ranged from 60-75%, which excludes low confidence studies and OWF with higher rates that have certain design metrics.

1.1.1.8 Evidence for the mortality rate of displaced birds has been derived from various studies that predict the population level consequence of displaced seabirds, including gannets, from OWFs using simulation models together with GPS tracking studies that compare bird behaviour around OWFs. Empirical evidence has also been sought from gannet colony data to determine whether any changes have occurred to colony population trends since the operation of local OWFs in support of high mortality rates of up to 10%.

1.1.1.9 The results of simulation models on the impacts of OWF displacement on gannet adult survival are incompatible with a mortality rate of 10% and are suggested to be considerably less from the evidence. As one study showed that incorporating a 10% additional mortality rate had far greater population level consequences than those based on simulation models. Although it is difficult to translate predicted population level effects to additional mortality rates for gannets displaced from OWFs an estimation of additional mortality has been made for gannets at the Flamborough and Filey Coast Special Protection Area (FFC SPA) connected to Hornsea Four. These calculations borrowed additional population mortality rates from other model simulations, which showed low variability in mortality effects between OWFs, predict an additional mortality for displaced birds of 0.4% depending on the proportion of breeding adults that make up the observed bird counts in the Hornsea Four array area.

1.1.1.10 Furthermore, empirical evidence supports mortality rates of considerably less than 10%. Additional mortality effects from displacement at the Heligoland colony population level appear negligible under current monitoring conditions as the colony has continued to show substantial growth for the last several years. This is despite evidence of high macro avoidance of local OWFs during the breeding season which have been in operation since 2015.

1.1.1.11 In summary, the displacement rate for used in the Hornsea Four DCO Application (within EIA and HRA reporting) considered a precautionary 60-80% displacement rate, as advocated by SNCBs. However, evidence from this review supports the application of seasonal displacement rates of 40-60% during the breeding season and 60-75% during the non-breeding season for Hornsea Four. The non-breeding season displacement rate has been refined on account that Hornsea Four's development design layout does not meet the criteria thresholds for variables associated with displacement rates greater than 75%. This review also provides further support for the use of a maximum of 1% mortality being used for assessing potential impacts associated with displacement for gannets from OWFs. Combined, the review of both OWF displacement and consequent mortality rates for gannet provide additional supporting evidence that the impacts put forward for assessment for Hornsea Four are precautionary in nature.

2. Introduction

2.1.1.1 An accumulating number of studies report or predict consequent changes in seabird behaviour at sea to offshore wind farm (OWF) developments between the pre-construction and operational phases. Various assessments and methodologies have been utilised to determine and assess these changes in behaviours for different seabirds. These include:

- Changes in habitat use, in terms of birds being displaced from the area within an OWF (area within which wind turbine generators (WTGs) are located) and their immediate surroundings to varying extents.
- Changes in flight direction and flight heights around and within an array area in relation to the perimeter or to the WTGs termed macro-, meso- and micro-avoidance; and
- Changes to flight lines on approach to an OWF resulting in complete detours around an OWF and termed as a barrier effect.

2.1.1.2 Changes in seabird behaviours towards an OWF may have consequential effects on survival rates and breeding success, which are required to be assessed for Environmental Impact Assessment (EIA) and Habitat Regulations Assessment (HRA) reporting and where necessary within a project's post-consent monitoring. Displacement effects may result in changes in a seabird species' abundance and distribution within an OWF's footprint and potentially out to varying distances beyond its perimeter as a response to construction, operation, and maintenance of the site. Effects have to date generally been assessed by comparing abundance and distribution data from at-sea transect surveys between different phases of studied developments, whilst other approaches have analysed gradients in seabird density in relation to distance from the OWF.

2.1.1.3 Macro-avoidance, together with meso- and micro-avoidance, are used to assess the collision risk of birds in flight to WTGs. These behaviours have been typically recorded by visual observation, radar studies, aerial digital surveys and / or tagging technologies. Data from macro-avoidance studies are primary to inform on the tendency of a bird to enter an OWF or not. However, flight track data can inform on how birds utilise an OWF area in comparison to the wider area and can be used to determine differences in habitat utilisation within a study area. These habitat utilisation values, and macro-avoidance rates are not directly comparable to displacement rates. This is primarily because they consider birds in flight only, are representative of only a very small number of birds from a sub-set of a local population and often only cover selected areas of an OWF. Despite this, in the absence of displacement effect data the use of macro-avoidance rates, habitat utilisation and density gradients can provide a broad indication of the displacement effect that may be occurring.

2.1.1.4 In addition to displacement effects, barrier effects may also influence bird behaviour towards OWFs. Barrier effects are related to changes in flight paths made by birds attempting to reach areas beyond an OWF area either to reach foraging areas or during migration. Changes in distribution of birds in flight around an OWF and their direction of flight from at-sea surveys together with data from macro-avoidance studies can inform on the barrier effect rate and the extent of detours made by birds.

2.1.1.5 Seabird displacement analysis has been considered a major challenge requiring advanced statistical methods to contend with substantial zero counts, spatial correlation, temporal correlation, and non-linear relationships. However, due to not having reached a consensus as to the statistical approach to incorporate into these studies for impact assessment, various statistical methods have been used to analyse displacement effects. For this reason, results need to be treated with caution because of uncertainties regarding their statistical validity and significance. While some studies have reported displacement from OWFs (e.g., Leopold *et al*., 2013; Vanermen *et al*., 2015; Skov *et al*., 2016), others have reported little or no displacement for the same species (Vallejo *et al*., 2017, MacArthur Green, 2021 and APEM, 2022).

2.1.1.6 Studies with high numbers of zero counts (>75%) are accepted to have problems in reliably predicting a displacement rate as spatial and temporal variations in distribution, which occur naturally in mobile species, will dwarf a displacement effect, as highlighted in Leopold (2018) and further highlighted in APEM's review on auk displacement (APEM, 2022). For example, low abundance auk data from the Alpha Ventus, Bligh Bank, Thorntonbank, Horns Rev and similar OWF data sets are problematic to derive a reliable displacement rate, as statistical models have yet to be developed that can robustly incorporate these types of data sets. Conclusions from an international workshop (Leopold, 2018) and the re-analysis of data sets (Zuur, 2018) have resulted in Integrated Nested Laplace Approximations (INLA) analysis to be a recommended method of choice, which incorporates and examines the issues mentioned above to some extent.

2.1.1.7 The aim of this review was primarily to focus on providing the latest reported displacement rates from OWF sites within the North Sea and UK Western Waters to better understand what variables might be influencing the varying degree of gannet displacement reported at different operational OWFs. The review's objective was to utilise this information to provide a more evidenced-based gannet displacement rate for impact assessments and to better understand the likely consequence of displacement in terms of consequential mortality. As studies have utilised various methods of data collection and analysis for post-consent monitoring, gannet displacement rates are not available for all OWFs. However, results from studies that provide macro-avoidance data such as habitat utilisation (e.g., Peschko *et al*., 2021) and density gradient analyses (e.g., Rehfisch *et al*., 2014) have been used in this review to gather evidence of displacement effect for these OWFs.

3. Results

3.1.1.1 Displacement studies on gannets in response to OWFs have previously been summarised in a published review (Deirschke *et al*., 2016), which included gannet displacement analysis from 12 OWF sites. Since the publication of that displacement review there have been several additional OWF sites to have reported displacement effect and macro avoidance studies on gannets (APEM, 2014, APEM, 2017, Webb *et al*., 2017, Garthe *et al*., 2017a, 2017b and 2021, APEM, 2021 and MacArthur Green, 2021) or updates from their monitoring programs (Vanermen *et al*., 2017, 2019 and Degraer *et al*., 2021). A breakdown of the latest displacement / avoidance rates reported at various OWF sites for gannet has been collated and summarised in **Table 1**. Within **Table 1**, the 'years of operational phase monitoring data' refers to the year(s) to which data have been analysed from or combined to, since operational commencement of the OWF. All sources of information used to populate **Table 1** are cited in **Section 3.2**, which summarises the results and conclusions of displacement analysis for each OWF.

Table 1 **Collated results of gannet displacement and macro avoidance at OWFs reported in monitoring studies and peer reviewed publications.**

OWF	Gannet Displacement / Macro-Avoidance Rate							
	Year of Operational Phase Monitoring Data							Survey Period
	Construction Phase	1	2	3	4	5	6	
Beatrice		>60-80%[1]						May - July
Robin Rigg	24%	50%	(-)	(-)	(-)	(-)		Year Round
Westermost Rough	69%	77%	77%/(-)[2]					Year Round/July
North Hoyle		(-)	(-)	NSE[3]				Year Round
Thanet	24%	(-)	38%	57%[4]				October - March
Kentish Flats			NSE					Year Round
Lincs, Inner Dowsing, Lynn	NSE	NSE	72%	62%				Year Round
London Array				NSE				November-February
Gunfleet Sands		(-)[2]						October-March
Greater Gabbard			50-75%[5]					October - November
Bligh Bank (Belwind)*	(-)	30%		85%		82%[6]		Year Round
Thornton Bank Phase I, II, III	NSE			99%	97%		98%	Year Round
Prinses Amalia				~90%				Year Round
Egmond aan Zee					~75%			Year Round
Horns Rev 1			(-)					March-May/September-November
Horns Rev 2			86%					November-April
Walney 1, 2				40-50%				May-October
Alpha Ventus	NSE			79%				March-May/September-November
Helgoland Cluster & Butendiek			37%[7]/89%[8]					May-July

Table Notes: [1] displacement effect statistically significant but rate not specified but inferred from report, [2] avoidance observed but numbers too low for analysis, [3] analysis may not have been sensitive enough to detect any differences, [4] difference in density between OWF and 1 km buffer not statistically significant [5] density gradient analysis using three months of survey data conducted in year 2 reported a displacement rate of 95% however this likely to be an overestimate due to the analysis method, displacement rate in table is a re-calculation, [6] 4.5 years of operational survey data, [7] reduction in habitat utilisation derived from tracking data, [8] avoidance was classified as birds that did not enter the OWFs on more than three occasions and stayed for more than 30 min inside the OWFs during each occasion. NSE; no significant effect, (-); avoidance inferred by authors, but displacement rate not quantified.

3.2 Critical appraisal of OWF monitoring studies and publications

3.2.1.1 For each OWF described below, grey-literature reports and peer-reviewed publications have been collated, reviewed and critically appraised. Site conditions and study outcomes have been summarised and displacement effects described. Attention has been paid to the limitations of the study including design, results and conclusions reached by the authors and any reasons for applying caution when interpreting the displacement or macro avoidance rate. This has permitted any uncertainties in the confidence of study results to be highlighted for each OWF and when deriving a gannet displacement rate range to OWFs for impact assessment in general, which is discussed in further detail in **Section 3.3**.

3.2.2 Beatrice

3.2.2.1 Survey data for Beatrice OWF included one year of pre-construction surveys from 2015 and one year of post-construction surveys from 2019, six surveys in total from each year for May to July. Model based population estimates of birds on the water pre-construction were a peak of 708 gannets in the study area with 229 within the OWF area, whereas during the first year of operation a peak estimate of 391 gannets in the study area with 128 within the OWF. The spatial modelling comparisons indicated a significant decrease centred on the OWF and extending to the coast, the remainder of the survey area was almost identical between 2015 and 2019 (MacArthur Green 2021). For birds in flight only, comparison between pre-construction and operation phases suggested complete macro-avoidance of the OWF with the exception in one survey. It should be noted that construction activities including piling were ongoing at the adjacent Moray East OWF during the survey period of the study area that may have influenced gannet displacement and macro-avoidance behaviours to some degree. It should be stressed that Moray East is in line with the general direction of approach for gannets arriving to forage from the nearest breeding colony at Troup Head.

3.2.2.2 *Conclusions*: The first year of operational monitoring observed a high degree of OWF avoidance, authors suggest displacement may exceed 60-80%, but a given rate was not specified. Macro-avoidance was suggested to be high, but not complete, suggesting the OWF was acting as a barrier to birds commuting beyond the OWF. However, it is unknown whether ongoing construction activities at the adjacent Moray East OWF may have compounded the impact of the operational Beatrice OWF on the behaviour of gannets.

3.2.3 Robin Rigg

3.2.3.1 Survey data from the Robin Rigg OWF includes five years of post-construction data covering all seasons, gannets were seen primarily during the summer months, particularly in June and July, with only sporadic sightings between October and March. Except for a survey in July 2007 there is a three-year period between the last pre-construction survey and commencement of the construction phase surveys in 2008. The post-monitoring report after years one and two of operation suggested a decline, compared to the pre-construction phase, in the number of gannets recorded during (24% decline of birds on the water and 17% decline of birds in flight) and after construction (50% decline after year one of operation), with a degree of recovery suggested during operational year two compared to one (Walls et al., 2013; Canning *et al*., 2012). Five years of successive post-construction monitoring has observed gannets within the OWF, although not to the same densities seen pre-construction (0.17 to 0.01 birds / km^2 within the OWF) suggesting a high level of avoidance was still apparent (Canning et al., 2013, Nelson et al., 2015). However, declines seen over time across the wider survey area (0.15 to 0.09 birds/km^2) related to natural changes in distribution may distort the true level of the displacement effect and habituation (Nelson et al., 2015). Mapped observations covering the five-year monitoring period clearly show avoidance of the OWF in comparison with the wider area, with gannets that are observed within the OWF predominantly close to the boundary turbines. Gannets in flight were not recorded within the OWF during any of the five operational years. This may indicate macro-avoidance of the Robin Rigg OWF by flying gannets, however numbers were too low across all three development phases to test this statistically.

3.2.3.2 *Conclusions*: High macro-avoidance suggested from lack of birds in flight within the OWF, although not statistically tested due to low study area numbers. Displacement of up to 50% reported during the first year of operation compared to pre-construction, but current rate of displacement not determined. However, mapped observations clearly show restricted use of the OWF, in particular the central area in comparison with the wider study area, with gannets that are observed within the OWF predominantly close to the outermost or boundary wind turbine generators (WTGs). Therefore, evidence of some displacement effect is present, possibly less than 60-80%, but without spatial modelling the true extent is undetermined.

3.2.4 Westermost Rough

3.2.4.1 Two years of operational surveys were conducted of the Westermost Rough OWF and a separate reference or control area during all seasons and mean seabird densities estimated. Population estimates indicated gannet numbers had declined since the pre-construction surveys, but also did so in the reference area. Gannet numbers were highest at the end of the breeding season, peaking in September, but also in comparable numbers in June. A pairwise comparison of gannet densities between different phases of the development and between the development area and the reference area suggested significant declines during construction and operational years. Declines equated to 69% during construction and 77% in operational years one and two, when compared to the pre-construction phase (Percival and Ford, 2017). However, these changes did not account for any natural variations in the wider study area which was shown occurring in the reference area between years. A further study consisting of three surveys were conducted of the Westermost Rough OWF and an 8 km buffer after two years of operation during July, which represents a period during the migration-free breeding season for gannets from the nearest colony at the FFC SPA to the north. The results represent a total of 164 gannets in flight of which only one was observed within the OWF (APEM, 2017). The number of gannets observed were insufficient for detailed analysis of OWF effects, however mapped distribution of gannets recorded during the three surveys suggests a degree of avoidance to the OWF if birds are travelling to and from the FFC SPA.

3.2.4.2 *Conclusions*: These two studies suggest displacement from the Westermost Rough OWF during construction and operation phases are evident together with macro-avoidance. However, low counts recorded during pre-construction surveys and increases in abundance between years over the whole study area (peak estimates in the refence area varied from 19 to 873 gannets between years) reduces the confidence in the rates reported given the statistical approaches lacked spatial modelling and relied on pairwise comparisons of mean densities.

3.2.5 North Hoyle

3.2.5.1 Monthly surveys were conducted year-round at the North Hoyle OWF. The first-year operational monitoring report inferred gannets flying further away in general from the OWF, though some birds had been observed entering the OWF, however no detailed analysis was conducted (May, 2005 and PMSS, 2006). The second-year monitoring report suggested a barrier effect was evident, though again some gannets still passed through the OWF site since it had become operational (PMSS, 2007). The third-year monitoring report showed the numbers of gannets entering the array area were beginning to rise but not to the numbers seen in the pre-construction phase, suggesting habituation. The results of a density analysis suggested that there is no evidence of change in usage between the development phases (PMSS, 2008).

3.2.5.2 *Conclusions*: Although these studies demonstrated gannets were discouraged, but not excluded, from the North Hoyle OWF area, particularly in the first two years of operation, it is difficult to determine the displacement/barrier effect rate with any accuracy due to changes in abundance in the wider study area between project phases. Although the third-year study report suggests there is no statistically significant differences between phases, the analysis may not have been sensitive enough to exclude displacement effects are occurring at any level.

3.2.6 Thanet

3.2.6.1 Surveys were conducted over the Thanet OWF site and a buffer as well as a control area during the winter and migratory periods (October to March) with baseline surveys recording gannets in low numbers within the OWF site. During construction gannets were largely absent from within the OWF site, with numbers concentrated within the eastern extents of the buffer areas around the OWF site (Hillyer, 2010). As numbers remained relatively unchanged within the buffer areas and control area between pre-construction and construction phases, displacement is suggested to have occurred from the OWF. Statistical comparisons indicated a significant difference in abundance between the pre-construction phase and year one of operation within the OWF with a distance effect out to 1 km (Ecology Consulting, 2012a). Statistical comparisons after two years of operation suggested a 38% displacement rate from the OWF compared to the pre-construction baseline (Ecology Consulting, 2012b). Although evidence of partial displacement is suggested the number of gannets throughout the surveys, especially during pre-construction, were low within the OWF. In the operational phase gannet numbers remained concentrated within the eastern areas of the OWF. This was evident from the spatial distribution maps in all three operational years showing a degree of avoidance of the central, western, and southern areas of the OWF. This may, to some extent, be explained with the difference in marine traffic activity associated with the OWF site between the eastern and western areas of the OWF. This would suggest areas of lower vessel activity such as in the eastern areas of the OWF are associated with lower avoidance by gannets (see **Figure 1**).

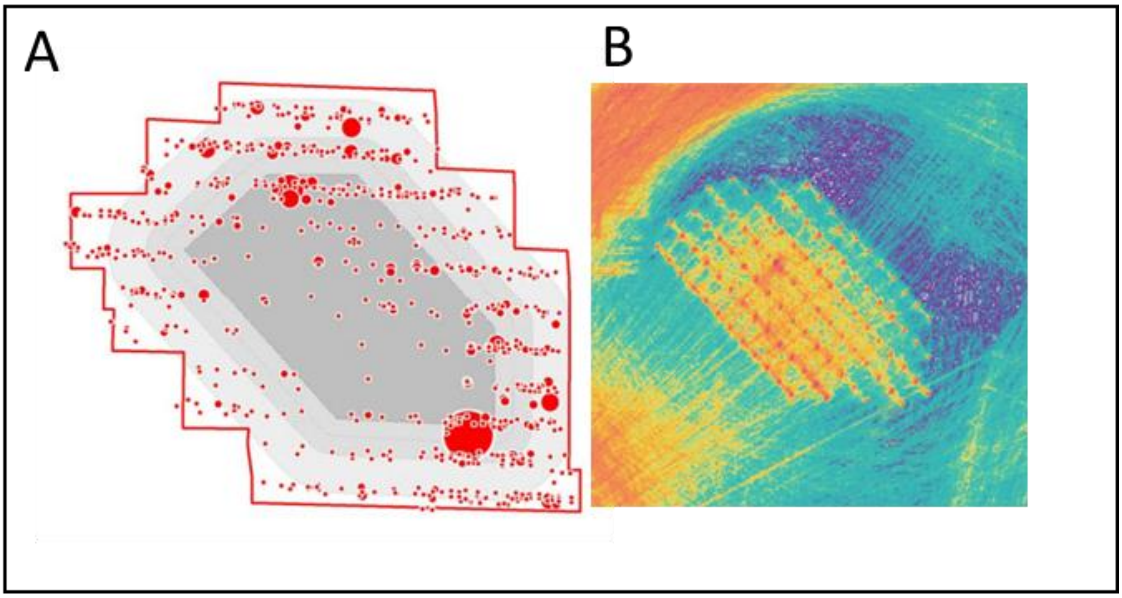

Figure 1 Comparison of gannet spatial distribution and marine traffic activity at Thanet OWF. Spatial distribution of gannets at Thanet OWF operational year three (A) (reprinted from Percival, 2013, p19). Marine traffic density at Thanet OWF and surrounding area. Marine traffic density compiled from MarineTraffic, accessed March 17, 2022, https://www.marinetraffic.com/.

3.2.6.2 The final report, following three years of operations, suggested there was no statistically significant evidence of any effect from the OWF on gannets (Percival, 2013). However, gannet density was clearly lower inside the OWF than outside in year three of operation, with a 57% reduction in numbers compared to areas 1 km from the OWF.

3.2.6.3 *Conclusions*: Caution needs to be applied to the displacement effects reported (<60%) at the Thanet OWF, as the site supported very low numbers of gannets during the pre-construction surveys and abundance was highly variable across the survey area between years. Statistical analysis was based on mean grid square count differences and not on spatial modelling comparisons, which may have lacked the power to demonstrate changes in abundance in the OWF and distributional changes across the study area. Although the final monitoring report suggests no evidence of any significant effect from the Thanet OWF on gannets, this is unlikely given a distance effect was shown in the report and with the benefit of correlations of vessel traffic activity alongside gannet distribution data at the OWF.

3.2.7 Kentish Flats

3.2.7.1 Surveys were conducted each month with gannets recorded from May to October in the study area with the highest numbers recorded during the breeding season, however numbers were low with a substantial number of zero counts. The results of the quantitative seabird density comparisons between the pre-construction, construction and operational phases suggested that gannet numbers show no evidence of change (Gill *et al*., 2008).

3.2.7.2 *Conclusions*: Caution needs to be applied to the conclusions reached in the report that states there are no displacement effects occurring, as the Kentish Flats OWF site supported very low numbers of gannets throughout the surveys.

3.2.8 Lincs, Inner Dowsing and Lynn

3.2.8.1 Gannet abundance was very low in the Lincs, Inner Dowsing and Lynn OWF study area with a peak in the autumn (September), when gannets would have been migrating through the area. There was a gradient in the displacement effect for all post-construction years, but not the construction phase, likely to be due to a masking effect from the significant increases in abundance in the wider study area during the construction period. The displacement gradient was only statistically significant in the second year, when the displacement was up to 3 km from the OWF, whilst in the three years combined data the displacement was out to 1 km from the OWF (Webb *et al*., 2017). Displacement rates calculated for year two of operation and the three years combined data, assuming birds relocated within the Greater Wash study area, were 71.9% and 61.7%, respectively (Webb *et al*., 2017).

3.2.8.2 *Conclusion*: A displacement effect was detected at the OWF, however, its magnitude and distance differed between years. Caution needs to be applied to these results due to the very low observed counts; mean predicted density pre- and post-construction of <0.2 birds/km^2 across the OWF. The distribution of gannet in the wider study area changed during the monitoring period; with areas of relatively high abundance during the pre- and during-construction phases used less during the operational phase, though this may have masked any localised patterns in distribution when comparing between these phases.

3.2.9 London Array

3.2.9.1 Analysis of the London Array OWF was based on winter surveys (November to February) consisting of one year pre-construction, two years construction and three years of post-construction data (APEM, 2021). Two zones where surveyed; Zone 1 surrounding the OWF area and Zone 2 an adjacent reference or control area. Non-parametric analysis was undertaken for gannets, to investigate if there was any significant difference in densities between the development phases for Zone 1 and Zone 2. Gannet mean density decreased in Zone 1 across development phases from 0.38 birds km^2 (pre-construction) to 0.13 birds km^2 (post construction). The Kruskal-Wallis test showed that the density of gannets in Zone 1 was not significantly different between each of the development phases (APEM, 2021). Counts within the OWF site between all phases were too low for any meaningful assessment, with seven individuals pre-construction, zero during construction and zero, two and three during operational years 1 to 3, respectively.

3.2.9.2 *Conclusion*: Caution needs to be applied to the results suggesting there are no OWF displacement effects from London Array, due to the very low observed counts and few gannets observed within OWF area pre-construction for meaningful comparisons.

3.2.10 Gunfleet Sands

3.2.10.1 Analysis of the gannet assessment for Gunfleet Sands OWF consisted of survey data collected between October to March during the first year of operation. Gannet counts were low (total count of 4) and only observed in October and December surveys. Gannets were observed in flight only and did not pass through the OWF (Percival, 2010).

3.2.10.2 Conclusions: Numbers of gannets were too low to make any meaningful comparisons between phases to assess displacement effects.

3.2.11 Greater Gabbard

3.2.11.1 Four surveys were conducted during autumn passage between October and November two years after the construction of Greater Gabbard OWF. Surveys consisted of randomly selected transects that crossed or abutted the OWF and started and ended 10 km from the OWF. Modelled relationships between the distance to the nearest WTG and gannet counts outside of the OWF suggested gannet avoidance effects of up to 2 km from the nearest WTG. The displacement rate was calculated as 95% for the OWF footprint using the mean density within the OWF compared to background density outside the OWF (Rehfisch *et al*., 2014).

3.2.11.2 *Conclusions*: A high displacement rate was observed for the Greater Gabbard OWF footprint, with effects reported applying to the autumn migratory season and consisting of modelled data from one survey season. Habitat utilisation of the OWF area pre-construction was not compared to the post-construction phase to determine whether other factors had influenced distribution. Hence the avoidance rate may be overestimated, as it presumes a homogenous distribution of gannets in the absence of the OWF, which is not the case. The rate of avoidance is reduced to 50-75% if mean densities of birds that keep more than 0.5 km from the nearest WTG inside the OWF are compared to background densities.

3.2.12 Bligh Bank

3.2.12.1 Gannet displacement effects for Bligh Bank OWF are based on four and a half years of post-construction data including all months. Gannet numbers were highest during the autumn migration peaking at 0.98 birds / km^2 prior to construction (Vanerman and Steinen, 2009). During the construction phase an avoidance effect was considered due to changes in densities within the OWF, however when compared to the control area it did not reach statistical significance (Vanerman et al, 2011). Assessment of the first year of operational data showed gannets were significantly displaced from the OWF, by approximately 70% (Vanerman *et al*., 2012). After three years of operations gannets were suggested to avoid the OWF area and up to 3 km from the nearest WTG (Vanermen *et al.,* 2013). The displacement rate was calculated to be approximately 85% and gannets that were observed within the OWF were those recorded towards the outermost WTGs (Vanermen *et al.,* 2015). After five years of operational monitoring, gannets were suggested to avoid the OWF area and a 0.5 km buffer, with an estimated displacement rate of 82% (Vanermen *et al.,* 2016). However, there was significant zero-inflation in the data set and the authors highlight that up to 10 years of monitoring may be needed to obtain sufficient power to be confident that even substantial changes in density are reliable. There is also evidence of habituation, with displacement effects decreasing from up to 3 km to 0.5 km from the OWF after five years of operations.

3.2.12.2 *Conclusions*: Caution should be used when comparing the changes in bird densities in the study area using the before-after-control-impact (BACI) approach. The control area displayed increases in densities of more than double in months with maximal numbers, though these changes may not have represented the natural temporal changes occurring in the study area or being close to the study area may have included birds displaced from the OWF, which would inflate the displacement rate reported. Furthermore, the study area is complex with regard to the number of OWF projects (two tight clusters of Belgian and Dutch development sites) and the timing and locations of construction activity. The assessment of impacts over the five-year operational study phase was not, strictly speaking, free from construction activity during this period of assessment. The final five-year impact assessment includes data commencing from September 2010, even though construction activities did not end until December 2010 on site. Furthermore, during 2013 at the northeast boundary of the site the Belwind demonstration WTG was being constructed, during 2013 to 2014 Northwind OWF 9 km to the southeast was being constructed and Thorntonbank Phase II and III was also being constructed between 2010 and 2013. Therefore, only the final 10 months of the survey data over the four and half years of assessment was collected when the Belgian OWF concession zone was free of any construction activities. Given that the impacts on gannets predominantly reflect the autumn migration, in which gannets have been shown to pass through the Belgian North Sea in a south westerly direction, construction activities may have influenced natural flight paths more than an operational OWF. It would be prudent to, therefore, consider whether the high displacement rates reported for gannets in Belgian operational OWFs may also reflect compounded construction impacts including related vessel activity, which may have resulted in higher disturbance effects. It should also be noted that the WTG layout within the Belgian OWF concession zone lies on a northwest to southeast axis, with no substantial corridors running along the general south-westerly autumn migration flight path (see **Figure 2**). This, in turn, may lead to the higher avoidance rate reported for both Bligh Bank and Thorntonbank OWFs as there is no clear line of sight through the OWF cluster that would not require negotiating WTGs on a flight path.

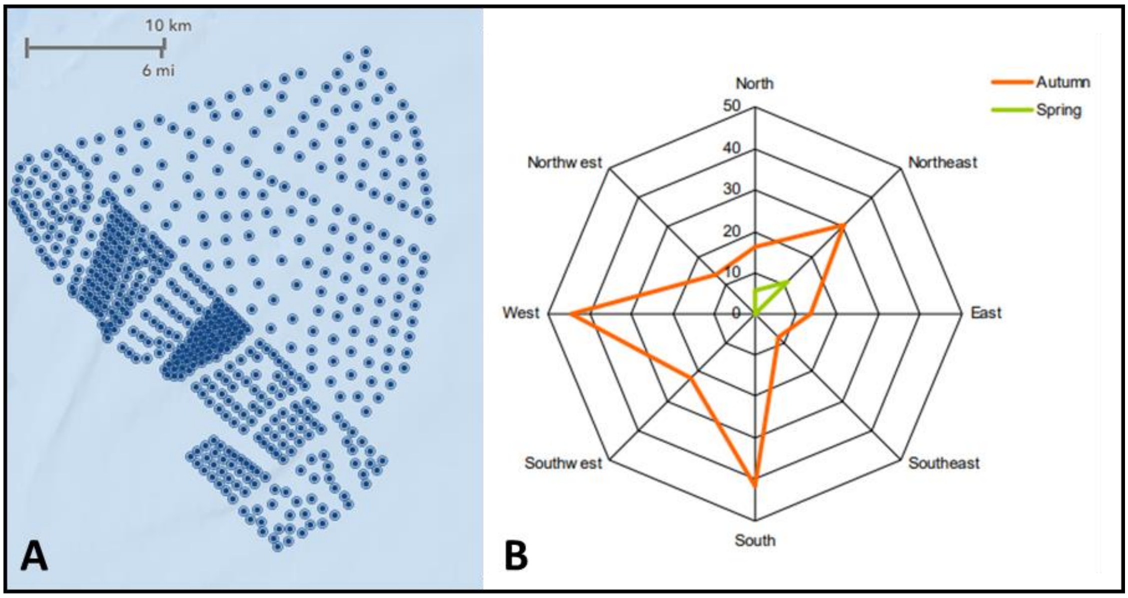

Figure 2 Belgium/Dutch OWF cluster layout from 2020 (A) adapted from 4Coffshore accessed March 17, 2022, https://map.4coffshore.com/offshorewind/, gannet migratory season flight directions (B) reprinted from Vanermen and Stienen, 2009p89.

3.2.13 Thorntonbank I, II, III

3.2.13.1 Thorntonbank OWF was constructed in three phases: Phase I from 2008 to 2009, Phase II 2010 to 2012 and Phase III from 2011 to 2013. Gannet displacement effects for Thorntonbank OWF are based on 6 years post-construction data, including all months in each year, with gannet numbers highest between September and February and peaking in autumn at 1.14 birds / km^2 prior to construction (Vaneman and Steinen, 2009). During the construction of Phase I an initial displacement rate of 43% was reported, based on changes in densities (Vaneman and Steinen, 2009), however, in the subsequent monitoring years changes in densities for the operational phase I OWF were not considered an effect from the OWF as similar changes were seen in the control area (Vaneman *et al*., 2011, 2012 and 2013). During construction of Phase II and III avoidance of the OWF was suggested for gannet, however these changes were not statistically significant (Vanermen *et al.,* 2013). The three-year operational assessment concluded that gannet had been displaced from the OWF and 0.5 km buffer by 99% and significant displacement was also shown for the 0.5 to 3 km buffer (Vanermen *et al.,* 2016). The four-year operational assessment, which added only a further four surveys, showed a significant displacement rate of 97%. This was not too different to the previous assessment, as would be expected with only a few extra surveys included since the 2016 report. However, the number of gannets observed within the OWF increased from one in the previous period to 42 during that year's assessment (Vanermen *et al.,* 2017).

3.2.13.2 *Conclusions*: Results after six years of post-construction data collection showed a gannet displacement rate of 98% for the OWF and 0.5 km buffer, but no significant displacement was shown for the 0.5 to 3 km buffer as in previous assessments (Vanermen *et al.,* 2019), therefore a displacement effect was no longer apparent in the surrounding buffer zone. The six-year operation assessment included surveys undertaken during construction of Thorntonbank Phase III, Northwind

OWF within 8 km to the northwest, Nobelwind OWF further to the northwest, Rentel OWF and Norther OWF, which are 1 km distant either side of Thorntonbank. Therefore, only the survey period during 2015/16 collected data when the Belgian OWF concession zone was free of any construction activities and coincides when surveys reported the highest number of gannets within the OWF. The Belgian OWF concession zone should now be considered as one large OWF cluster, which also comprises the now completed Dutch OWF cluster to the north. It will be interesting to see what gannet displacement rates are reported now the concession zone is fully occupied by WTGs and construction activities in this zone have ceased. Preliminary surveys of the Belgian OWF concession zone suggest gannets showing signs of habituation to the OWFs and that displacement rates may be considerably reduced (Degarer et al 2021).

3.2.14 Prinses Amalia and Egmond aan Zee

3.2.14.1 Analysis of Prinses Amalia and Egmond aan Zee OWFs was conducted under one study (Leopold *et al*., 2013). The OWFs were built in close proximity to each other and in succession but are of a different design. One year of pre-construction surveys (2002-04) and four years of operational surveys (2007-12) were undertaken, with six surveys throughout the year covering approximately the same months. Additional survey lines covering the OWFs were introduced in the third and fourth survey years. Surveys were undertaken by boat and completed within one week for each survey month. The first year of survey data for Egmond aan Zee OWF were undertaken while construction (post-pile driving) was occurring at the nearby Prinses Amalia OWF. Gannets observed in the study area (n=485) comprised of 55% flying and 45% swimming (sitting on the water). The modelled analysis suggested that gannets avoided the OWF with the few birds that did enter the OWF remaining close to the OWF's boundaries and only observed flying and not foraging, in contrast to birds observed outside the OWF, which frequently recorded foraging.

3.2.14.2 Conclusions: Avoidance of both OWFs was shown to be statistically significant for gannets with displacement rates of ~90% and ~75% (rates not provided but estimated from the report) for Prinses Amalia and Egmond aan Zee, respectively (Leopold *et al*., 2013). Similar numbers were seen in both OWFs however background levels were higher around Prinses Amalia resulting in the higher estimated displacement rate. The higher displacement rate for Prinses Amalia may have been skewed by data for the first year, including surveys prior to the completion of the construction phase.

3.2.15 Alpha Ventus

3.2.15.1 Alpha Ventus is a small OWF of only 4 km^2 consisting of 12 WTGs. A single year of surveys conducted in winter and spring during the construction phase provided no evidence of direct impacts on gannets (BSH 2011). Post-construction a spatial gradient analysis was designed to detect small scale differences in the spatial distribution of seabirds resulting from the presence of the OWF without the inclusion of pre-construction data. Four control sites were selected: north, south, east and west of the OWF for comparison. Gannet counts were low with a total of 60 gannets across three years (77 surveys) of which approximately 3 were within the OWF, suggesting a high number of zero counts. Significant differences were shown for two of the control sites, east and west at 2 and 4 km from the OWF, respectively, but not the north and south sites that bordered the OWF. The study reported gannets were 79% less abundant inside the OWF than outside (Welcker and Nehls, 2016).

3.2.15.2 *Conclusions*: The study suggests a high displacement rate for gannets, however gannet abundance at the two control sites bordering the OWF were not significantly different compared to the sites located 2 km or more away from the OWF. This can be interpreted as either the displacement effects extend beyond the OWF but within 2 km or differences reflect natural spatial scale variation in gannet abundance due to distributional changes in covariables such as prey. Together with the low counts observed, caution should be applied to the interpretation of a high displacement rate reported for this study.

3.2.16 Walney 1 and 2

3.2.16.1 Surveys of the study area for Walney 1 and 2 were undertaken for two years pre-construction (2008-09) and during construction (2010-11) and three years of post-construction surveys (2012-14). The surveys covered a 4 km buffer area and two reference areas and were conducted from May to October. Gannet numbers peaked during July with a peak density of 0.98 birds / km^2 with similar densities recorded in the 2-4 km buffer area. During the autumn migratory season gannets were recorded in lower numbers. The highest densities occurred during the breeding season, whilst densities decreased from pre-construction to construction phase and increased during the operational phase, but not to levels recorded pre-construction. However, a similar trend between phases was seen in the reference area, which would suggest changes in abundance in the wider area have also influenced changes in the OWF. Changes in mean densities between all phases and zones were presented graphically, suggesting some partial displacement effect may be occurring of 40-50%, but without any statistical verification and when accounting for changes in abundance in the wider survey area the evidence from this study is poor.

3.2.17 Horns Rev 1 and 2

3.2.17.1 Two years of post-construction surveys were conducted for Horns Rev 1 in year two and three of operations during spring and autumn. Gannets were observed in the study area both in flight and foraging, with a total of 66 gannets were recorded, but only two entering the OWF (Blew et al 2008). Baseline aerial surveys for Horns Rev 2 conducted between November to April indicated low gannet abundance in the area with a mean density of 0.012 birds / km^2, however, abundance of gannets in the Horns Rev area is known to be highly variable from year to year (Petersen *et al*., 2014). Operational surveys of the wider area including both Horns Rev 1 and 2 was conducted in 2011/12, covering the autumn to spring migratory seasons and recorded few gannets (n=58). The majority of birds were recorded to the west of the OWF on the opposite side of where tracking studies were performed, but also included observations on the periphery and within the OWF. Due to low numbers being recorded, gannets were not chosen for pre- or post-construction comparison. Post-construction monitoring at Horns Rev 2 OWF included monitoring potential impacts of operations on bird migration, such as collision risk and barrier effects. Monitoring was based on radar- and rangefinder-based tracking methods capable of collecting species-specific data. However, this was from a single point and coverage of the OWF, therefore was not complete and was biased towards calm weather conditions. Operational monitoring was performed during the autumn and spring migratory seasons, September to November and March to May, respectively, for two consecutive years. Gannet flight patterns showed limited directional trend, thus indicating birds observed in the study area during the migratory period do so for feeding and resting as they migrate to their wintering areas. As they are uncommon wintering birds in the area, observed gannets during the migratory seasons can be considered as resident staging birds. Recorded tracks of gannets were predominantly outside the OWF but included tracks along the OWF boundary as well as movements penetrating the OWF. Data consisted of 72 gannet tracks of which 10 entered the OWF area, resulting in an 86% macro-avoidance rate. (Skov *et al*., 2012).

3.2.17.2 Conclusions: Due to low counts reported for Horns Rev 1 and 2 no conclusions can be made regarding displacement from OWFs. Tracking studies during the migratory seasons estimated on the basis of the number of tracks entering the OWF suggest a macro-avoidance rate of 89%, derived from 72 tracks covering a period from autumn to spring. However, caution should be applied to this rate as tracks were only recorded from a single point within the OWF and the general distribution of gannets in the area is highly variable.

3.2.18 Heligoland Cluster & Butendiek

3.2.18.1 Gannet responses to OWFs in the Heligoland area have been studied using GPS data loggers to analyse flight tracks of birds breeding at the colony on the island of Heligoland (Garthe *et al*., 2017a, 2017b and 2021). Data from three chick-rearing birds were analysed, with the tracked data from approximately three to 10 weeks during the 2014 breeding season. The distribution of gannets from ship-based and aerial surveys prior to OWF construction were predominantly to the west and south of Heligoland. The tracking studies were undertaken when none of the OWFs of the Heligoland cluster (Amrumbank West, Nordsee Ost and Meerwind OWFs) or the Butendiek OWF were operational. Development stages at each site were as follows; all WTGs had been constructed at Meerwind OWF, WTG installation at Nordsee Ost and foundation installation at Amrumbank and Butendiek OWFs. Flight tracks showed the highest density to the west and south of Heligoland as expected from the pre-construction distribution data, with one bird demonstrating tracks to the north flying towards the development sites and flying through Butendiek construction site. The area of sea surrounding the OWF developments was demonstrated to have a gannet density of four-fold less than to the west and south of Helgoland pre-construction and therefore is not surprising to find the majority of tracks in this area. The flight tracks of a single individual that foraged in the direction of the OWF gives the impression of avoidance of OWFs with WTGs installed, with only a single track within the OWF boundary, but did not avoid developments at the foundation installation stage. Garthe et al., (2017b) conducted a similar tracking study in 2015, when at such time the OWFs mentioned above were fully operational, with the exception of Amrumbank OWF which was partially constructed with some WTGs generating power. Flight tracks showed that most flights targeted areas for foraging to the north and northwest of Heligoland, this is in contrast to distribution during the pre-construction period showing the highest densities for gannet to the west and south of Heligoland. The study showed flight tracks of three individual birds with tracks that head towards the OWFs and then passed around them much more frequently than flying through them, with a higher number of tracks through the partially constructed OWF than the fully operational ones. The study reported that five of the 14 gannets tracked did not enter the OWFs, four only flew into the OWFs once, while four visited them occasionally and one frequently. A further study combined the tracking results of Garthe et al (2017b) with further tracking data collected from another 14 gannets during the breeding season of 2016, at which time the three OWFs in the Heligoland cluster were fully operational (Peschko *et al*., 2021). Modelling was applied to test whether habitat use (an area up to 15 km from the OWF border) was affected by the presence of OWFs. Avoidance was classified as birds that did not enter the OWFs on more than three occasions and did not stay for more than 30 min inside the OWFs during each occasion. Under this classification 89% of birds tracked avoided the OWFs, however, only 25% showed complete avoidance of OWFs and 11% (n=3) of birds frequently entered the OWFs and others further from the colony. Individuals that entered the OWF areas did so to commute to foraging areas and forage within the OWF, whilst resting within an OWF area was rare. Gannets entering the OWF showed a strong avoidance from the area up to 250 m distance from the WTGs, the data also revealed that individuals entering the OWF tolerated closer distances to WTGs than birds that passed on the outside. Individual birds avoiding the OWFs tended to commute and forage to areas west and north-west of the colony, a core foraging area identified during pre-construction surveys. Habitat utilisation models revealed a significantly reduced selection of the OWFs compared with the surrounding area of 21% in 2015 and 37% in 2016 (note in 2016 a further OWF which became operational was included in the analysis).

3.2.18.2 Conclusions: Based on limited data of n=3 and n=14 per study over two consecutive breeding seasons, the evidence suggests avoidance of OWFs once WTGs are present, but avoidance is not complete with 65% of birds tracked showing, to varying degrees, commutes through the OWFs. Gannets entering the OWFs did so mostly along the periphery, passing along the boundary of the OWF, but flights through the OWF were also recorded (Garthe et al., 2017a and 2017b). The most comprehensive tracking study to date for the area showed gannet behaviour to operating OWFs is complex. Birds that completely avoided the OWF areas, mostly visited areas that were core foraging areas away from the OWFs that were intensely used for many years as a key foraging area prior to the OWFs being present, so this may not actually be OWF avoidance, but a preference for a key foraging area over all other areas. A total of 75% of birds showed use of the OWF areas and 11% frequent use for both commuting and foraging. Although avoidance of OWF areas was evident its use compared to the surrounding areas was shown to be reduced by 37% in the latest year, which is considerably less than that reported by line-transect survey analysis.

3.2.18.3 Gannets may accept passing through OWFs more during the breeding season if it reduces their travel time and costs considerably. Avoidance estimated from survey data (investigating effects on density or abundance of species) cannot be compared directly with values estimated from tracking data (inferring resource selection), and the resulting reduction in resource selection is not readily comparable to the reduction in abundance.

3.3 Deriving an evidence-based displacement rate for gannets

3.3.1.1 A compilation of post-construction monitoring studies, including 22 OWFs reporting on the assessment of displacement effects for gannets, has been presented in **Section 3.2**. These studies suggest gannet displacement effects vary considerably within different study sites displaying a range of displacement rates, including rates outside the current predicted range advocated for impact assessment by UK Statutory Nature Conservation Bodies (SNCBs) and the RSPB of between 60-80% displacement for gannets.

3.3.1.2 When considering gannet behavioural responses to OWFs it is important to distinguish behaviours that result in displacement and / or barrier effects in the reports, as not only will this have different consequences in terms of mortality effects but also as this may overestimate the displacement rate. For example, the conclusions from studies suggest that OWFs are avoided and detoured to a greater extent by migratory birds in the non-breeding season than by resident birds. Therefore, unless the OWF resides in a staging area the OWF is likely to cause predominantly barrier effects only, but would be classed under a high displacement rate using current analysis and reporting methods. Similarly, during the breeding season impacts can result in both displacement and barrier effects depending on whether the birds are foraging beyond an OWF, which again may inflate the displacement rate. Therefore, where evident barrier effects were noted these have been reported in the results summary table. Tracking studies may overestimate avoidance as they will include tracks from birds not approaching the OWF or intending to enter the OWF and should only assess tracks which show behavioural changes in flight direction due to the presence of the OWF.

3.3.1.3 Appraisal of the displacement analysis methods and the quality of the data sets used in the OWF studies within this report reveal considerable differences in data quality and confidence in the predicted displacement effects and rates. Therefore, taking all reported rates to be used as a range in predicting displacement effects would only add to the uncertainty of the impact assessment. For example, certain studies have not incorporated statistical modelling on the data collected or conducted any form of statistical verification in support of the displacement effect reported. Studies with inferred high or no displacement effects tend to have low and / or very variable gannet abundance between surveys and construction phases. These studies, which have high numbers of zero counts, make displacement rate prediction highly problematic and inaccurate given the natural spatial and temporal variation in this highly mobile species. Therefore, displacement rates reported from these types of data sets are considered likely to be unreliable. For example, the re-analysis of low count data from other species such as auk data for Prinses Amalia and Egmond aan Zee, which previously reported significant displacement effects, was not able to detect a significant effect using INLA analysis (Zuur, 2018) suggesting results are not robust.

3.3.1.4 In reaching a displacement rate for gannet which can be applied broadly to any OWF, it is apparent that the conclusion of an earlier review by Dierschke *et al*. (2016) is generally correct; in suggesting that gannets show a strong avoidance response, however this should only reflect the migratory season. This review has added a further 10 OWF displacement assessments to the evidence base and considered the strengths and weakness of each analysis. These data would suggest that there is a larger range in the rate of displacement from the 60-80% currently used in impact assessments. A summary of the displacement studies for each OWF collated in this review is presented in **Table 2**. Displacement rates have not been assessed within all the OWF studies available in this review, therefore macro-avoidance results have been used such as density gradients and habitat utilisation scores from flight track data to provide an indication of the likely displacement range.

3.3.1.5 Displacement rates presented in **Table 2** are coded red (where precaution is required regarding results due to low confidence in the survey methods and / or data collected, the reasons for which are outlined in **Section 3.2**) or green (for studies with greater confidence in their survey methods and / or data collected, the reasons for which are outlined in **Section 3.2**) in order of increasing confidence in the reported effects, with emphasis on data sets that have a low number of observations or limited statistical verification and therefore highlighted to incur a degree of uncertainty. However, the failure to detect changes in bird numbers should not be taken to mean that no changes are occurring, especially as the majority of studies have three or less years of monitoring data. Nor that a high macro-avoidance rate implies a high displacement rate from the OWF. Study design is critical to the statistical power to detect change (Degraer *et al*., 2012), but is often not adequate for this purpose. The power to detect change from survey data alone is related to the frequency of surveys, their temporal extent and spatial coverage (Maclean *et al*., 2013). The number of years of data that may be needed to be able to demonstrate statistically significant changes (due to ‘natural’ year-to-year fluctuations in populations), has been suggested to be more than the three-year monitoring studies often employed (Vanerman *et al*., 2012). Unless declines are substantial (e.g., > 50%) or survey effort is considerable (e.g., > 80 surveys), the likelihood of being able to detect declines is likely to be low (Maclean *et al*., 2012). Therefore, studies that have inferred no displacement effects have been assigned a precautionary displacement rate of ≤ 60% rather than 0% in **Table 2**. This takes into consideration weak displacement effects that may have gone undetected in studies that have reported no significant effects due to the power of the study to detect small changes.

Table 2 Summary results of gannet displacement and macro avoidance analysis and selected study characteristics representative of the most recent monitoring report or published studies.

OWF	Assigned Displacement Rate	Evidence of Barrier Effect	Evidence of Habituation	Number of Years Pre-Construction Data	Number of Years Operational Data	Season Assessment Predominantly Applies
Beatrice	(>80%)	✓		1	1	Breeding
Robin Rigg	(<60%)		✓	2	5	Breeding
Westermost Rough	(<60%)	✓		1	2	Breeding
Helgoland Cluster (3 OWFs) & Butendiek	<60%*			14	3	Breeding
Kentish Flats and Extension	(<60%)			3	2	Breeding
Walney 1 and 2	<60%			2	3	Breeding/Autumn Migration
North Hoyle	(60-80%)	✓	✓	<1 winter only	3	Breeding/Autumn Migration
Westermost Rough	60-80%			1	2	Autumn Migration
Lincs, Inner Dowsing, Lynn	60-80%		✓	3	3	Autumn Migration
Greater Gabbard	60-80%*			N/A	2	Autumn Migration
Bligh Bank (Belwind)	60-80%	✓	✓	2-10	4.5	Autumn-Spring Migration
Thornton Bank Phase I, II, II	>80%	✓	✓	2-10	6	Autumn-Spring Migration
Thanet	(<60%)		✓	1	3	Autumn-Spring Migration
London Array	(<60%)			2	3	Autumn-Spring Migration
Gunfleet Sands	(>80%)	✓		1	1	Autumn-Spring Migration
Alpha Ventus	60-80%			N/A	3	Autumn-Spring Migration
Prinses Amalia	>80%			1.5	3	Autumn-Spring Migration
Egmond aan Zee	60-80%			1.5	4	Autumn-Spring Migration
Horns Rev 2	(>80%)*			N/A	1	Autumn-Spring Migration

Table Notes: Rate range assigned in () are inferred and are not reported as statistically significant in reports. * Rates assigned using evidence from avoidance analysis such as density gradients and macro-avoidance rate.

3.3.1.6 When predicting gannet displacement rates to an OWF **Table 2** suggests that seasonal effects are evident, as the collated studies indicate behavioural changes towards OWFs by gannets in the breeding versus non-breeding seasons. During the migratory seasons gannets are likely to be passing through rather than feeding in study areas, with the exception of locations that are used as staging areas (ref), which can be determined by whether the birds recorded during surveys are in flight, on the water or feeding within the OWF. The general displacement rate that emerged from studies conducted during the migratory season was a displacement rate of 60-80%, with the exception of rates of <60% reported from studies mostly of low confidence. Studies reporting displacement rates of >80% with an assigned confidence of medium or low should be considered with caution and not applied generally to displacement prediction for other OWFs. These higher displacement rates tended to be from studies on macro-avoidance or using density gradients or having distinct OWF variables that may have compounded the displacement, such as; using tracking studies to estimate displacement (Horns Rev 2), have complex layouts and had ongoing construction activities in proximity to the study area (Thorntonbank), highly variable distribution and abundance data between development phases (Prinses Amalia) or utilised distance effects during one season to derive a macro-avoidance rate rather than displacement analysis (Greater Gabbard). Therefore, these predicted rates may only be applicable to OWFs under certain scenarios. The environmental and OWF design variables are considered further in **Section 3.4** in an attempt to understand differences in predicted displacement rates that have been reported between OWFs.

3.3.1.7 In conclusion, a gannet displacement rate that may be broadly applicable to the OWFs in impact assessments, after considering all available evidence to-date, is 60-80% for the non-breeding season and 40-60% for the breeding season, with the caveat that certain variables may influence displacement rates and adjustments made accordingly.

3.4 Variables Influencing Displacement Rate for Gannet

3.4.1.1 Despite the number of studies reporting on displacement effects, there has been very little discussion on variables that might influence displacement rate. This is despite the reporting of variable displacement rates from OWFs in different locations and with variable WTG scale, design and layouts. Collation of data in this review has therefore provided an opportunity to identify any explanatory variables that maybe associated with displacement effects. This would be useful to determine when a more refined displacement rate may be applicable to an OWF assessment rather than applying a broad range which is currently used. This approach may be used in predicting displacement rates to reduce uncertainty for the Hornsea Four impact assessment (see **Section 3.5**). A comparison of the OWF environmental variables and OWF design metrics that have been used to examine variables associated with displacement effect are shown in **Table 2**. Spearman's Rho (rs) statistic, which measures the strength and direction of the relationship between two variables, was first used to scan the data for correlations to investigate further. OWFs were then split into groups according to displacement rate range using values indicated in **Table 2** as a guide. Each environmental variable and the OWF design metrics were compared between the two groups using an unpaired t-test to test for significant differences.

Table 3 **OWF environmental variables, WTG design and layout metrics. The proposed Hornsea P4 OWF metrics are shown at the top of the table for general comparison to the OWFs reviewed in this report.**

OWF	Location	Year Fully Operational	Number of Turbines	Array Area (km^2)	Capacity (MW)	Array Density ($turbines/km^2$)	Density (% total windswept area)[1]	Blade gap height above MSL	Rotor Diameter	Distance from Shore	Distance between Turbines (max.)	Water Depth	Post-construction Peak Density (n/km^2)
Hornsea P4	UK Southern North Sea	N/A	180	492	1000	0.37	2.67	40	305	65.0	1500	35-55	1.43*
Beatrice	UK Northern North Sea	2019	84	131	588	0.64	1.19	33	154	13.5	1170	35-68	0.35
Robin Rigg	Irish Sea	2010	58	18.3	90	3.16	3.00	25	110	11.0	400	0-12	0.27
Westermost Rough	UK Southern North Sea	2015	35	35	210	1.00	1.90	22	155	8	950-1150	12-22	0.65
Thanet	UK Southern North Sea	2010	100	35	300	2.86	1.83	22	90	12	500-800	15-25	1.67
North Hoyle	Irish Sea	2004	30	9.6	60	3.11	1.55	30	80	7.2	360-800	6-11	1.67
Kentish Flats and Extension	UK Southern North Sea	2005 2015	30 15	9.95 8.28	90 49.5	2.47	1.92	25	90	8.5	700	1-5	0.2
Prinses Amalia	Dutch North Sea	2008	60	21.6	120	4.30	1.40	21	80	23	550	19-24	0.36
Egmond aan Zee	Dutch North Sea	2006	36	24.5	108	1.30	0.94	20	90	10	600-850	15-19	0.2
Greater Gabbard	UK Southern North Sea	2012	140	146	504	1.04	0.87	22	108	36	650-1900	2-34	0.32
London Array	UK Southern North Sea	2013	175	107	630	1.64	1.85	22	120	20	650-1000	0-25	0.13
Lincs Lynn Inner Dowsing	UK Southern North Sea	2013	75	38.3 7.9 8.8	270	2.14	2.43	22	120	8	500-1000	6-15	0.2
Walney 1 and 2		2012	102	73	367.2	1.39	1.58	30	107/120	14	750-950	21-26	0.98
Thornton Bank Phase I, II, III	Belgian North Sea	2013	54	19.7	325.2	2.71	3.40	32	126	27	500-900	12-27	>0.1
Belwind (Bligh Bank)	Belgian North Sea	2010	55	17	165	3.24	2.06	27	90	46	500-650	15-37	0.45
Alpha Ventus	German North Sea	2010	12	3.9	60	3.05	3.51	30	126	56	800	26-29	0.2
Helgoland Cluster[2] & Butendiek	German North Sea	2015 2015	80 48	30.2 35.3	302 295	2.65 1.36	3.00 1.69	30 34	120 126	35 57	550-1450 600-1250	23-25 23-24	0.2

OWF	Location	Year Fully Operational	Number of Turbines	Array Area (km^2)	Capacity (MW)	Array Density (turbines/km^2)	Density (% total windswept area)[1]	Blade gap height above MSL	Rotor Diameter	Distance from Shore	Distance between Turbines (max.)	Water Depth	Post-construction Peak Density (n/km^2)
		2014 2015	80 80	39.80 31.3	288 288	2.01 2.56	2.27 2.89	29 32	120 120	53 32	600-800 750-900	19-23 17-21	
Gunfleet Sands	UK Southern North Sea	2010	48	15.8	172.8	3.04	2.72	22	107	7	450-950	0-13	0.02
Horns Rev 1	Danish North Sea	2003	80	20.7	160	3.87	1.94	30	80	17.9	560	6-14	0.02
Horns Rev 2	Danish North Sea	2009	91	33.21	209.3	2.74	1.86	21	93	31.73	550-900	6-18	0.02

Table Notes: [1] Density (% total windswept area) represents the total windswept area of all the turbines as a percentage of the array footprint, [2] Helgoland cluster includes Amrumbank West, Nordsee Ost and Meerwind OWFs. * pre-construction abundance estimate.

3.4.1.2 Comparison of displacement rates between the breeding season and the non-breeding season, which in most studies represented the migratory seasons, showed a significant difference (p = <0.01) with displacement rates lower during the breeding season (**Figure 3**). The displacement rate for the Beatrice OWF was the highest for the breeding season, however this high rate was inferred and not determined statistically and represents a single season with other factors that may have compounded the displacement rate other than direct OWF effects (as discussed in **Section 3.2**).

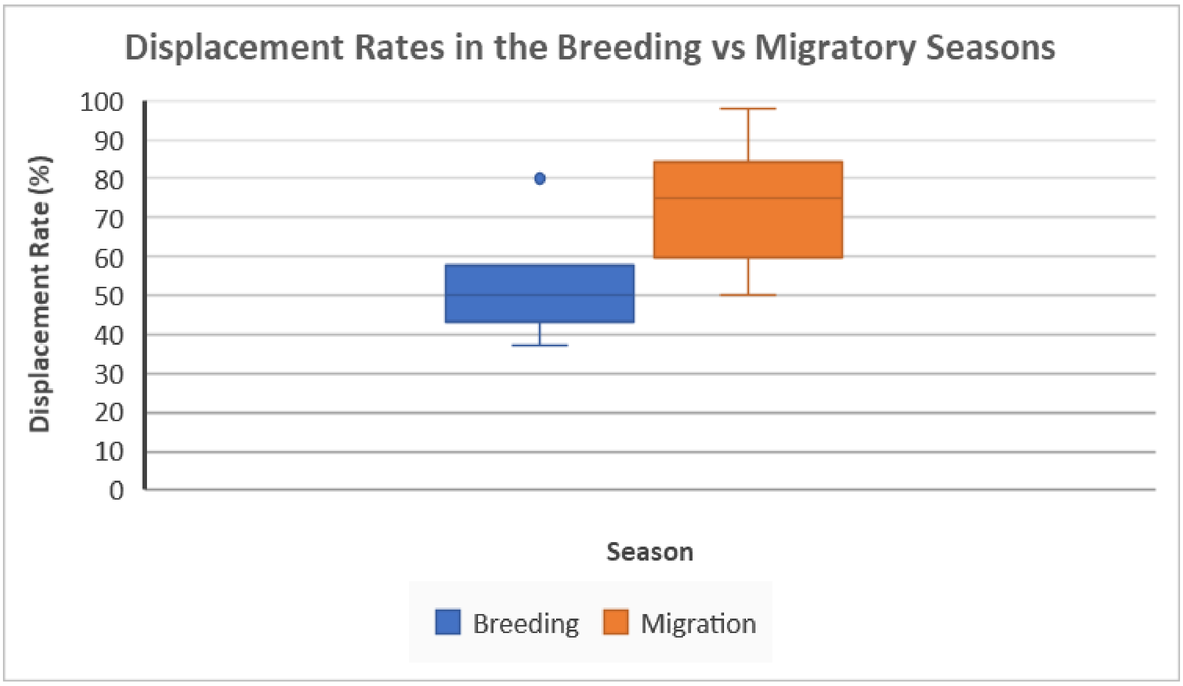

Figure 3 **Displacement rate comparison between breeding and non-breeding seasons.**

3.4.1.3 How birds perceive an OWF is expected to influence their behaviours towards it therefore, variables associated with OWF layout and WTG design may correlate with avoidance behaviours. We compared OWF metrics associated with ten OWF layout and WTG design variables (as shown in **Table 3**) with gannet displacement rate. Spearman's Rho (r_s) statistic, which measures the strength and direction of the relationship between two variables, was first used to scan the data for correlations to investigate further. The OWFs were grouped according to the displacement rate predicted from study reports using values indicated in **Table 1** or assigned to a group according to the inferred magnitude of an effect described in the study report. Two groups were created of OWFs reporting gannet displacement rates of: ≤ 75% and > 75%. Various other displacement rate ranges were compared such as 0-60% and 60-100% and including three-way splits such as 0-50%, 50-75% and 75-100%. However, stratifying OWFs at a displacement rate of 75% provided the clearest effect differences. Each environmental variable and the OWF design metrics were compared between the two groups using an unpaired t-test to test for significant differences. There were too few (five) OWFs reporting displacement rates for the breeding season alone for correlation analysis to be sensitive enough to identify any variables associated with displacement rate. Therefore, bivariant analysis is presented for the non-breeding season only. Results from the Spearman's Rho correlation statistic showed negative correlation between displacement rate and distance between WTGs (r_s = -0.51) and OWF area (r_s = -0.50) and a positive correlation between displacement rate and WTG density (r_s = 0.44) and distance from shore (r_s = 0.46). These correlations were investigated further for significant differences between the two groups of OWFs with different levels displacement.

3.4.2 Distance between WTGs

3.4.2.1 It would be predicted that if an effect is occurring from a visual disturbance (such as presence of standing structure and rotating blades) and / or from the noise of the turbine generator and rotating blades, this will diminish with distance from the WTGs. To determine if a threshold exists, where gannets are more likely to enter an OWF if they can maintain a certain distance from the WTGs, we compared the minimum and maximum distances between WTGs of OWFs between the two displacement rate groups. No significant difference was shown in displacement rate for minimum distances, but a significant ($p < 0.05$) difference was shown for maximum distances between WTGs (**Figure 4**). It should be noted that the outlier in **Figure 4** represents Greater Gabbard OWF which has a single wide corridor, otherwise the maximum distance between WTG in the remainder of the OWF is 1.1 km.

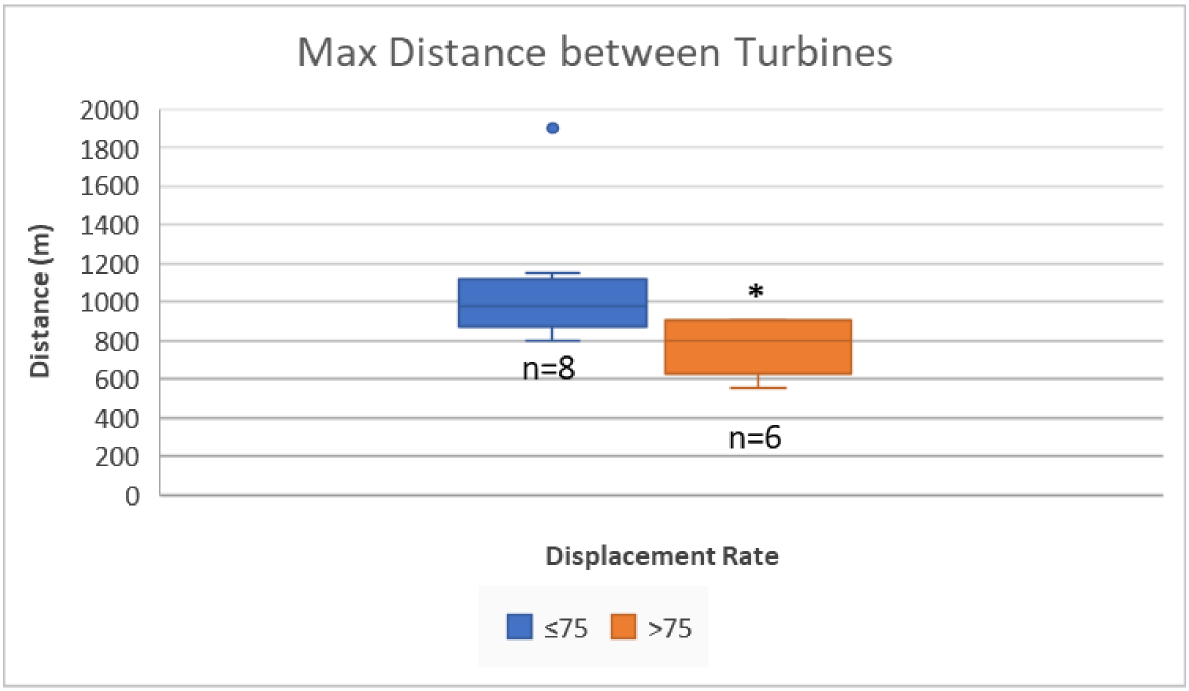

Figure 4 Comparison of maximum distance between WTGs and OWF grouped according to displacement rates of equal or less than 75% and higher than 75%.

3.4.2.2 Minimum distances usually represent within row distances whereas maximum distances usually represent between row distances. The results would suggest that OWFs with design layouts that incorporate wide corridors are less likely to discourage gannets from entering the OWF and reduce the level of displacement. The result suggests that when the average maximum distance between WTGs is reduced to less than 900 m the OWF is more likely to be associated with a displacement rate that exceeds 75%. As these displacement rates reflect the migratory season, corridors orientated in line with the direction of migration may lend further in reducing displacement and barrier effects.

3.4.3 Area of an OWF

3.4.3.1 The size of an OWF was shown to negatively correlate with displacement rate. Comparison between the two displacement rate groups (**Figure 5**) showed a significant difference ($p<0.05$). The results would suggest that a threshold is reached as OWFs get smaller when gannets will tend to increasingly detour around them on migration and avoid entering them. The result suggests that when the size of an OWF is reduced to less than 25 km^2 the OWF is more likely to be associated with a displacement rate that exceeds 75%.

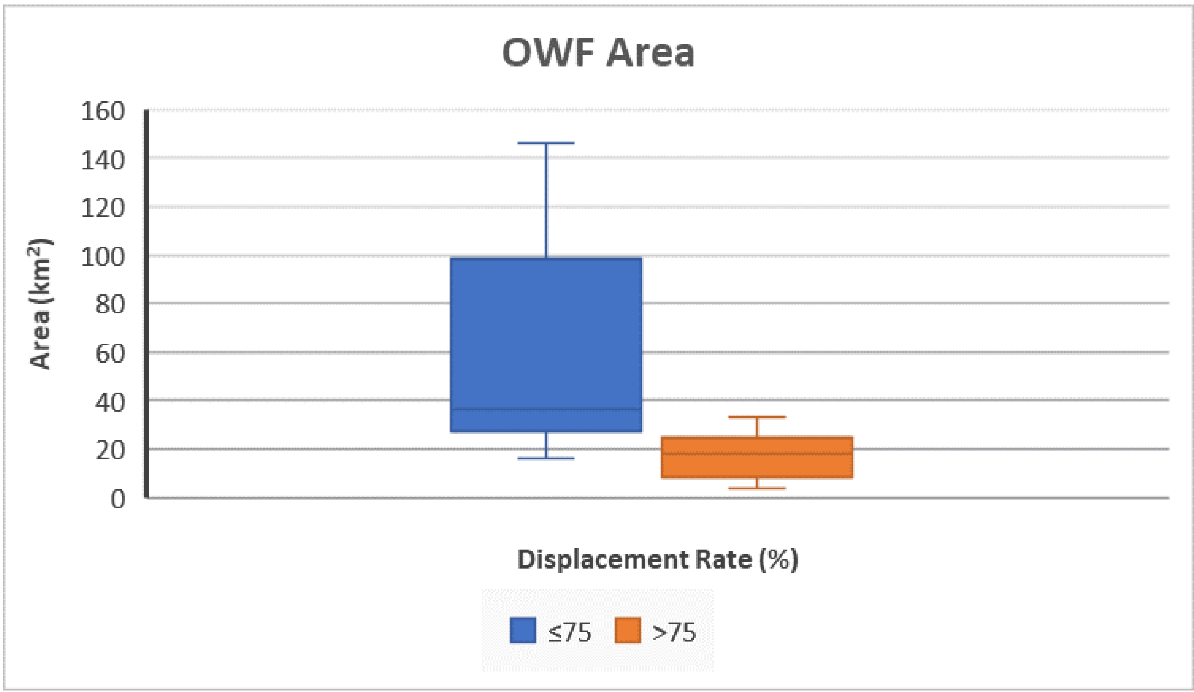

Figure 5 **Comparison of OWF size and OWF grouped according to displacement rates of equal or less than 75% and higher than 75%.**

3.4.4 WTG density

3.4.4.1 The density of WTGs within an OWF was assessed in two different ways, either as the number of WTGs per km^2 or by taking into account the area occupied by the rotating blades calculated as the total windswept area of all WTGs combined and represented as a percentage of the OWF footprint. A significant difference ($p < 0.001$) was only shown for density represented by WTGs per km^2 (**Figure 6**). This may be explained due to gannets tending to fly below rotor height and therefore the perceived density from individual WTG columns is more important than the area occupied by the rotating blades when determining whether a gannet enters the OWF area. The result suggests that when the density of an OWF is increased to more than 2.7 WTGs per km^2 the OWF is more likely to be associated with a displacement rate that exceeds 75%.

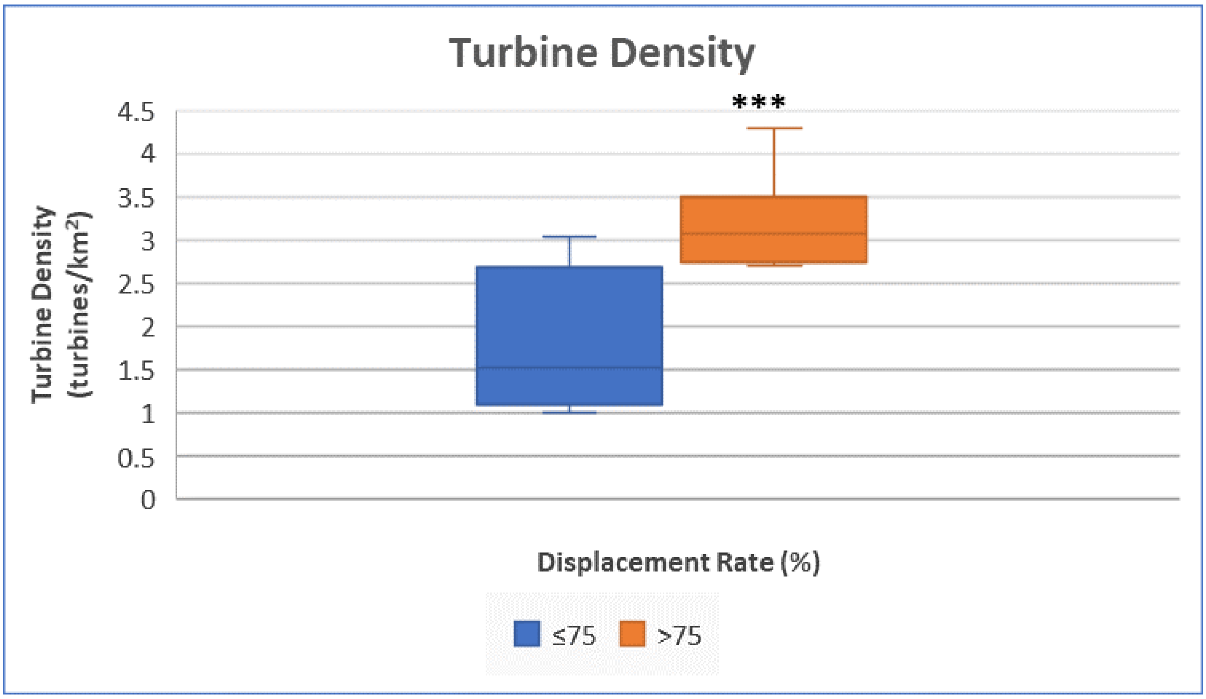

Figure 6 **Comparison of OWF density and OWF grouped according to displacement rates of equal or less than 75% and higher than 75%.**

3.4.5 Distance from shore

3.4.5.1 The distance from shore of an OWF was shown to positively correlate with displacement rate. Comparison between the two displacement rate groups (**Figure 7**) showed a significant difference ($p<0.05$). The result suggests that when the distance of an OWF increases to more than 19 km from the shore the OWF is more likely to be associated with a displacement rate that exceeds 75%.

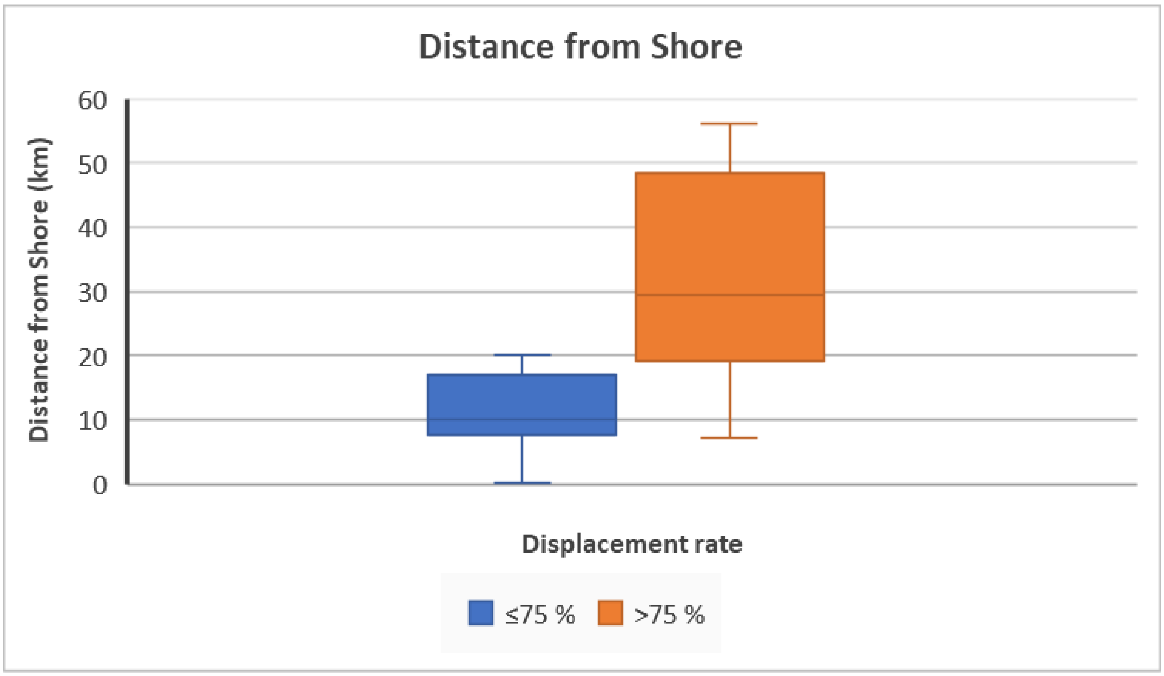

Figure 7 Comparison of the distance of an OWF from shore and OWF grouped according to displacement rates of equal or less than 75% and higher than 75%.

3.4.5.2 The association of distance from shore with a higher displacement rate may simply reflect the greater flexibility in the choice of alternate areas for foraging surrounding an OWF, which increases with distance from the shore. OWFs closer to shore will have a reduction in alternate areas for foraging as the distance to the shore is reduced. However, considering the displacement effects reflect the migratory seasons it is likely that OWFs further offshore display a high displacement effect as they act as a barrier, which is simply detoured around. Gannets migrating closer to shore tend to be juveniles, which may be less willing to move further out to sea to avoid passing through an OWF (Pollock *et al*., 2021).

3.4.6 North Sea Region

3.4.6.1 When comparing displacement rates within the region of the North Sea the OWF is located an interesting observation is apparent; that all UK OWFs are in the lower displacement rate groups and all other European OWFs in the higher displacement group (**Figure 8**). These differences are unlikely to be a result of different data collection or analysis methods used between the UK and mainland Europe. The regional differences are unlikely to be due to a density dependent effect, as gannet peak abundances with study areas did not show any correlation with displacement rate. On closer inspection of the OWFs in the UK the majority have been built within 20 km from shore, have a larger footprint and have less density of WTGs within their OWF designs, which are predicted above to be less associated with high displacement rates.

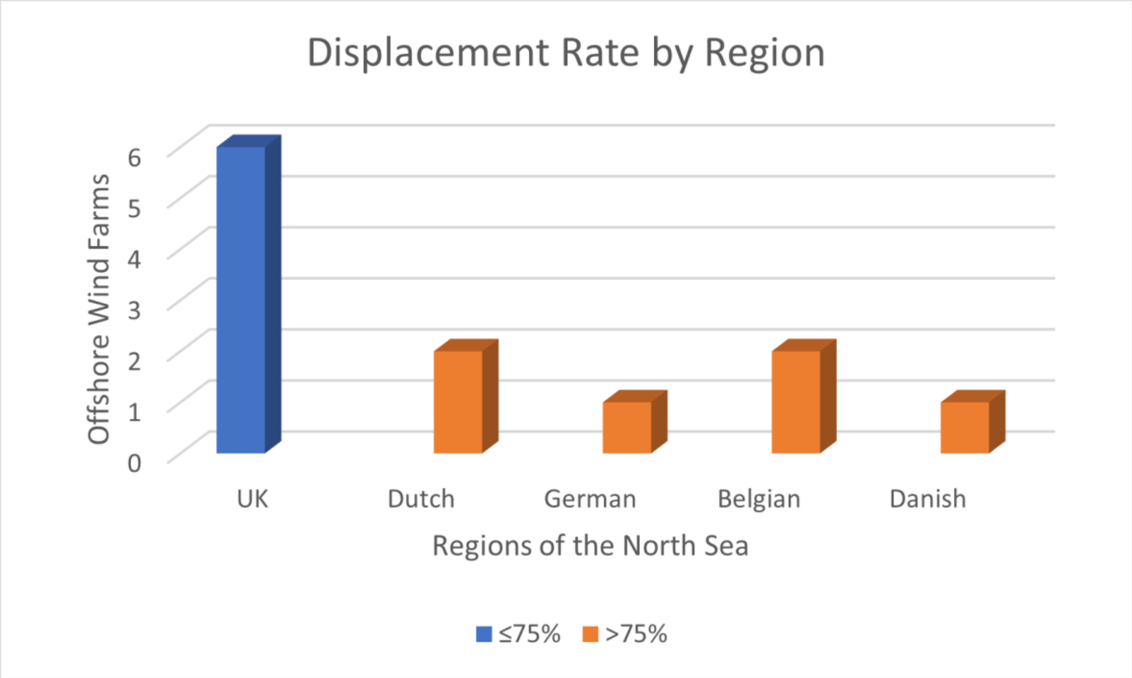

Figure 8 North Sea regional differences in OWF displacement rate.

3.5 Summary of Gannet Displacement Rates

3.5.1.1 This review has collated data from 19 study areas comprising of 25 individual OWFs, which in total consists of 34 years of post-construction data that has been critically appraised and meta-analysed. It identifies differences in methodologies used and type of data collected, and analytical techniques employed to assess displacement effects. The findings demonstrate that not all OWFs have displacement rates in the 60-80% range currently advocated for impact assessment for gannet by SNCBs. Although 26% of OWFs in this review fall into this 60-80% range, 32% report rates of >80% and 42% report or infer rates of <60% displacement. However, the findings also highlight that consideration must be made to quality of the data used in the assessment and the standard of analysis. As the majority of studies have various weaknesses, this results in the confidence of the displacement rate reported to be classified as mostly low to medium.

3.5.1.2 The meta-analysis has shown that there is evidence of a seasonal effect on the displacement rate at OWFs. Within the breeding season displacement rate is typically between 40-60%, whereas in the non-breeding season the displacement rate is typically between 60-80%. This is likely to be as a result of constrained foraging range during the breeding season and higher avoidance during the migratory seasons as gannets prefer to detour around OWFs.

3.5.1.3 The bivariant analysis compared 16 variables with non-breeding season displacement rate, four of which were shown to correlate with displacement rate. Two of these variables had a positive correlation with displacement rate (WTG density within an OWF and distance from shore) and the other two variables had a negative correlation with displacement rate (OWF size and distance between WTGs). These associations suggested that OWFs reporting high gannet displacement rates of >75% tend to have;

1. A particular layout, which include densities >2.7 WTGs per km^2;
2. Narrower corridors with average maximum distances between WTGs of <900 m;
3. Smaller OWF area footprints of <25 km^2; and
4. A distance from shore of >19 km.

3.5.1.4 All OWFs that fall into the high (>75%) displacement rate category possessed a minimum of three of the four criteria described above.

3.5.1.5 In conclusion, the findings of this report represent the most comprehensive review to-date on gannet displacement effects, which has refined the displacement rate range for gannet and provided the first evidence of OWF design variables that influence the magnitude of the displacement effect.

3.5.1.6 The review would suggest that using the best available evidence to-date the gannet displacement rates to be used for the Hornsea Four Development Application (within the EIA and HRA reporting) are overly precautionary using a flat rate range of 60-80%. Consideration of the use of 40-60% for the breeding season and 60-75% for the non-breeding season may be more appropriate for Hornsea Four from the supporting evidence in this review. The non-breeding season displacement rate has been refined from the 60-80% range as the evidence presented in this review would suggest that the Hornsea Four Development OWF design metrics do not meet the thresholds for this upper rate range, with the exception of distance from shore that would place it in the >75% displacement rate range.

4. Review of Evidence of Mortality Rates for Displaced Gannets

4.1 Understanding Gannet Displacement Consequent Mortality

4.1.1.1 Current evidence suggests that the response of seabirds to OWFs varies depending on the species and of the life stages of individual birds (APEM, 2022). Birds that avoid OWFs may do so entirely, including an area considered to be a buffer around an OWF, or do so partially. Avoidance of OWFs may be either on a spatial scale or temporally according to levels of competition outside the OWF or prey abundance within the OWF. Habitat loss is ultimately considered to be the consequence of these avoidance behaviours and therefore, a major challenge is understanding how displacement from OWF habitat may impact upon population processes.

4.1.1.2 Displacement effects may act at differing levels, including the individual, colony and wider population levels and are dependent on key factors:

1) The importance of the OWF area in the context of the surrounding area;
2) The fraction of the colony / population utilising the area of the OWF;
3) The degree (number of birds and distance) of displacement by the OWF; and
4) The consequences of habitat loss (in terms of the survival probability and productivity) as a result of the OWF.

4.1.1.3 Mortalities are likely to correlate strongly with the quality of the foraging habitat; if birds are displaced from a key foraging habitat area and the remaining foraging areas are already close to carrying capacity, then the mortality rates of displaced birds may become higher (Busch and Garthe, 2016). Likewise, if an OWF area being avoided by a species is not considered to be a key foraging area and the remaining habitat is able to carry additional capacity, then the mortality rates of displaced birds may be low or negligible.

4.1.1.4 The SNCBs currently advise that only mortality of individuals displaced from OWF site footprints (plus buffer) be considered in the 'Matrix Approach' at this time (SNCBs, 2017). However, displacement rates given in study reports currently do not distinguish from birds that have avoided the OWF, which previously foraged within them, from birds that generally passed through the OWF to forage beyond it. This is an important distinction, especially in the breeding season, as birds forced to find alternate foraging areas have the potential to incur higher energetic costs seeking these areas than birds that make detours around an OWF to reach a familiar foraging area. It can be assumed that the further from the breeding colony an OWF is located, especially when distances exceed the mean foraging distance that birds are less likely to be foraging beyond it. Indeed, the OWF may act to deflect birds back towards the colony, increasing their foraging efficiency if prey abundance is not a limiting factor. The mean foraging distance for gannets is 120 km (Woodward et al., 2019), therefore OWFs within 120 km of gannet colonies may subject gannets to both displacement and barrier effects in the breeding season.

4.1.1.5 The potential energetic consequences of gannets avoiding OWFs due to barrier effects should be given consideration. However, it seems likely that any deviations from their default course during the migratory season would have only negligible effects on fitness, given that gannets may migrate over 1,000 km from colony to wintering areas. The magnitude of barrier effects may be higher during the breeding season than during migration (Masden et al., 2010; Warwick-Evans et al., 2017) owing to repeated avoidance and higher overall energetic demand when acting as a centrally placed forager. The effect of displacement from foraging in an OWF is also likely to be negligible during migration given their flexibility in choosing alternate areas to forage, however little is known of the foraging habits of gannets on migration and if specific areas are used. Following a recent study gannet age-class should be taken into consideration when assessing impacts to barrier and displacement effects. As juveniles were shown to spend more time migrating through the North Sea to their wintering grounds and with a tendency to be confined along the coast (Pollock et al., 2021). Whereas adult gannets showed less constrained migratory routes distributed throughout the North Sea, suggesting flexibility in their choice of route (Pollock et al., 2021).

4.1.1.6 The current recommendation is the presentation of a range of mortality rates of displaced birds for all species taken forward to displacement matrix assessments (SNCBs, 2017). The appropriateness of using mortality rates as high as 10% for gannets in assessments is unclear, given the lack of evidence, though UK SNCBs regularly advise the use of a range of 1–10% mortality for gannets based on expert opinion. In contrast, environmental impact assessments (EIAs) for recent OWF development applications have reported that 1% mortality or up to 2% mortality in the breeding season is more appropriate (Norfolk Boreas Limited, 2019; SPR, 2019; Ørsted, 2018b), though these assessments were also almost entirely based on expert judgement. Anecdotal evidence to support a 1% mortality was supported primarily as they score highly for habitat flexibility (Furness and Wade, 2012) and have been given a classification of ‘very low’ for population vulnerability to displacement (Bradbury et al., 2014). This lack of empirical evidence has led to the 1-10% mortality rate range continuing to be recommended despite it being a ‘best guess’ to allow for precaution.

4.1.1.7 However, since the joint SNCBs interim advise note on displacement and mortality rates was issued and updated in 2017 (SNCBs, 2017) there have been two studies (described below) with updates to predict the fate or population consequence of displaced seabirds, including gannets, from OWFs (Searle *et al*., 2014 and 2018; van Kooten *et al*., 2019). In addition to this, anecdotal evidence is available (presented below) of implied low additional mortality rates from gannet colony stability on Helgoland in German North Sea waters (Dierschke *et al.*, 2018), despite gannet displacement effects being reported (Garthe *et al*., 2021) and OWFs having been operated in the area since 2014.

4.2 Studies determining Gannet Displacement Consequent Mortality

4.2.1 Studies by van Kooten et al.

4.2.1.1 The paper from van Kooten *et al*. (2019) applied an assessment method to estimate full life-cycle population effects in the North Sea caused by OWF-induced habitat loss. The study included assessment of gannet for the breeding and non-breeding seasons and included all existing and planned North Sea OWFs as presented in van der Wal *et al*. (2018). The analysis consisted of habitat quality maps based on seabird distribution data and determined the cost of habitat loss using an individual based energy-budget model. Together the potential cost of habitat loss in terms of reduced survival rates of bird redistribution, due to a change in the availability and configuration of the foraging area under OWF scenarios, were calculated. Although acknowledged, many steps in the calculations are characterised by uncertainties, such as using best available estimate for the degree of displacement and uncertainty in the bird distribution data, which the habitat models are based. Mortality rates were based on the *Individual Based Model* (IBM), using an energy budget approach to quantify this effect, and the outputs from the *Habitat Utilization Maps*, displacement rates were set at 80% based on Dierschke *et al*. (2016). The modelling process assumes individual birds have an amount of energy available at any particular time, have an intake of energy and incur energetic costs over time. Utilising the values in the habitat maps, the model calculates energetic gain or losses of moving to different locations to produce a frequency distribution of survival probabilities. The results produced several outputs that may be used to inform the effects of displaced birds from OWFs. The effect of OWF displacement at the North Sea wintering population level are shown below for gannet as the 5th percentile additional monthly mortality rate during the period of OWF exposure using 80% displacement scenario in the IBM model.

<u>*Non-Breeding Season*</u>

- 8.38E-04 for juveniles (age 0);
- 4.18E-04 for immatures (age 1); and
- 1.85E-04 for immatures (age 2, 3, 4) and adults.

<u>*Breeding Season*</u>

- 4.18E-04 for juveniles (age 0);
- 4.18E-04 for immatures (age 1); and
- 2.78E-04 for immatures (age 2, 3, 4) and adults.

4.2.1.2 The paper from van Kooten *et al*., (2018) calculated the simulated annual median additional mortality from OWF displacement from the IBM using 80% displacement and 10% mortality, which was 0.30% for the breeding season and 0.32% for the non-breeding season at the population level. However, gannet breeding colonies have been observed to increase everywhere in Europe (BirdLife International 2015), especially UK colonies, including the Flamborough and Filey Coast (FFC) Special Protection Area (SPA) colony, which display exponential growth (Murray et al. 2015; Lloyd, 2019). Therefore, these model scenarios predicting population declines from OWFs for gannets assume more impact than would occur in reality, which suggests consequential mortality from displacement is significantly less than 10%.

4.2.2 Studies by Searle et al.

4.2.2.1 Searle *et al*. (2014) presented what is still considered to be the most comprehensive assessment of the effects of displacement and barrier effects from OWFs on breeding seabirds, using the best available empirical data and advanced modelling approaches. The study developed time and energy models of foraging during the chick-rearing period to estimate the population consequences of displacement from proposed OWF developments for key species of seabirds, including gannet breeding at local SPAs. Population effects were modelled for the SPA colonies at Buchan Ness to Collieston Coast SPA, Fowsheugh SPA, Forth

Islands SPA and St Abb's Head to Fastcastle SPA and four local wind farms: Neart na Gaoithe, Inch Cape, Seagreen Alpha and Seagreen Bravo.

4.2.2.2 The model presented by Searle *et al.* (2014) simulated foraging decisions of individual seabirds under the assumption that they were acting in accordance with optimal foraging theory. Each individual selected a suitable location for feeding during each foraging trip from the colony based on bird density maps and assuming that the foraging behaviour of individual seabirds was driven by prey availability, travel costs, provisioning requirements for offspring, and behaviour of conspecifics. The impacts of the proposed OWFs were assessed by comparing simulated values of adult and chick survival in models that included the OWFs against the baseline simulations. The scenarios run reflected possible assumptions regarding food availability (good, moderate or poor), the spatial distribution of prey (homogeneous or heterogeneous), and the percentage of birds affected by barrier and displacement effects. The final simulations assumed moderate food availability, a 1 km buffer around each OWF and that 60% of birds experienced displacement and barrier effect.

4.2.2.3 The results of the model simulations consistently yielded estimated OWF effects on SPA adult survival that corresponded to declines of less than 0.1% for gannets. The estimated SPA additional adult mortality from individual OWFs ranged very little from 0.01% to 0.02%. The models implied the proportion of birds interacting with OWFs is comparatively high, but associated costs are very small relative to the overall cost of foraging trips, so overall any adverse effects are negligible at most and considered to be of no significance.

4.2.2.4 How these modelled changes in SPA adult survival are translated to predict additional mortality for birds that are displaced from OWFs is not straight forward. The model would require a number of assumptions to be made that would benefit from parameterisation with local data for comparison to the Hornsea Four array area, in particular distance from colony. Another consideration of using a separate displacement rate in the breeding season, as determined in this review, is suggested to be 40-60% vs 60% used in the models. Using the FFC SPA colony population size, predicted changes in adult survival from the models and mean peak numbers of birds observed in the array area and 2 km buffer during the breeding season, a crude estimation can be made on mortality effects of displaced birds.

4.2.2.5 For example: If considering the FFC SPA gannet population size as 13,392 pairs (Lloyd, 2019) and use the predicted 0.02% additional adult mortality from the model simulations an additional 3 birds would be subject to displacement consequent mortality from the Hornsea Four from the FFC SPA per annum. If we then consider the breeding season mean peak number of gannets observed in the array area and 2 km buffer, which is 1,265 individuals, and apply a precautionary upper displacement rate of 60% (the range from this review predicts 40-60% displacement in the breeding season) this would mean that of the 759 birds displaced, 3 would be subject to displacement consequent mortality to account for the predicted SPA level effects. This translates to an additional mortality rate of 0.4% for birds displaced from the OWF in the breeding season. However, calculations presume that the majority of birds observed in the array area and 2 km buffer are birds from FFC SPA.

4.2.3 Studies by Daunt et al. and Warwick-Evans et al.

4.2.3.1 Daunt et al., (2020) produced population level estimates for impacts of different hypothetical offshore renewable energy development scenarios for gannet using the displacement matrix approach. The mortality rates used for displaced birds were 0.5% for the breeding season and 0.25% for the non-breeding season. These rates were selected in consultation with the Project Steering Group based on expert judgement, largely originating from a workshop held in 2015 (JNCC, 2015) and summarised in a Joint SNCB Advice Note (SNCB, 2017).

4.2.3.2 Warwick-Evans et al., (2017) developed a spatially explicit IBM to investigate the potential impacts of the installation of OWFs in the English Channel and North Sea on body mass, productivity and mortality of a breeding population of gannets. No differences were observed in the physiological state or mortality rate of the gannets between the baseline model and models where gannets showed avoidance behaviour (Warwick-Evans et al., 2017). The simulations only showed increases in adult and chick mortality when the size of the OWFs increased considerably (≥1,000 km^2) and if avoidance behaviour was displayed.

4.2.4 Impact of OWF operation on Heligoland gannet colony population trends

4.2.4.1 The results of simulation models by Searle *et al*. (2014), Warwick-Evans *et al*., (2017) and van Kooten *et al.* (2019) on the impacts of OWF displacement on gannet survival are incompatible with a mortality rate of 10%. Their studies suggest that additional mortality effects from displacement at a colony or population level would be negligible or undetectable under current monitoring conditions. Whereas an additional mortality level of 10% for displaced birds would likely be detectable after several years of monitoring, especially if continued moderate displacement from an OWF is occurring. Although published studies with empirical evidence to support this are lacking, impacts on demographic effects from OWF displacement can be inferred from colony population trends, where displacement effects on gannet distributions have been reported. One such colony is that on Heligoland in the German North Sea in which avoidance rates for gannets have been predicted to be 89% during the breeding season from the nearby Heligoland OWF cluster (Garthe *et al.*, 2017a, 2017b and Peschko *et al*., 2021).). Operation of OWFs within the Heligoland cluster and surrounding area commenced in 2014, allowing a substantial time period for any correlation between operation of the OWFs and changes in colony demographics to be detected if significant additional mortality from displacement is occurring. The number of breeding gannets at the Heligoland colony has continued to show a substantial increase in breeding pairs for the most recent colony counts, including 2014 (656 breeding pairs), 2016 (780 breeding pairs) and 2021 (1,458 breeding pairs) (Garthe et al 2017, Dierschke *et al.*, 2018, Gerlach *et al.*, 2019, FFIVH, 2021), which includes seven years of OWF operations in the vicinity of the colony and with additional OWFs becoming operational. This suggests that applying a 10% mortality range for displaced birds is overly precautionary as at this level of mortality, changes in breeding population trends would have been detectable at the colony, correlating with the period of OWF development and operation.

4.3 Summary of Gannet Displacement Consequent Mortality Rates

4.3.1.1 In summary, studies using simulation models of time and energy budgets for gannets during the breeding and non-breeding season suggest that displacement effects, even at their highest impacts, are not compatible with an overly precautionary 10% mortality rate for displaced birds. Based on the available evidence from the model simulations, and consultations for using the displacement matrix approach it is suggested that mortality rates for displaced gannets are negligible or less than 1% (0-0.5%) for both the breeding and non-breeding season. Therefore, applying the current evidence, the use of additional mortality rates of >1% for gannets appear overly precautionary. Several gannet simulation models of displacement effects at the population level and empirical evidence from colony demographic trends suggest additional mortality rates from displacement effects of up to 1% to be more reflective of the evidence base.

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