Northern gannet collision risk with wind turbines at the southern North Sea

Extension of the impact assessment for KEC 4.0, additional analyses of the assessment framework

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1 Introduction

Potiek *et al.* (2022) assessed the population level effects of bird collisions in wind farms named in the 'North Sea Programme 2022-2027' (also referred to as KEC 4.0) for a number of relevant bird species. This was an update of Rijkswaterstaat (2019) (KEC 3.0) and included updates of the bird input parameters as well as the wind farm scenarios.

In Potiek *et al.* (2022), the number of collision victims was predicted using a collision rate model, based on among others bird density maps, assumptions about avoidance and other bird characteristics, and turbine characteristics. This resulted in an estimated number of collision victims per wind farm. For each of the scenarios, the victims were summed for the relevant combination of wind farms. The impact of habitat loss due to wind farms was simultaneously assessed by Soudijn *et al.* (2022). For northern gannet, the impact due habitat loss was much lower than the impact due to collisions.

Subsequently, the population-level impact was assessed using population models. These population models project the population trajectory for the situation without wind farms (null scenario) as well as for each wind farm scenario. The outcome of these population models was assessed by comparing these to a threshold set by LNV (Acceptable Level of Impact, ALI). These thresholds were based on a method developed by Potiek *et al.* (2021), in which the probability of a certain decline because of the impact was compared to a threshold set on beforehand.

For northern gannet, the defined ALI threshold was a maximal 50% probability of a 30% decline after 30 years, as a result of the impact. Based on this analysis, the assessed impact on northern gannet resulted in a violation of the ALI threshold for each of the scenarios formulated within the North Sea Programme 2022-2027.

As an extension of the KEC 4.0 study, Rijkswaterstaat asked for a refinement of the cumulative impact assessment for northern gannet, with a focus on the assessment of collision mortality. This consists of several topics:

Collision rate modelling:

1. Literature study to assess whether the input parameters of the sCRM should and could be updated.
2. Literature study of the avoidance rate, combined with assessment of the appropriateness of the use of the avoidance rate in the current model and situation.
3. Assessment of the sCRM input parameters, as well as the results.

Population modelling:

4. Discussion of the used population definition, and the manner of applying the collision victims to this population.
5. Update of the age distribution among victims to match the expected age distribution within individual wind farms.

6. Reassessment of the population effects of collision mortality on northern gannet based on the results from topics 1 to 5.
7. Sensitivity analysis of the population model predictions to life history parameters.

2 Collision rate model: literature study of input parameters and assessment of the model

2.1 Background

Collision rate modelling in KEC 4.0 with the sCRM for northern gannet in 163 wind farms in the North Sea resulted in an estimate of over 8,806 collisions annually in the international scenario (Potiek *et al.* 2022). The average across all wind farms was 54, with the highest being 239 and lowest 2. For the national scenario, a total of 1,925 collisions per year was estimated across the Dutch wind farms. The average was 80, the maximum 244 and the lowest 5. An avoidance rate of 0.989 was used (Cook *et al.* 2014).

Estimates are driven by input parameters of the sCRM, of which those that define the number of passages through the rotor swept have most influence on the results. Most notably, aerial bird density, nocturnal activity factor, number of turbines, proportion of time in operation and avoidance rate have a key role, but also flight height distribution, rotor diameter, lowest tip height, and to a lesser extent flight speed, can strongly influence the results.

The influence of number of turbines and rotor diameter on the collision estimates is evident in several wind farms, particularly IJmuiden Ver with a large number of wind turbines (*i.e*. 267) and Marr Bank, Berwick Bank and Scottish Sectoral Marine Plan – E1 with a large rotor diameter (*i.e*. 280 m). In the collision rate model these two factors influence the numbers of birds passing through the rotor area and consequently the numbers of collisions.

2.2 Results literature study

2.2.1 Avoidance rate

Avoidance is a key factor in collision rate modelling, as it directly influences the flux through the rotors and ultimately the number of collisions. In relation to collision rate assessments, avoidance refers to birds in flight only. Estimates for the avoidance of wind farms by northern gannets remain largely based on expert opinion and lower values of these estimates are frequently used. Note that for example a change of the avoidance rate from 0.99 to 0.98 results in double the number of estimated collision victims.

Table 1 presents estimates for avoidance rates for northern gannet and the figures used in several Environmental Statements for offshore wind farms in the UK. Most of these refer to the cautionary figure given in Cook *et al.* (2014). More recently this figure has been updated in Bowgen & Cook (2018). Within KEC 4.0, we used 0.989 as an estimate provided by Cook *et al.* (2018), the most recent peer-reviewed article on summarizing the available knowledge on offshore avoidance rates, although the figure derived for northern gannet remains largely based on expert opinion and no estimates are available for this species for use with the extended Band model due to lack of available information. Within the previous version of the KEC (KEC 3.0, Gyimesi *et al.* 2018), the avoidance of northern gannet was assumed to be 99.5% (Maclean *et al.* 2009). Estimates of avoidance for the extended model are generally lower than for the basic model due to the method used for estimating these rates.

Aerial bird densities within the sCRM are generally based on pre-construction data. In those cases, the avoidance rate needs to include the expected effect of the construction of wind farms on the aerial bird density within the area, which is part of macro-avoidance. Estimates reported in Table 1 represent total avoidance rates (unless otherwise given), including the effects of construction on the bird densities after construction. These do not include displacement of local birds and refer only to flying birds.

Table 1. Avoidance rates for northern gannet and the figures used in Environmental Statements for offshore wind farms in the UK. Most figures refer to Cook et al. (2014).

Avoidance rate	**Publication**	**Comments**
0.980	SNH. 2010. Use of avoidance rates in the SNH wind farm collision risk model. SNH Avoidance Rate Information & Guidance Note. Scottish Natural Heritage, Inverness, UK.	
0.995	Maclean, I. M. D., Wright, L. J., Showler, D. A. & Rehfisch, M. M. 2009. A review of assessment methodologies for offshore windfarms. BTO Report commissioned by COWRIE Ltd.	Used within KEC 3.0 (Gyimesi *et al.* 2018).
0.64 Macro 0.989 Total	Cook, A.S.C.P., Humphreys, E.M., Masden, E.A., Band, W. & Burton, N.H.K. 2014. Scottish Marine and Freshwater Science Volume 5 Number 16: The Avoidance Rates of Collision Between Birds and Offshore Turbines.	Total estimate for use in basic model, no extended model estimate.
0.816 Macro 0.9205 Meso 0.9500 Micro 0.999 Total	Bowgen, K. & Cook, A. 2018. Bird Collision Avoidance: Empirical evidence and impact assessments. JNCC Report No. 614, JNCC, Peterborough, ISSN 0963-8091.	Recommends 0.995 for use in basic model.
0.9988 Greater Gabbard (Macro 0.9502, Micro 0.976-1.00) 0.991 Egmond aan Zee	Rehfisch, M. Barrett, Z. Brown, L. Buisson, R. Perez-Dominguez R. & Clough S. 2014 Assessing northern gannet avoidance of offshore windfarms. Apem Report 512775.	Suggests estimate to use 0.999
0.998 (from Whitfield & Urquhart 2013) 0.995 recommended precautionary value 0.99 or 0.98 basic model 0.97 Dudgeon 0.98 EOWDC 0.98 Galloper 0.98 Sheringham Shoal	In SMartWind, Forewind and MacArthur Green 2015. (Hornsea advice document) Review of Avoidance Rates in Seabirds at Offshore Wind Farms and Applicability of Use in the Band Collision Risk Model Whitfield, D.P. & Urquhart, B. (2013). Avoidance rates in offshore collision risk modelling: a synthesis. Report from	

Avoidance rate	Publication	Comments
0.9962 Teesside 0.99 Thanet 0.98 Triton Knoll	Natural Research Projects (NRP) to Marine Scotland. NRP, Banchory.	
0.989 used for Aberdeen, Beatrice, Blyth, Dudgeon, Galloper, Greater Gabbard, Dogger Bank Creyke Beck Projects A and B, Dogger Bank Teeside A and B (now Sofia), East Anglia ONE, East Anglia ONE North, East Anglia THREE, East Anglia TWO, Forth (Seagreen) Alpha and Bravo, Hornsea Project One, Hornsea Project Two, Humber Gateway, Hywind, Inch Cape, Kentish Flats, Kincardine, Lincs, London Array, Neart na Gaoithe, Norfolk Boreas, Norfolk Vanguard, Race Bank, Rampion, Sheringham Shoal, Teeside, Thanet, Tier, Triton Knoll, Westermost Rough	In Royal Haskoning DHV, East Anglia Two Appendix 12.3 Supplementary Information for the Cumulative Assessment Environmental Statement Volume 3 (2019)	
0.980 0.988 0.995	Cork Ecology, Mainstream Neart na Gaoithe Offshore Wind Farm Ornithology Technical Report June 2012	0.998 stated as likely closer to actual figure.
Uses Cook *et al.* 0.995 – 0.989	Warwick-Evans, V, Atkinson, PW, Walkington, I and Green, JA 2017. *Predicting the impacts of wind farms on seabirds: An individual-based model.* Journal of Applied Ecology, 55 (2). pp. 503-515. ISSN 0021-8901	
0.989 used Cook *et al*. 75% collisions female, 25% males	Lane, JV, Jeavons, R, Deakin, Z, Sherley, RB, Pollock, CJ, Wanless, RJ, Hamer, KC 2020. Vulnerability of northern gannets to offshore wind farms; seasonal and sex-specific collision risk and demographic consequences. Marine Environmental Research, 162. 105196. ISSN 0141-1136	

2.2.2 Other parameters

Nocturnal activity and foraging range

Nocturnal activity is a correction for the percentage of time that birds spend flying at night compared to during the daytime when densities are measured. This factor is used as the percentage of the daytime aerial bird density active during nighttime hours. In the current model a nocturnal activity correction of 8% was applied for all wind farms throughout the year as a worst-case scenario, based on the estimate of Furness *et al.* (2018) for breeding birds. However, Furness *et al.* (2018) also estimated this value for birds outside the breeding season at a value of 3%. We propose that it would be appropriate to apply a nocturnal activity correction of 3% for all wind farms, except those within mean foraging range of breeding colonies and during the breeding period of between April and July, which for this study is the assumed area and period in which breeding birds are active.

Currently, a maximum foraging range of 315 km around breeding colonies is used for northern gannet (figure 1). Several studies show this distance is realistic (Hamer *et al.* 2007, Thaxter *et al.* 2012). Nevertheless, the distributions of birds away from the colonies are unlikely to be uniform, with birds favouring specific areas and distance from colony being constrained when provisioning chicks (Hamer *et al*. 2000, Hamer *et al*. 2001, Hamer *et al.* 2007, Wakefield *et al.* 2013, Langston *et al*. 2013).

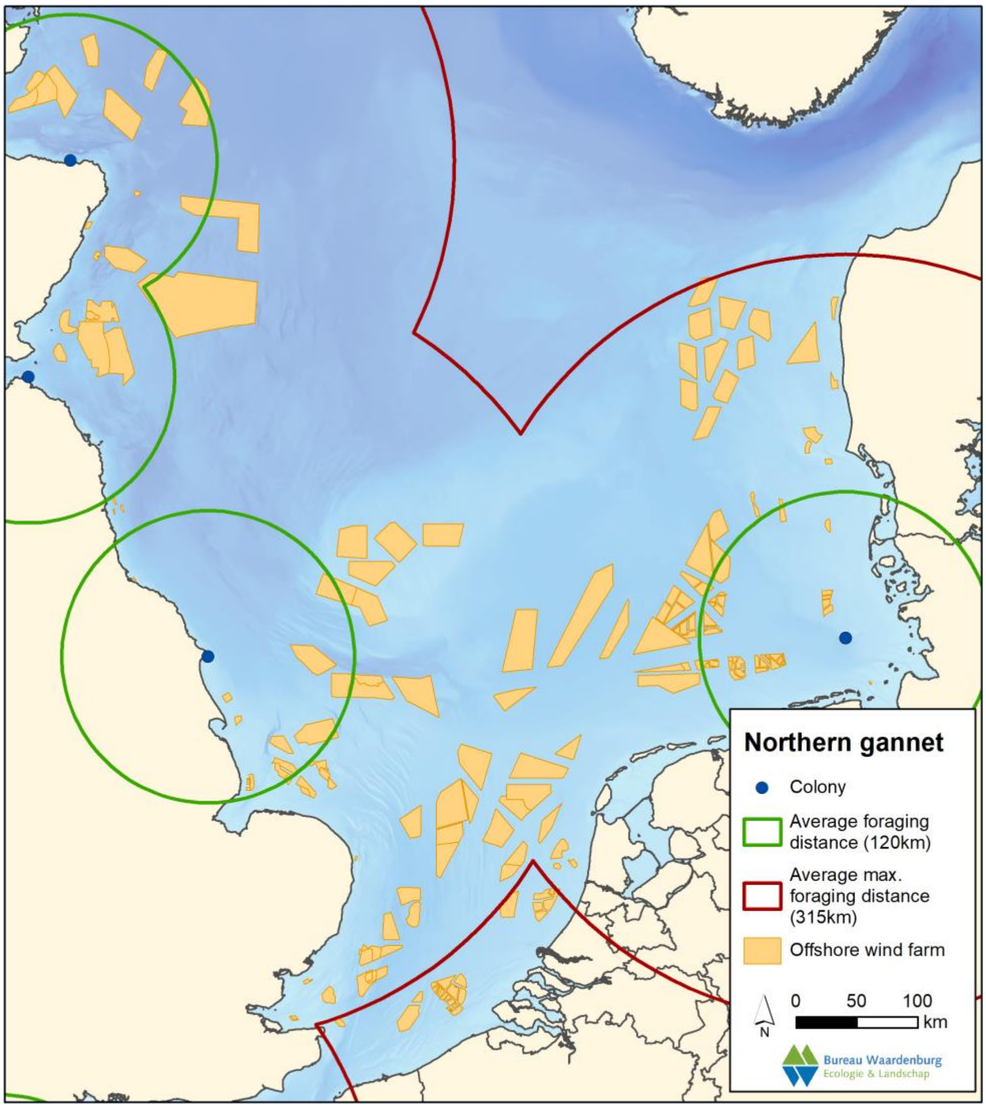


Figure 1. Foraging range of northern gannet in the breeding season based on a maximum foraging range of 315 km measured from breeding colonies.

Rotor height

The height of the lowest tip above sea level used in the current modelling for several wind farms is lower than expected in practice and results in notably high collision estimates. The value used for East Anglia One, Norfolk Boreas, Northwind and Inch Cape are all under 18 m and these wind farms have some of the highest annual collision estimates for northern gannet, being between 102 – 228 victims per wind farm. Lowest tip height values used for these three, and several other UK wind farms, are lower than is likely the case, where a minimum air gap of 22 m (highest astronomical tide) HAT or ca. 25 (mean sea level) MSL is required in the UK. The low value used likely explains the high estimates for these wind farms and it highly influences (in combination with the flight height distribution used) the flux through the rotor-swept area.

Bird densities

The densities of birds can explain much of the estimated collisions, with higher densities leading to higher fluxes and resulting in proportionately higher collision estimates. Amongst the estimated densities used for northern gannet, there are some areas where densities are higher than could be expected, at least when comparing the estimated densities with other areas. In particular, the densities used for wind farms in Belgium and around the Dutch Borssele area bordering Belgium, are unexpectedly high when compared to those in other parts of the Dutch- and English North Sea and are comparable to areas of the Scottish North Sea that are in close proximity to colonies with high numbers of individuals of this species. Figure 2 shows the mean monthly density of northern gannet per wind farm in each country used in the current assessment. Here, the five Dutch wind farms with the highest densities of northern gannet are those at Borssele, and the densities here and at the neighbouring Belgium wind farms are higher than all English wind farms except Hornsea project 3 and similar to those estimated for Scottish wind farm areas. In addition, monthly densities at some sites are also remarkably high, such as those for June and July at several areas off the north coast of East Anglia (Triton Knoll, Inner Dowsing, Lincs, Triton Knoll and Humber Gateway) and similar densities can be found in other months for other areas. Comparing data from the JNCC and based on kriged data from the ESAS database (figure 3) such high figures cannot be found in the breeding season. A previous analysis of ESAS data revealed high at-sea concentrations close to colonies and low numbers elsewhere (Kober *et al*. 2010). Similar patterns are reported by Waggitt *et al*. (2019). Tracking data of breeding birds reveal a similar pattern (*e.g.* Hamer *et al*. 2007, Wakefield *et al.* 2013, Langston *et al.* 2013).

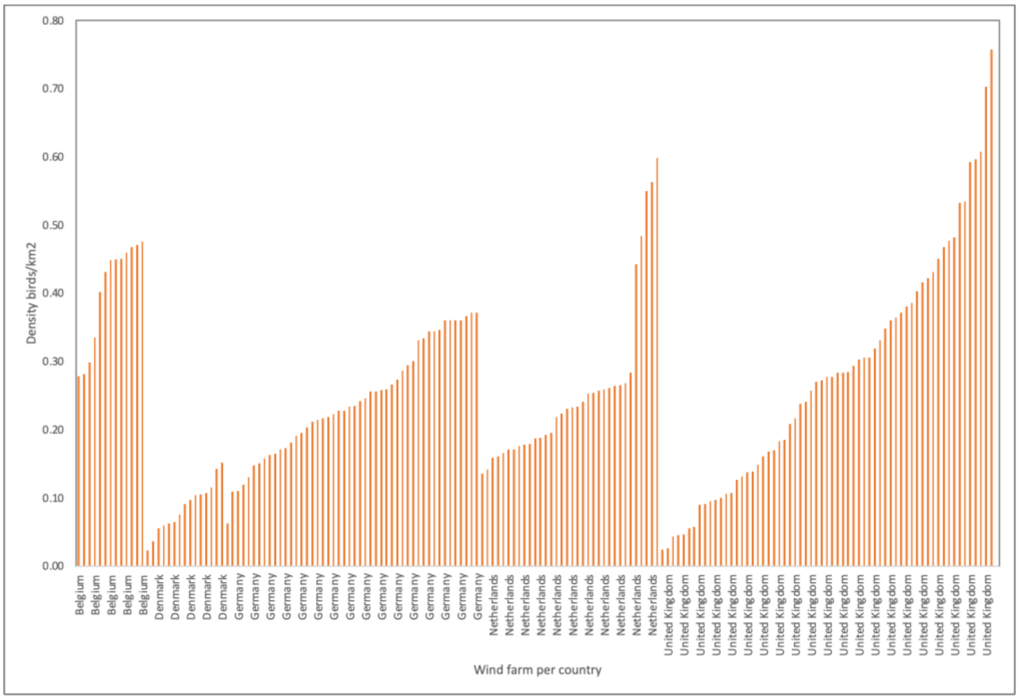


Figure 2. Mean monthly density of northern gannet estimated at wind farm locations in each country and sorted within country per aerial bird density.

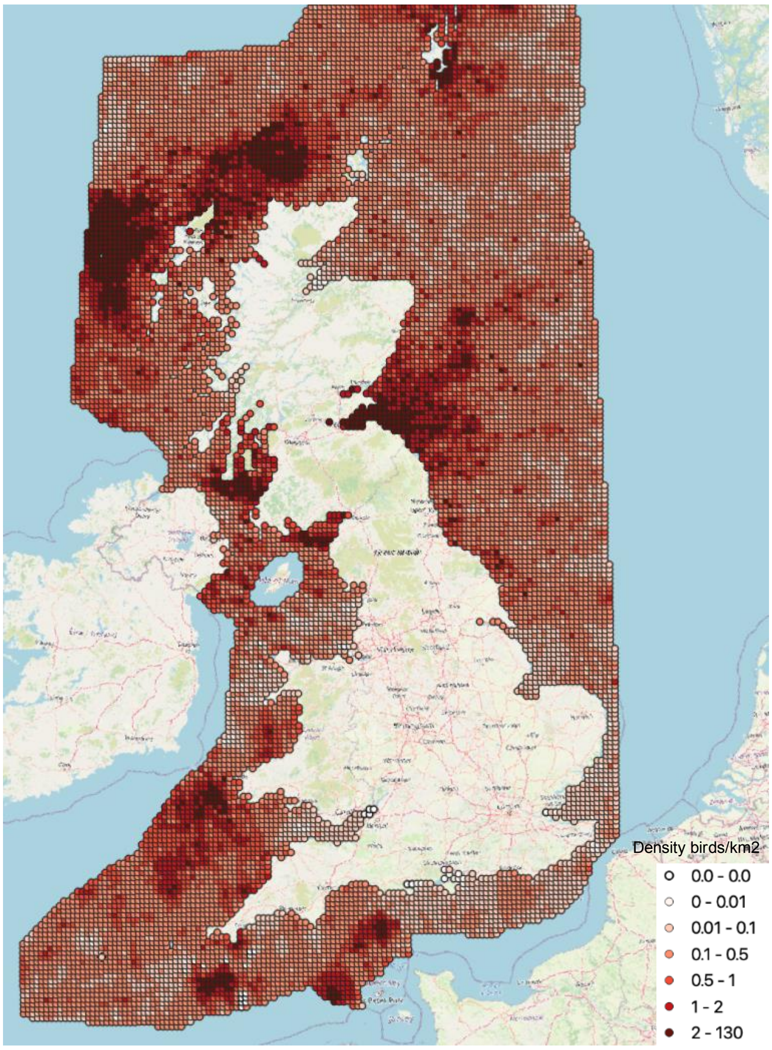
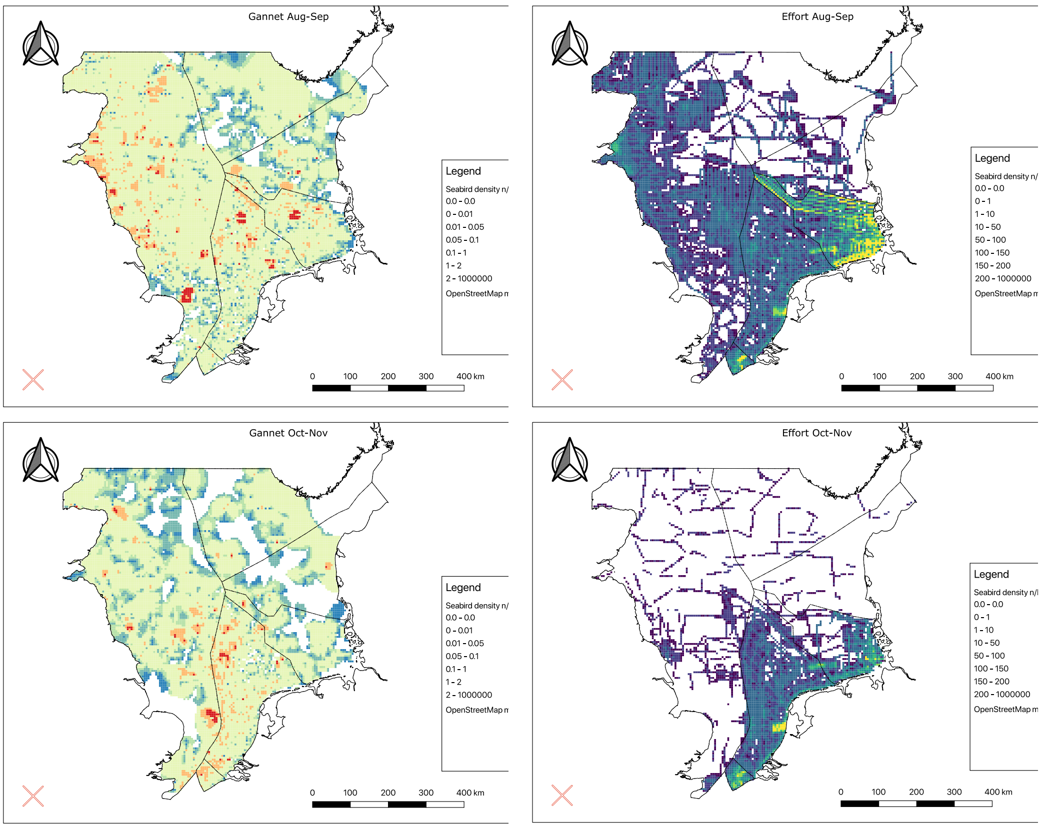
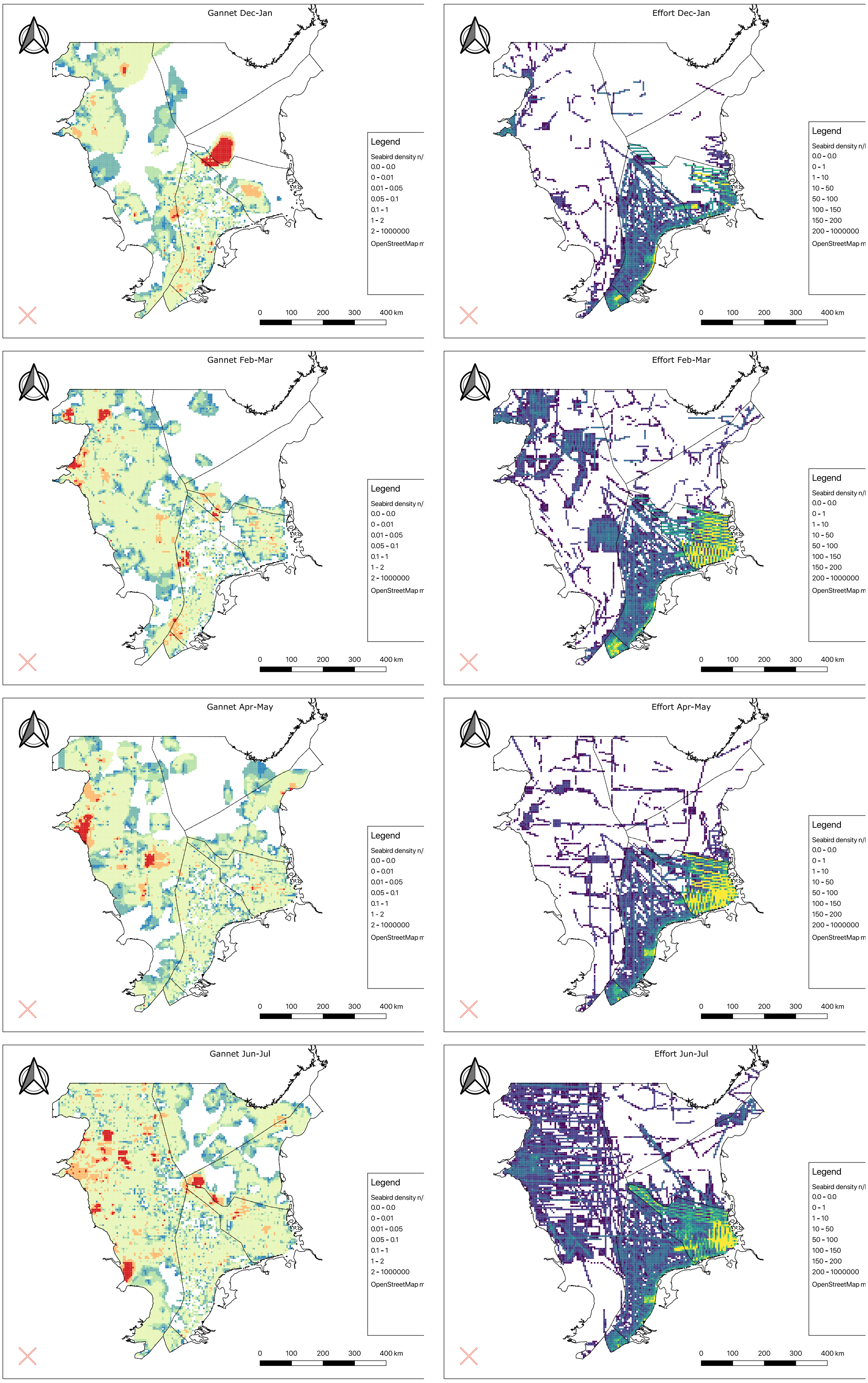


Figure 3. At-sea distribution of northern gannet in UK coastal waters, revealing high densities in Scottish waters in close proximity of the breeding colonies and lower densities along the coast of England, bordering the Dutch North Sea area (data from JNCC, https://data.gov.uk/dataset/815c1b02-26d3-4ab3-af76-c2c46a340d68/at-sea-densities-of-gannet-in-the-breeding-season).

Estimated densities used for the collision rate modelling are shown in figure 4, alongside the effort per area. It is clear that the effort in Germany, the Netherlands and Belgium is higher than that in the UK and Danish waters. Only surveys used for the periods June to September in some areas of the UK show effort levels nearing those in more frequently counted countries. This is also evident in data held in the ESAS database (figure 5). Not all recent counts undertaken in UK waters are added to the ESAS database, particularly where the focus is related to offshore wind farms. Only volunteer surveys, undertaken using ferries, have been added, as is evident in the survey coverage map in figure 5. Although not available from these maps, it can be expected that the UK data are older and more infrequent than data for other countries, as recently at-sea surveys are more often carried out by non-ESAS methods (adapted ship-based surveys, or aerial or digital aerial surveys) and are driven by offshore development (resulting in spatially and temporally concentrated surveys that are not fed into the ESAS database). It is also worth noting that the northern gannet population at the largest colony (Bass Rock) has almost doubled since the turn of the century and that at Bempton Cliffs has increased almost six-fold in the same period. Seabirds at sea data are typically characterized by high frequencies of zeros or low counts and irregular higher counts. Increased effort can be expected to encounter higher frequencies of these higher counts and may explain some of the variation in estimated densities. Kober *et al.* (2010) noted this and described how survey effort in UK waters is concentrated in a few areas and along ferry routes.

Furthermore, methodological differences between countries and projects, even within the general ESAS methodology, and particularly for how flying birds are sampled and recorded, may also lead to variation in estimates between areas and make data on flying birds incompatible (Maclean et al. 2014). Traditional ESAS methodology favours recording birds as 'on water' rather than in flight and using a snapshot strip method (rather than Distance transects) for sampling flying birds. This can result in birds being double counted or over-estimates if pooling all data and is therefore discouraged (Tasker *et al*. 1984). Methods in some projects or regions differ in how flying birds are recorded, particularly more recently where wind farms have been the focus of such surveys. The exclusion of flying birds from the analysis, especially for species that are predominately recorded in flight and have high detection rates such as northern gannet, are likely to influence density estimates. Both these possibilities can be easily examined through simple data exploration.





Gannet Dec-Jan
Effort Dec-Jan
Gannet Feb-Mar
Effort Feb-Mar
Gannet Apr-May
Effort Apr-May
Gannet Jun-Jul
Effort Jun-Jul
Legend
Seabird density n/
0.0 - 0.0
0 - 0.01
0.01 - 0.05
0.05 - 0.1
0.1 - 1
1 - 2
2 - 1000000
OpenStreetMap m
Legend
Seabird density n/l
0.0 - 0.0
0 - 1
1 - 10
10 - 50
50 - 100
100 - 150
150 - 200
200 - 1000000
OpenStreetMap m
0 100 200 300 400 km

Figure 4. Estimated densities of northern gannet in the North Sea per two-month period (left) and survey effort on which these estimates are based (right).

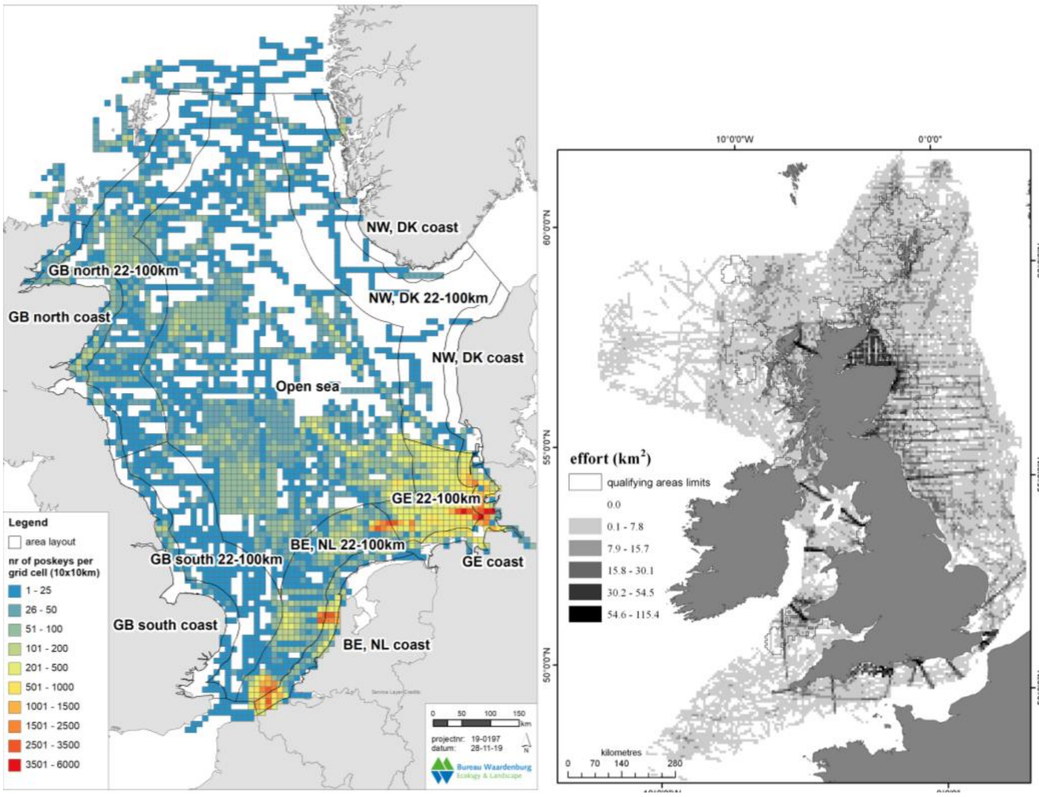


Figure 5. Overview of poskeys (as indication of effort) held in the ESAS database used for this analaysis (left) and ESAS coverage based on JNCC data (from Kober et al*. 2010).*

2.2.3 Assumptions sCRM

The sCRM is based on the SOSS Band model that was published by the SOSS in 2012 (see www.bto.org/our-science/wetland-and-marine/soss/projects). This model has several assumptions on the behaviour of birds, including that birds fly at a constant height, fly in a straight line and at a constant speed, etc. Although this is unlikely to mirror the real-life behaviour of these species, this simplification is necessary for the purpose of modelling and the source data that feed into it, including for example, flight height data and aerial bird densities.

One assumption is that birds cross the rotor-swept area perpendicular to the plane of the rotors. The reasoning for this is described in the guidance document accompanying the model (Band 2012). This guidance document also shows that a non-perpendicular approach would result in similar outcomes. Similarly, the calculation of bird flux through the rotor-swept area by using bird densities directly in front of the wind turbine can be expected to give comparable results when taking into account the entire area surrounding the rotor-swept area combined with multiple flight directions.

One part of the model that is potentially sensitive to the used flight speed is the calculation of the flux. Here, bird densities are translated into fluxes based on flight speed in m/s converted into a distance per hour. This leads to a magnification of the selected input values, as well as any uncertainties. This is most evident with higher bird densities. In contrast, flight speed also influences collision risk. These two factors generally counteract each other with faster flight speeds resulting in a lower collision risk but higher fluxes.

The sCRM, as all models, is as good as the data used as input. Although it is valuable to assess where input data can be improved, this process should be done in parallel to a critical assessment of the model and most importantly of the entire objective of the modelling process: in the case of the collision rate model this would be to assess whether collision rates or fluxes through the rotor swept area can be measured or estimated through more direct means, such as camera systems.

2.2.4 Conclusions

Based on the findings above, there is no strong evidence for using an alternative avoidance rate for northern gannet. It is recommended to use the nocturnal activity rates in Furness *et al.* (2018) for breeding and non-breeding seasons and for the relevant areas. The outcome of using these figures is described below in 2.4.

Foraging ranges during the breeding season and densities of northern gannets used should be investigated further to see whether these are realistic and can be improved. The current density estimates used likely influence the high number of estimated collisions at certain wind farms. A reassessment of the data and selection process would be a suggested first step.

2.3 Check of model outcome

The sCRM used for the modelling of collision rate estimates has been funded and published by the Scottish Government (see https://www.gov.scot/publications/stochastic-collision-risk-model-for-seabirds-in-flight/). This model is based on the previous model commonly known as the Band model and most recently published by the SOSS in 2012 (see www.bto.org/our-science/wetland-and-marine/soss/projects).

To ensure that there were no errors in the code of the model and that the outputs were trustworthy, a check of the various aspects of the code and comparisons with the previous version of the model were made. This exercise revealed that the outputs of the two models were comparable, and no calculation errors were detected.

2.4 Update of collision rate estimates

The sCRM for both the international and national scenarios for northern gannet was run using updated figures for nocturnal activity (see 2.2.2, figure 1 and 2.2.3). The results per wind farm are presented in appendix 1.

For the international scenario (table A1), the total estimated number of collisions across all 163 wind farms was 8,774 collisions annually. The average across all wind farms was 54, with the highest being 241 and lowest 2. Compared to the KEC results these results were between 4 higher and 6 lower at individual wind farms. Although the lower nocturnal activity rate used outside the breeding season and for wind farms outside the foraging range of northern gannets resulted in lower fluxes going into the model, this change was relatively small and much of this variation between these two sets of results can be explained by stochasticity in the model and around model parameters.

For the national scenario (table A4), the total estimated number of collisions across all 24 wind farms was 1,907 collisions annually. The average across all wind farms was 79, with the highest being 242 and lowest 5. Compared to the KEC results these results were between 1 higher and 3 lower at individual wind farms. The lower nocturnal activity rate was applied to around half of the wind farms in the national scenario year-round and for the remainder outside the breeding season only. As with the international scenario, the difference was relatively small with much of the variation being explained by stochasticity in the model and around model parameters.

3 Population model: assessment of methods and assumptions

3.1 Introduction

In KEC 4.0, matrix population models were used to assess the effect of OWF casualties on the growth rates of the bird populations (Potiek *et al.* 2022; Soudijn *et al.* 2022). Within these population models, the population trajectory is simulated for the scenario without additional wind farms (null scenario), as well as the scenarios with additional wind farms. Within this chapter, we discuss some of the main assumptions within the assessment.

After predicting the numbers of casualties, the impact needs to be assessed on a certain population. This population can be defined in different manners, which are described within §3.2. For both habitat loss and collisions, the KEC 4.0 assessment predicts casualties per bimonthly period and OWF scenario. The manner of incorporating the predicted number of casualties is described in §3.3. In addition, the casualties are apportioned to different age classes. Within §3.5, this apportionment is updated to include spatial variation in age distribution based on ESAS data (as analysed within Potiek *et al.* 2019).

For both types of impact, the estimated number of casualties is directly proportional to the estimated local density around (planned) OWF sites. The density maps also provide estimates of the total number of individuals per bimonthly period and area ('international' vs. 'national'). The national and international density maps were based on different data (see Potiek *et al.* 2022 and Soudijn *et al.* 2022). The estimates of the annual number of casualties were combined with estimates of population abundances to estimate OWF-induced mortality that can be used in the population model. The next section outlines and reviews methodological aspects for the calculation of the annual population-level mortality from the casualties per bimonthly period.

3.2 Population definition

We reviewed the estimate of population abundance to be used in the calculation of the annual mortality rate. Because the estimated number of casualties is based on the density maps used in the KEC 4.0 assessment, it was decided to use a measure of population abundance derived from these density maps. We assumed that the maximum abundance of the different bimonthly periods represents the total number of individuals simultaneously present in the North Sea. We therefore decided to use the maximum abundance as derived from the density maps as the measure of population abundance, denoted by N_{max}.

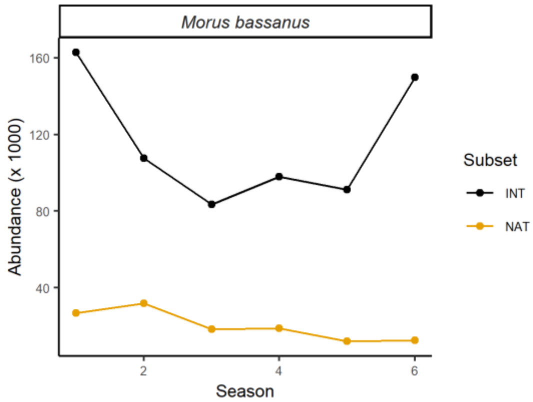


Figure 6 *Abundance of the northern gannet as derived from density maps created in the KEC 4.0 assessment (Soudijn et al. 2022).*

The maximum northern gannet abundance as derived from the density maps equalled 162,867 individuals for the international maps and 31,858 individuals for the national maps (Figure 6). These estimates are substantially lower than the estimated breeding population of northern gannets in the UK and Ireland based on counts of breeding individuals in the colonies (Table 2), and the number of birds estimated to be present in UK North Sea waters during the non-breeding period (Furness 2015). Accounting for 0.81 immatures per breeding adult (Furness 2015) and 2 individuals per breeding pair, the most recent survey of breeding gannets in the UK and Ireland (293,161 breeding pairs; Table 2) would yield a total population abundance of 1,061,243 northern gannets. Our estimated abundance of the northern gannet for the southern North Sea is 15.3% of this total population estimate and 3.0% for the Dutch continental shelf. Although it is unknown what fraction of the total breeding population in the UK and Ireland make use of the southern North Sea on a regular basis (it is likely that individuals use the northern North Sea, Norwegian Sea and Atlantic Ocean as well, maybe even to a greater extent), the estimated maximum population abundances from the density maps are likely precautionary.

Table 2 *Overview of estimates of northern gannet population abundance from UK colony counts and density estimations. Numbers are not directly comparable due to differences in units (individuals vs. breeding pairs) and geographical extent of the surveys. Breeding pairs are measured as Apparently Occupied Nests/Sites (AOS).*

Source	**Period**	**Region**	**Abundance estimate**	**Units**	**Reference**
KEC 4.0 assessment	1991-2020	Southern and Central North Sea	162,867	Individuals	Soudijn *et al.* (2022)
KEC 4.0 assessment	2000-2020	Dutch continental shelf	31,858	Individuals	Soudijn *et al.* (2022)
Gannet census (2013-2015)	2013-2015	UK colonies	293,161	Breeding pairs	JNCC (2022)

Gannet census (2003-2004)	2003-2004	Great Britain and Ireland colonies	261,561	Breeding pairs	Wanless *et al.* (2005); Mavor *et al.* (2008)
Seabird 2000 census	1998-2000	Great Britain and Ireland (inland and coastal colonies)	259,311	Breeding pairs	Mitchell *et al.* (2004)
SCR Census	1985-1988	Great Britain and Ireland (coastal colonies only)	186,508	Breeding pairs	Mitchell *et al.* (2004)
Operation Seafarer	1969-1970	Great Britain and Ireland (coastal colonies only)	137,661	Breeding pairs	Mitchell *et al.* (2004)

Furness (2015) estimated the non-breeding-season population sizes of seabirds around the UK, including the UK North Sea. These figures are based on the proportions of each geographical breeding population present in the area in each season. For the UK North Sea and Channel waters, northern gannets breeding in Iceland, Norway, Ireland, Germany and around the UK were deemed to be present in varying proportions. This resulted in totals of 456,299 and 248,385 northern gannets in the UK North Sea and Channel waters between September - November and December - March respectively. This suggests that the numbers in the entire southern North Sea may be even larger. Furthermore, most colonies have increased in size since Furness (2015) was published, including Bass Rock (55,482 to ca. 8,000 pairs), Bempton (11,061 to 13,400 pairs), Helgoland (632 to 1,250 pairs), Norway (4500 to 6,250 pairs) and Iceland (28,500 to 37,000 pairs). These estimates of breeding birds do not include non-breeding individuals. With these additions it can be expected that numbers during the non-breeding season would be even higher.

Note that the population size used in KEC 4.0 is calculated as the sum of the bird densities that are used for the collision rate modelling. This effectively considers collisions as a proportion of birds present at any given moment. This assumes a closed population where all birds are present in the study area at any given moment, which for KEC 4.0 is any bi-monthly period. However, many birds move in and out of the study area and further turnover occurs. This means that the actual population is undoubtedly larger than estimated based solely on density maps. Although this presents a precautionary approach, it would be useful to investigate the actual population size and potential for using different definitions of population size in the future.

3.3 Mortality calculation from collision victims

The bimonthly casualty estimates are combined with the population abundance estimates to estimate OWF-induced mortality. For this step, the KEC 4.0 assessment used the mean of the number of casualties of all six bimonthly periods, denoted by $\overline{M}$, as a representation of the bimonthly number of casualties for all six periods. Taking the mean over all six bimonthly periods was done to reduce the effect of large variation in the estimated number of casualties resulting from unrealistic high local density estimates. The mean number of casualties was used to calculate a bimonthly mortality probability as $m_{period} = \frac{\bar{M}}{N_{max}}$. Subsequently, m_{period} was converted to an annual mortality probability m_{annual} as:

$$m_{annual} = 1 - \left(1 - m_{period}\right)^6$$

Alternatively, one could adopt an approach that first calculates the annual number of casualties as the sum of the number of the bimonthly casualties for all six bimonthly periods, and then divide by the maximum population abundance, i.e.:

$$m_{annual} = \frac{\sum_{i=1}^{6} M_i}{N_{max}}$$

Where M_i is the estimated number of casualties per bimonthly period ii. This second method is comparable to the adopted method if there are no outliers in the estimated number of casualties.

3.4 Adjustment of mortality for age classes present

If some of the age classes are absent from the southern North Sea, these are not among the estimated collision victims. However, these individuals are part of the relevant population size, as these return at later age. Within KEC 4.0, subadults were assumed to be absent from the southern North Sea, and the fraction mortality was adjusted for this.

These assumptions were discussed again for the current analyses, which led to the conclusion that subadults mostly stay in the southern North Sea (Furness 2015). For that reason, this adjustment of the mortality fraction for a larger population was not performed within the current analysis. This means that, in contrast to the approach in KEC 4.0, the numbers of individuals present in the southern North Sea are not corrected for any age classes being absent from the southern North Sea.

3.5 Age distribution among collision victims

For KEC 4.0, the age distribution of northern gannet victims was assumed to follow the average age distribution of northern gannets on the southern North Sea (Potiek *et al.* 2022). This approach assumed 73% adults among victims, with the remaining 27% divided among other age classes following the relative age distribution.

One of the aims of this study was to update the analyses, using area-specific age distributions, as determined based on ESAS data, within Potiek *et al.* (2019). The area-specific percentages of adults are reported in Table 2. With the different areas, the distance to the coast is taken into account (coast up to 22 km offshore, 22-100 km from the coast, open sea > 100 km offshore) as well as country (Belgium + the Netherlands, UK, Germany, Norway + Denmark). Although these zones are arbitrary, they give better insight into spatial differences in age distribution than when using one estimate for the southern North Sea.

The classification into different zones is based on the area of each wind farm in the different zones (Appendix I, Table A1). If a wind farm overlaps with two zones, we chose to use the zone in which most of the wind farm is located. In case of Hollandse Kust Zuid, this approach resulted in some of the sub-areas (kavels) being assigned to the zone 'BE, NL 22-100km' (zones I and II), while other sub-areas were assigned to 'BE, NL coast' (zones III and IV). In this case, we considered Hollandse Kust West as one entity, and used the zone 'BE, NL coast' for all sub-areas. In addition, the German wind farm Hohe See was assumed to be in the zone 'open sea', instead of the zone 'GE 22-100km'.

The number of victims is estimated using the sCRM for each wind farm. Each of the scenarios within KEC 4.0 consists of a combination of wind farms. These victims are divided among adults and other stages. For each wind farm, the expected age distribution is based on the ESAS data for the zone in which that wind farm is located. As a result, the expected age distribution differs between the scenarios. For each scenario, the percentage of adults is calculated as the number of adult victims, divided by the total number of victims. This results for each specific scenario in the percentages of adults among victims as shown in Table 4.

In comparison, the percentage of adults among northern gannet victims within KEC 4.0 was assumed to be 73%. In other words, the zone-specific approach results in higher percentages of adults among victims for the national scenarios, but somewhat lower for the international scenario up to 2030. A higher percentage of adults among the victims results in a higher impact on the population level.

Table 3 *Area-specific percentages of adults based on ESAS data.*

Area	**Percentage adults**
BE, NL coast	64.5
BE, NL 22-100km	75.5
GB north coast	71.8
GB north 22-100km	93.1
GB south coast	58.0
GB south 22-100km	69.6
GE coast	48.6
GE 22-100km	57.8
NW, DK coast	12.5
NW, DK 22-100km	33.3
Open sea	75.1
Overall estimate	*73 %*

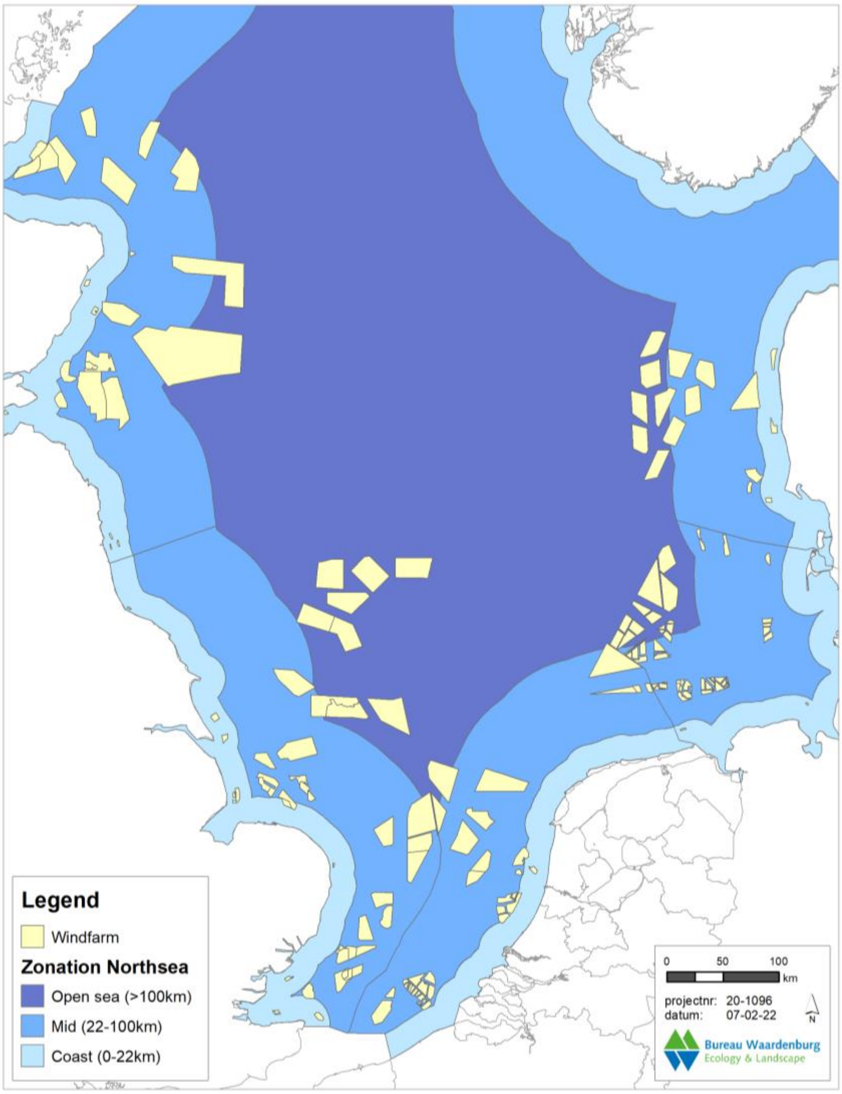


Figure 7 *Overview of relevant wind farms for KEC 4.0, including different zones within the North Sea. For each zone, a specific age distribution is determined based on ESAS data within Potiek* et al. *(2019).*

Table 4 *Expected percentage of adults among victims for each scenario, based on zone-specific ESAS data.*

Scenario	**Percentage adults based on zone-specific ESAS data**
Basic nat 30	0.752
Rekenvariant I	0.753
Rekenvariant II	0.753
Rekenvariant III	0.753
Int 30	0.723

4 Updated results population model

The KEC 4.0 assessment estimates mortality caused by offshore wind farms (OWFs), either through collisions or resulting from habitat loss. Subsequently, matrix population models are used to calculate whether mortality from OWFs leads to a violation of the Acceptable Levels of Impact (ALIs), as defined by Potiek et al. (2021). The ALIs define upper allowable limits to the probability that OWF-induced mortality is responsible for a predefined decrease in population abundance within a certain time frame, compared to a situation without OWFs. For the northern gannet, the probability that OWF-induced mortality leads to a 30% lower population abundance over 3 generations compared to a situation without OWFs, should not exceed 50%. As such, the evaluation of the ALI compares the projection of the population without OWFs ('null' scenario) to the projected population abundance with OWFs.

New results population model

The population models were updated using the updated numbers of collision victims and the spatial variation in age distribution (§ 2.4 and § 3.4). This resulted in the adjustment of survival rates as shown in Table 5.

This estimated level of additional mortality results in violation of the ALI threshold for each of the scenarios (Table 4.2). Population growth rates change from 1.001 in the null scenario to 0.948-0.971 in the impacted scenarios. In Table 6, P causality gives the probability that the violation of the threshold population size (X, for this species 30% decline over 30 years compared to the null scenario) is caused by the impact and not by uncertainty in the population models. For this species, the probability that a population abundance is 30% lower than the null scenario as result of the impact is between 59% and 62%, depending on the scenario.

Table 5 Additional mortality for each scenario (mean casualties per bimonthly period / max abundance), and adjusted stage-specific survival rates.

scenario	Mean casualties	Max abundance	Additional mortality	survival S0	survival SJ	survival SA
null	0	31859	0	0.481	0.862	0.918
Basic_2030	196	31859	0.036	0.468	0.839	0.881
Rekenvariant_I	280	31859	0.051	0.463	0.829	0.865
Rekenvariant_II	293	31859	0.054	0.462	0.828	0.862
Rekenvariant_III	318	31859	0.058	0.46	0.825	0.857
International	1160	162868	0.042	0.464	0.832	0.876

Table 6 Summary northern gannet population level effects; the median, 5% and 95% percentiles of the population growth rates (lambda) are reported. P causality represents the probability that a violation of the X threshold results from an OWF induced impact. The last column shows whether P causality violates the ALI threshold.

Scenario	Lambda median	5%	95%	P causality X = 30%	ALI 0.5
Null	1.001	0.959	1.037		
Basic_2030	0.971	0.929	1.008	0.589	TRUE
Rekenvariant_I	0.956	0.913	0.992	0.621	TRUE
Rekenvariant_II	0.953	0.911	0.99	0.622	TRUE
Rekenvariant_III	0.948	0.906	0.985	0.623	TRUE
International	0.966	0.923	1.002	0.606	TRUE

Sensitivity analysis

For each scenario, including the ‘null’ scenario, there is variation in the predicted population growth rate. This variation stems from variation in the model parameters that describe reproduction, survival and transitions of individuals between different life stages. Consequently, all model parameters are represented by a probability distribution, instead of a fixed value. The mean and standard deviations of the parameters of the northern gannet population model are shown in

Table . The distribution for the population growth rate is obtained by creating many population projection matrices through sampling from these parameters. The median value of this distribution is adopted as default estimate for the population growth rate.

Although the approach adopted in the KEC 4.0 assessment accounts for variation in demographic rates (survival and reproduction), it is possible that the true mean values of the population parameters differ from those used (Table 7). Therefore, a sensitivity analysis was performed to assess the extent to which changes in mean parameter values result in changes in the median value of population growth rate (λ) for each scenario. In addition, the sensitivity analysis also assesses whether violation of the ALI depends on the mean parameter values of the northern gannet population model.

The sensitivity analysis was performed by varying all model parameters on a one-by-one basis. Each parameter was varied over a range defined by a minimum, a maximum and a 'stepsize' value (

Table), with all other parameters at their default value. A change in mean value of one of the parameters of the population model implies a change in the value of λ for the 'null' scenario. Because the ALI is defined in reference to this baseline value of λ, the population abundance associated with an ALI violation needs to be reassessed for each new combination of mean parameter values. In other words, changing the mean value of a model parameter also changes the population abundance threshold of the ALI. The definition of the ALI for the northern gannet will of course remain the same.

Table 7 Parameter values of the northern gannet population model.

Parameter	Mean	SD	Min	Max	Step	Description
F_A	0.700	0.0820	0.20	0.90	0.10	Breeding success
P_F	0.050	0.1250	0.02	0.52	0.05	Probability floater
S_0	0.481	0.0853	0.20	0.60	0.10	Survival age 0
S_1	0.816	0.0393	0.20	0.95	0.10	Survival age 1
S_2	0.884	0.0293	0.40	0.95	0.10	Survival age 2
S_3	0.887	0.0301	0.40	0.95	0.10	Survival age 3
S_A	0.918	0.0199	0.60	0.98	0.01	Adult survival

Figure 4.1 shows the response of the median value of λ for each OWF scenario to changes in the mean parameter values of the northern gannet population model. The median value of λ that is associated with the ALI 'X' threshold (a 30% lower abundance over 3 generations compared to the "null" scenario) is indicated by the black line and is referred to as λ_X. Because the ALI is defined in reference to the 'null' scenario of no OWF disturbance, changing the mean values of the model parameters leads to a change in the median value of λ_X that is parallel to the change in the median value of λ for each of the scenarios (Figure 4.1).

To calculate whether the ALI is violated for each scenario, we compare $\mathrm{P}_{\mathrm{causality}}$ to the ALI Pt value as defined for the northern gannet (Pt = 0.5). $\mathrm{P}_{\mathrm{causality}}$ represents the probability that a population growth rate lower than λ_X is caused by an OWF impact and is calculated as:

$$\mathrm{P}_{\mathrm{causality}} = \frac{\mathrm{P}_{\mathrm{impact}} - \mathrm{P}_{\mathrm{falsepos}}}{\mathrm{P}_{\mathrm{impact}}}$$

with $\mathrm{P}_{\mathrm{impact}}$ the proportion of λ-values for a specific scenario that is below λ_X and $\mathrm{P}_{\mathrm{falsepos}}$ being the value of $\mathrm{P}_{\mathrm{impact}}$ for the null scenario. The ALI is violated if $\mathrm{P}_{\mathrm{causality}} > Pt$.
Figure 8 shows the value of $\mathrm{P}_{\mathrm{impact}}$ for each scenario as a function of the range of mean values for all model parameters. The conclusion about ALI violation is changed only for the national basic scenario at values of adult survival (0.6), which is far below the natural range of this parameter. Overall, the sensitivity analysis reveals that the ALI method is very robust against changes in model parameters. This is mainly because the ALI method compares a baseline population trajectory against an impacted population trajectory.

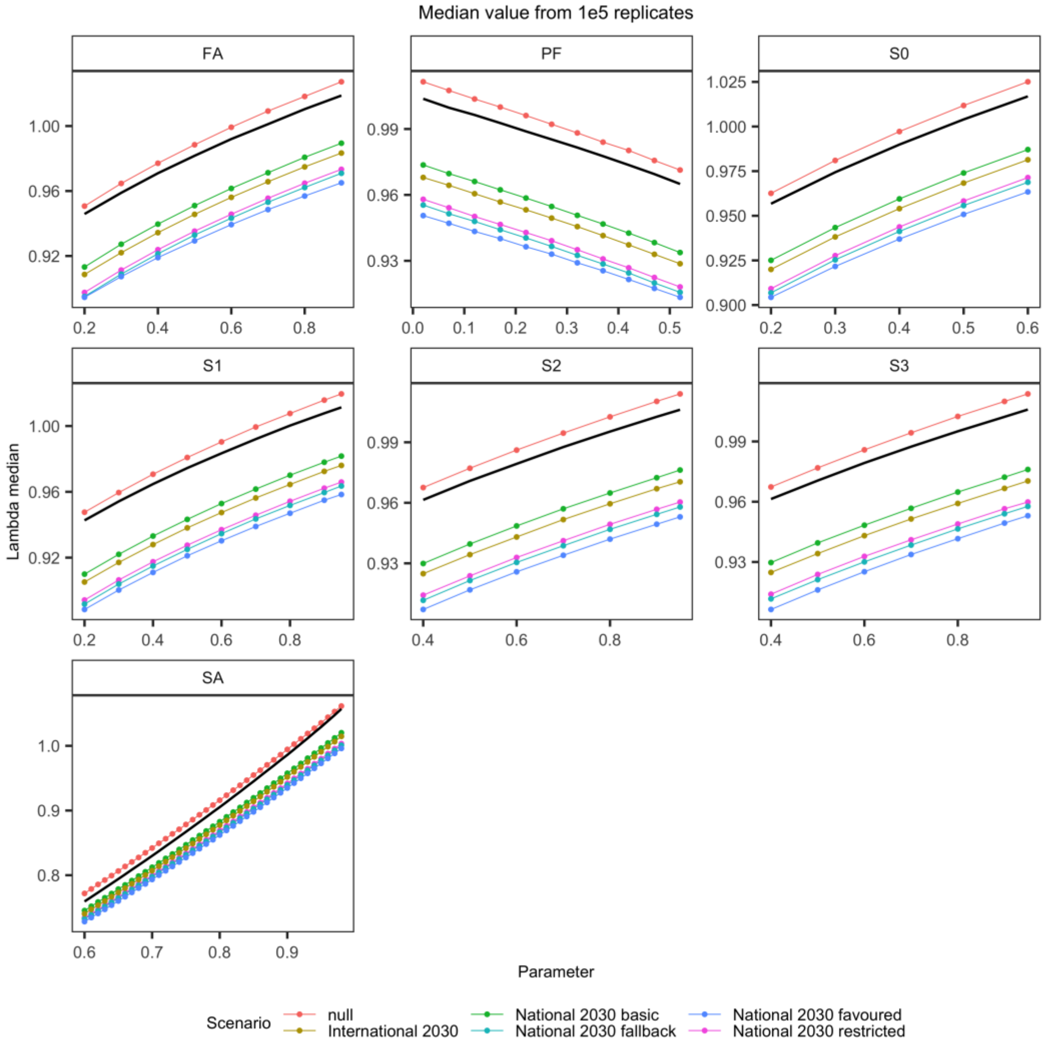


Figure 8 Outcome of the sensitivity analysis for the population growth rate (λ) of the northern gannet population model. Coloured lines are the median values of the distribution of λ for each OWF scenario and for the 'null' scenario. Black lines are the median values of λ that result in a 30% lower population abundance over three generations compared to the "null" scenario (the ALI X threshold).

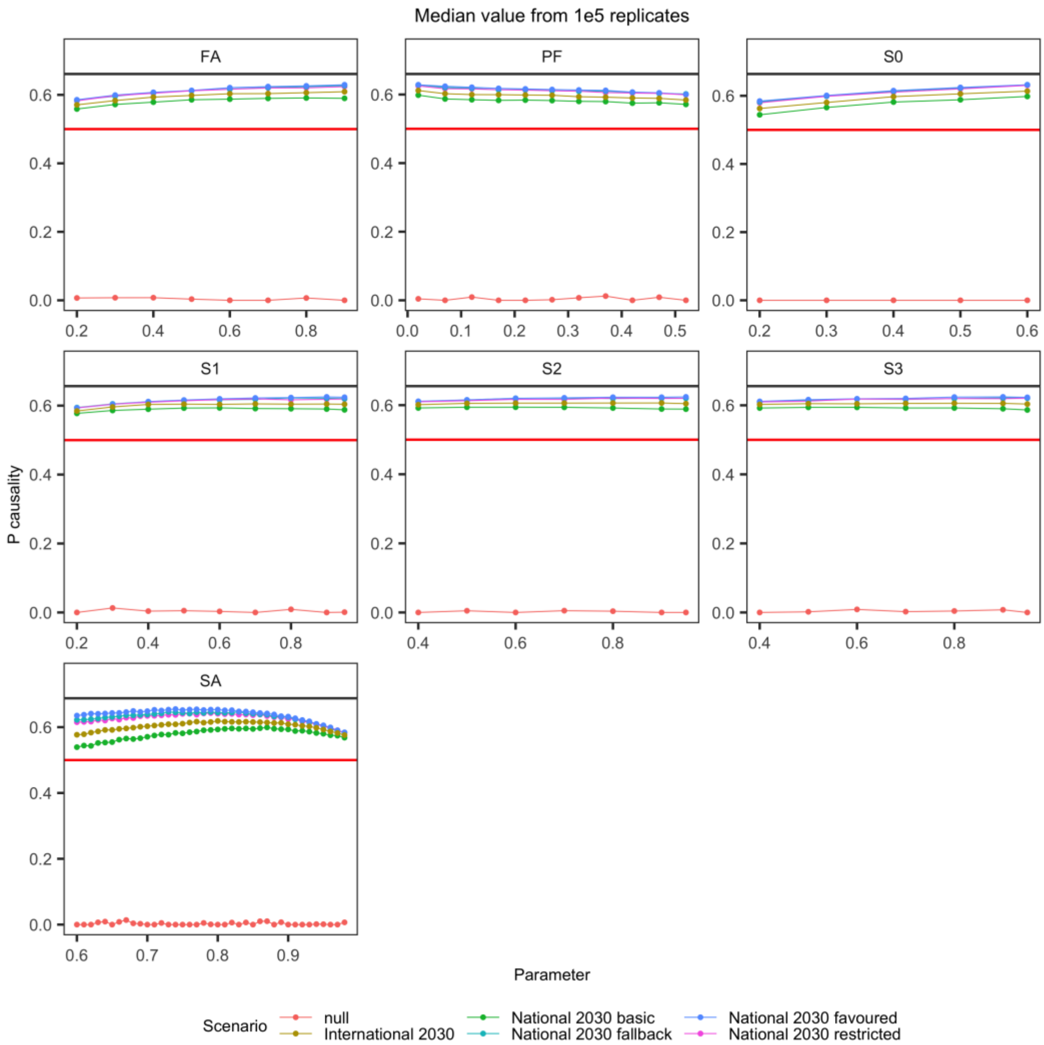


Figure 9 *Outcomes of the sensitivity analysis for the probability that an impact is caused by additional OWF mortality per OWF scenario, including the 'null' scenario (in colors). Red lines represent the northern gannet Pt value (0.5). All values above the red line imply a violation of the ALI.*

5 Conclusion and discussion

The update of the sCRM parameters resulted in adjustment of nocturnal activity during the breeding season outside the foraging range of the colonies, as well as during the non-breeding season. This slightly affected the estimated number of causalities. In addition, spatial variation in age distribution is incorporated within these additional analyses. These adjusted numbers of collision victims and age distribution among victims did not change the qualitative outcome of the population models. For each of the scenarios, the acceptable level of impact (ALI) is still violated. In other words, the estimated number of causalities due to collisions is too high, compared to the current ALI threshold. Several assumptions in the impact assessment may have resulted in an over- or underestimation of the number of causalities. Here we discuss the main assumptions and potential further analyses.

The current collision rate model is particularly sensitive to the avoidance rate parameter and the value used for aerial bird density (and to a lesser extent flight height distribution and rotor height), as the estimated number of casualties is directly proportional to these factors. Applying the model at such a scale as done here, and for where no site-specific data have been collected specifically for use in the model (cf. Band 2012), results in questions as to how realistic the used aerial bird densities and thus the estimates annual collision rates are. If using the model at such a scale, then it could be suggested to use a range of estimates for aerial bird density rather than a single value. Nevertheless, estimates will ultimately be driven largely by the aerial bird densities and avoidance rates used.

The disbalance in the international and national survey effort and variation in how aerial bird densities are recorded makes it more difficult to make reliable density maps for the northern gannet. This also underlines the importance of the use of a statistical model for the density maps that can correct somewhat for differences in survey effort and zero inflated data. Such a statistical model could predict bird density from a series of covariates and could deal with uncertainties resulting from low survey effort in a consistent manner. Including uncertainty in the most important input parameters increases the degree of confidence that can be assigned to any particular outcome. Data should also be explored to reduce the variation between surveys, regions and over time, and to investigate the possibility of using collected aerial bird densities rather than pooled data for input into collision rate models. Furthermore, defining populations to which any estimates apply is an important step in applying model outcomes. An additional analysis for herring gull (Soudijn *et al.* 2022) showed that a predictive model based on distance to coast, vessel activity and water depth fitted to the bird densities gives a more realistic density map than the ones used within this KEC 4.0 analysis. We recommend looking into options for updating the density maps for other species as well, including the northern gannet. In addition, other parameters such as distance to colony are likely to be informative for predicting bird densities for several species.

Furthermore, flight behaviour and areal use may differ between individuals, influencing the susceptibility of specific populations. The current approach does not incorporate differences in behaviour between individuals. Some individuals from the population will rarely make use of wind farm areas, while others enter wind farms regularly. For example, Peschko *et al.* (2011) studied the behaviour of adult northern gannets in relation to wind farms and found that during the breeding season only 3 out of 28 individuals regularly visited wind farms, while the others predominantly avoided them. This type of metric is not specifically used as input for the sCRM, but is incorporated, less specifically, in the measure for macro-avoidance. Note that if only a certain fraction of the population is at risk of collision, due to lower avoidance of wind farms, only this fraction of the population will decline. This would result in a lower number of individuals at risk and should be applied as such in assessments at the population level. Although the results from Peschko *et al.* (2011) are promising, further studies are needed to provide insight in differences between individuals, for different colonies and for breeding season as well as outside the breeding season. Moreover, avoidance may differ between age classes. Although individual-based differences in area use are not taken into account, such avoidance of wind farms could, over time, result in lower densities within wind farm areas. Conversely, birds may become accustomed to wind farms and avoidance may subsequently drop. Hence, more research on the development of aerial bird densities (for the assessment of collisions) and total densities (for the assessment of displacement) in operational wind farms is needed (*e.g.* Rehfisch *et al*. 2014).

The Band model was originally developed to estimate the potential number of collision victims for a specific planned wind farm and to make comparisons between planning variants using the Rochdale Envelope. The more widespread application of the Band model, such as conducted in KEC 4.0, leads to difficulties regarding estimates of bird fluxes and avoidance rates on larger scales; most specifically the summing of many worst-case assumptions made by the model. Fluxes used in the current project are based on modelled densities that are estimated with observational data not solely relating to aerial bird data and collected during periods sometimes many years prior to OWF deployment. Instead of focussing efforts entirely on refining certain input variables that are difficult to measure and by nature being highly variable, targeted research efforts should be used to investigate whether data on collisions can be collected directly, alongside the ground-truthing and validation of key parameters of the sCRM. One crucial aspect in collision modelling is the bird flux through the rotor, which is obtained by combining local bird density with bird flight speed. Potentially, field measurements of bird fluxes through OWFs can be derived from camera systems or radar, and give more reliable estimates of fluxes through wind farm areas, and specifically camera systems could measure collisions directly. This would remove the need to estimate avoidance.

Moreover, all variation within the population models is assumed to be the result of parameter uncertainty. This results in a precautionary approach, with a wider range of outcomes of the population model. As a result, the ALI threshold is more often violated. In addition, as the level of uncertainty plays a role within the ALI methodology, we advise to look further into the effect of this assumption.

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Appendix I Spatial variation in age distribution

Table A1. Results of incorporating spatial variation in age distribution per wind farm. Each wind farm is assigned to a zone based on the location, and the percentage of adults per wind farm is based on the age distribution of individuals within the ESAS database for that specific zone (analysis done in Potiek et al. *2019).*

Wind farm name	Zone	Percentage adults
Thornton Bank phase I	BE, NL 22-100km	75.5
Northwind	BE, NL 22-100km	75.5
Belwind	BE, NL 22-100km	75.5
Norther	BE, NL 22-100km	75.5
Rentel	BE, NL 22-100km	75.5
Seamade (SeaStar)	BE, NL 22-100km	75.5
Seamade (Mermaid)	BE, NL 22-100km	75.5
Nobelwind	BE, NL 22-100km	75.5
Thornton Bank phase II	BE, NL 22-100km	75.5
Thornton Bank phase III	BE, NL 22-100km	75.5
Northwester 2	BE, NL 22-100km	75.5
Princess Elisabeth - Noordhinder Noord - 2023 Tender	BE, NL 22-100km	75.5
Princess Elisabeth - Fairybank/Nordhinder Zuid - 2025 Tender	BE, NL 22-100km	75.5
Alpha Ventus	GE 22-100km	57.8
DanTysk	GE 22-100km	57.8
Borkum Riffgrund 3	GE 22-100km	57.8
Borkum Riffgrund 1	GE 22-100km	57.8
Amrumbank West	GE 22-100km	57.8
Nordsee Ost	GE 22-100km	57.8
Meerwind Süd/Ost	GE 22-100km	57.8
Butendiek	GE 22-100km	57.8
Global Tech I	Open sea	75.1
Gode Wind 3	GE 22-100km	57.8
Trianel Windpark Borkum II	GE 22-100km	57.8
Hohe See	Open sea	75.1
Sandbank	GE 22-100km	57.8
Gode Wind 1 and 2	GE 22-100km	57.8
EnBW He Dreiht	GE 22-100km	57.8
Nordergründe	GE coast	48.6
Riffgat	GE coast	48.6
BARD Offshore 1	GE 22-100km	57.8
Deutsche Bucht	GE 22-100km	57.8
Merkur	GE 22-100km	57.8
Trianel Windpark Borkum I	GE 22-100km	57.8
Nordsee One	GE 22-100km	57.8
N-3.5	GE 22-100km	57.8
N-3.6	GE 22-100km	57.8
N-3.7	GE 22-100km	57.8
N-3.8	GE 22-100km	57.8
N-6.6	GE 22-100km	57.8
N-6.7	GE 22-100km	57.8
N-7.2	GE 22-100km	57.8
N-8.4	Open sea	75.1
Borkum Riffgrund 2	GE 22-100km	57.8
Kaskasi	GE 22-100km	57.8
Veja Mate	GE 22-100km	57.8
Albatros	Open sea	75.1

N-9.1	Open sea	75.1
N-9.2	Open sea	75.1
N-10.1	Open sea	75.1
N-11-1	Open sea	75.1
N-12.1	Open sea	75.1
N-10.2	Open sea	75.1
N-12.2	Open sea	75.1
N-12.3	Open sea	75.1
N-12.4	Open sea	75.1
N-11-2	Open sea	75.1
N-13-2	Open sea	75.1
N-13-3	Open sea	75.1
N-9.3	Open sea	75.1
N-9.4	Open sea	75.1
Horns Rev 1	NW, DK coast	12.5
Nordsøen - Tender 1	Open sea	75.1
Nordsøen - Tender 3	Open sea	75.1
Nordsøen - Tender 2	NW, DK 22-100km	33.3
Nordsøen - Tender 4	Open sea	75.1
Nordsøen - Tender 5	Open sea	75.1
Horns Rev 2	NW, DK 22-100km	33.3
Horns Rev 3	NW, DK 22-100km	33.3
Nordsøen - Tender 6	NW, DK 22-100km	33.3
Nordsøen - Tender 7	NW, DK 22-100km	33.3
Nordsøen - Tender 8	NW, DK 22-100km	33.3
Nordsøen - Tender 9	Open sea	75.1
Nordsøen - Tender 10	Open sea	75.1
Thor - 2020 Tender	NW, DK 22-100km	33.3
Vesterhav Nord/Syd	NW, DK coast	12.5
Dudgeon	GB south 22-100km	69.6
Greater Gabbard	GB south 22-100km	69.6
Gunfleet Sands	GB south coast	58
Dogger Bank B	Open sea	75.1
Humber Gateway	GB south coast	58
Inner Dowsing	GB south coast	58
Kentish Flats	GB south coast	58
Lincs	GB south coast	58
London Array	GB south 22-100km	69.6
Lynn	GB south coast	58
Race Bank	GB south 22-100km	69.6
Dogger Bank C	Open sea	75.1
Sofia	Open sea	75.1
Hornsea Project Four	GB south 22-100km	69.6
Hornsea Project Three	Open sea	75.1
Hornsea Project Two	Open sea	75.1
Scroby Sands	GB south coast	58
Sheringham Shoal	GB south coast	58
Teesside	GB south coast	58
Thanet	GB south coast	58
East Anglia Hub - ONE North	GB south 22-100km	69.6
ForthWind Offshore Wind Demonstration Project Phase 2	GB north coast	71.8
Triton Knoll	GB south 22-100km	69.6
Westermost Rough	GB south coast	58
East Anglia Hub - TWO	GB south 22-100km	69.6
Scottish Sectoral Marine Plan - E3	GB north 22-100km	69.6
Scottish Sectoral Marine Plan - E2	Open sea	75.1
Scottish Sectoral Marine Plan - E1	Open sea	75.1
Scottish Sectoral Marine Plan - NE6	GB north 22-100km	69.6
Scottish Sectoral Marine Plan - NE7	GB north 22-100km	69.6

Scottish Sectoral Marine Plan - NE8	GB north 22-100km	69.6
Scottish Sectoral Marine Plan - NE3	GB north 22-100km	69.6
Scottish Sectoral Marine Plan - NE4	GB north 22-100km	69.6
Moray East	GB north 22-100km	69.6
Seagreen	GB north 22-100km	69.6
Aberdeen Offshore Wind Farm (EOWDC)	GB north coast	71.8
Race Bank Extension	GB south 22-100km	69.6
Dudgeon Extension	GB south 22-100km	69.6
Sheringham Shoal Extension	GB south 22-100km	69.6
Five Estuaries	GB south 22-100km	69.6
North Falls	GB south 22-100km	69.6
Kincardine - Phase 2	GB north coast	71.8
Seagreen 1A	GB north 22-100km	69.6
Round 4 - Area 1 (RWE Renewables)	Open sea	75.1
Round 4 - Area 2 (RWE Renewables)	Open sea	75.1
Round 4 - Area 3 (GIG & Total)	GB south 22-100km	69.6
Beatrice	GB north coast	71.8
Inch Cape	GB north 22-100km	69.6
Neart na Gaoithe	GB north coast	71.8
Kentish Flats Extension	GB south coast	71.8
Galloper	GB south 22-100km	69.6
East Anglia ONE	GB south 22-100km	69.6
East Anglia Hub - THREE	GB south 22-100km	69.6
Norfolk Vanguard	GB south 22-100km	69.6
Norfolk Boreas	GB south 22-100km	69.6
Blyth Offshore Demonstrator Phase 1	GB north coast	71.8
Berwick Bank	GB north 22-100km	69.6
Marr Bank	GB north 22-100km	69.6
Hywind Scotland Pilot Park	GB north 22-100km	69.6
Moray West	GB north 22-100km	69.6
Blyth Offshore Demonstrator Phase 2	GB north coast	71.8
Dogger Bank A	Open sea	75.1
Hornsea Project One	Open sea	75.1
Borssele 2	BE, NL 22-100km	75.5
Borssele 3	BE, NL 22-100km	75.5
Borssele 4 - Blauwwind	BE, NL 22-100km	75.5
Borssele Site V -Two towers	BE, NL 22-100km	75.5
Egmond aan Zee	BE, NL coast	64.5
Prinses Amaliawindpark	BE, NL 22-100km	75.5
Eneco Luchterduinen	BE, NL 22-100km	75.5
Gemini Zee energie	BE, NL 22-100km	75.5
Gemini Buitengaats	BE, NL 22-100km	75.5
Hollandse Kust Zuid Holland IV	BE, NL 22-100km	75.5
Hollandse Kust Zuid Holland III	BE, NL 22-100km	75.5
Hollandse Kust Zuid Holland II	BE, NL 22-100km	75.5
Hollandse Kust Zuid Holland I	BE, NL 22-100km	75.5
Borssele 1	BE, NL 22-100km	75.5
Hollandse Kust Noord (Tender 2019)	BE, NL 22-100km	75.5
Ten noorden van de Waddeneilanden	BE, NL 22-100km	75.5
IJmuiden Ver	BE, NL 22-100km	75.5
Hollandse Kust West - (Tender 2020/2021)	BE, NL 22-100km	75.5
Hollandse Kust West zuidelijke punt	BE, NL 22-100km	75.5
Zoekgebied 1 Noord	Open sea	75.1
Zoekgebied 5 Oost origineel	BE, NL 22-100km	75.5
IJmuiden Ver Noord	BE, NL 22-100km	75.5
Zoekgebied 1 Zuid	BE, NL 22-100km	75.5
Zoekgebied 2 Noord	BE, NL 22-100km	75.5

Appendix II Collision rate modelling results

Table A2. Results of the collision rate modelling for the international scenario using nocturnal activity rates of 3% and 8% only for wind farms within the foraging range of northern gannets and during the breeding season as described in 2.2.2.

Wind farm name	Collisions	SD	KEC Mean	Difference
Thornton Bank phase I	4	2.15	4	0
Northwind	179	78.12	184	-4
Belwind	78	38.23	80	-2
Norther	54	24.21	55	-1
Rentel	41	21.37	42	-1
Seamade (SeaStar)	37	17.68	38	-1
Seamade (Mermaid)	36	17.23	37	-1
Nobelwind	87	41.10	90	-2
Thornton Bank phase II	22	10.62	22	0
Thornton Bank phase III	11	5.19	11	0
Northwester 2	31	14.91	32	-1
Pr. Elisabeth - Noordhinder Noord - 2023	71	36.01	73	-2
Pr. Elisabeth - Fairybank Nordhinder Zuid	125	62.41	128	-3
Alpha Ventus	6	3.12	6	0
DanTysk	51	23.94	51	0
Borkum Riffgrund 3	58	28.97	58	0
Borkum Riffgrund 1	66	32.17	66	0
Amrumbank West	64	31.92	64	0
Nordsee Ost	42	20.20	42	0
Meerwind Süd Ost	78	41.28	77	1
Butendiek	43	21.37	42	1
Global Tech I	97	45.17	99	-2
Gode Wind 3	17	8.55	17	0
Trianel Windpark Borkum II	23	11.33	23	0
Hohe See	64	31.95	65	-1
Sandbank	51	25.65	50	1
Gode Wind 1 and 2	44	21.66	44	0
EnBW He Dreiht	53	25.14	53	0
Nordergründe	11	5.26	11	0
Riffgat	6	3.04	6	0
BARD Offshore 1	44	22.24	44	0
Deutsche Bucht	14	6.85	15	0
Merkur	43	20.55	43	0
Trianel Windpark Borkum I	22	11.16	22	0
Nordsee One	43	21.44	43	0
N-3.5	25	12.37	25	0
N-3.6	28	14.03	28	0
N-3.7	10	5.21	10	0
N-3.8	27	13.22	26	0
N-6.6	27	13.26	27	0
N-6.7	10	4.93	10	0
N-7.2	53	26.58	54	0
N-8.4	26	13.07	27	-1
Borkum Riffgrund 2	47	22.49	47	0
Kaskasi	39	17.54	39	0
Veja Mate	35	16.21	35	0
Albatros	14	6.78	14	0
N-9.1	30	14.78	29	0
N-9.2	35	17.30	35	0

N-10.1	38	19.05	39	-1
N-11-1	65	29.71	65	0
N-12.1	66	29.98	65	0
N-10.2	25	12.45	25	0
N-12.2	66	29.98	65	0
N-12.3	66	29.98	65	0
N-12.4	66	29.98	65	0
N-11-2	65	29.71	65	0
N-13-2	66	29.93	65	1
N-13-3	66	29.93	65	1
N-9.3	27	13.40	27	0
N-9.4	32	16.10	32	0
Horns Rev 1	7	3.73	7	0
Nordsøen - Tender 1	11	5.06	11	0
Nordsøen - Tender 3	20	9.19	20	0
Nordsøen - Tender 2	15	6.85	15	0
Nordsøen - Tender 4	7	3.04	7	0
Nordsøen - Tender 5	20	9.33	20	0
Horns Rev 2	34	16.21	33	1
Horns Rev 3	16	7.31	16	0
Nordsøen - Tender 6	11	5.16	11	0
Nordsøen - Tender 7	16	7.45	16	0
Nordsøen - Tender 8	30	13.84	30	1
Nordsøen - Tender 9	21	9.67	21	0
Nordsøen - Tender 10	28	12.75	28	0
Thor - 2020 Tender	24	12.16	25	-1
Vesterhav Nord Syd	11	5.17	11	0
Dudgeon	7	3.95	7	0
Greater Gabbard	57	27.55	58	-1
Gunfleet Sands	20	9.30	20	0
Dogger Bank B	60	34.82	60	0
Humber Gateway	108	52.30	106	3
Inner Dowsing	38	18.61	37	1
Kentish Flats	7	3.30	7	0
Lincs	109	51.60	106	4
London Array	81	39.14	81	-1
Lynn	36	17.43	35	1
Race Bank	26	13.78	25	1
Dogger Bank C	70	32.58	70	0
Sofia	99	54.04	99	0
Hornsea Project Four	50	22.73	49	1
Hornsea Project Three	124	64.77	126	-2
Hornsea Project Two	106	56.65	107	0
Scroby Sands	9	3.92	9	0
Sheringham Shoal	8	4.06	8	0
Teesside	11	5.86	11	0
Thanet	91	43.42	92	-2
East Anglia Hub - ONE North	12	6.26	12	0
ForthWind Demonstration Project Phase 2	6	2.92	6	0
Triton Knoll	74	33.31	73	2
Westermost Rough	22	10.85	22	0
East Anglia Hub - TWO	17	9.06	17	0
Scottish Sectoral Marine Plan - E3	95	43.08	94	1
Scottish Sectoral Marine Plan - E2	125	57.07	123	2
Scottish Sectoral Marine Plan - E1	241	110.00	238	3
Scottish Sectoral Marine Plan - NE6	103	46.89	103	0
Scottish Sectoral Marine Plan - NE7	116	52.98	117	0
Scottish Sectoral Marine Plan - NE8	40	18.30	40	0
Scottish Sectoral Marine Plan - NE3	26	11.73	26	0

Scottish Sectoral Marine Plan - NE4	34	15.38	33	0
Moray East	124	59.03	126	-1
Seagreen	69	35.98	68	1
Aberdeen Offshore Wind Farm (EOWDC)	21	10.50	20	0
Race Bank Extension	15	7.69	15	0
Dudgeon Extension	18	8.40	18	0
Sheringham Shoal Extension	2	0.74	2	0
Five Estuaries	9	4.17	9	0
North Falls	14	6.96	14	0
Kincardine - Phase 2	13	5.90	13	0
Seagreen 1A	22	11.70	22	0
Round 4 - Area 1 (RWE Renewables)	98	44.44	97	0
Round 4 - Area 2 (RWE Renewables)	75	34.10	75	0
Round 4 - Area 3 (GIG & Total)	29	13.14	29	0
Beatrice	30	15.76	30	0
Inch Cape	211	97.09	211	0
Neart na Gaoithe	60	33.39	59	0
Kentish Flats Extension	3	1.44	3	0
Galloper	21	9.42	21	0
East Anglia ONE	100	42.64	102	-2
East Anglia Hub - THREE	69	36.02	71	-2
Norfolk Vanguard	40	23.28	41	-1
Norfolk Boreas	223	95.41	228	-6
Blyth Offshore Demonstrator Phase 1	6	3.07	6	0
Berwick Bank	237	108.17	236	2
Marr Bank	236	107.73	233	3
Hywind Scotland Pilot Park	5	2.25	5	0
Moray West	103	54.86	104	-2
Blyth Offshore Demonstrator Phase 2	8	3.52	8	0
Dogger Bank A	49	28.43	49	0
Hornsea Project One	133	72.99	133	0
Borssele 2	66	30.08	67	-2
Borssele 3	50	23.74	52	-1
Borssele 4 - Blauwwind	56	26.54	58	-2
Borssele Site V -Two towers	3	1.45	3	0
Egmond aan Zee	21	10.16	22	0
Prinses Amaliawindpark	53	25.18	53	-1
Eneco Luchterduinen	29	14.00	29	0
Gemini Zee energie	61	30.34	60	0
Gemini Buitengaats	52	26.11	52	1
Hollandse Kust Zuid Holland IV	31	14.75	32	-1
Hollandse Kust Zuid Holland III	35	16.64	36	-1
Hollandse Kust Zuid Holland II	36	17.24	37	-1
Hollandse Kust Zuid Holland I	41	19.55	42	-1
Borssele 1	78	35.76	80	-2
Hollandse Kust Noord (Tender 2019)	68	29.85	69	-1
Ten noorden van de Waddeneilanden	33	16.24	32	0
IJmuiden Ver	216	107.90	219	-3
Hollandse Kust West - (Tender 2020 2021)	79	40.14	81	-1
Hollandse Kust West zuidelijke punt	37	18.61	38	0
Zoekgebied 1 Noord	132	60.12	134	-2
Zoekgebied 5 Oost origineel	151	75.09	151	0
IJmuiden Ver Noord	102	50.88	104	0
Zoekgebied 1 Zuid	66	30.13	68	0
Zoekgebied 2 Noord	163	74.33	164	0

Table A3. Results of the collision rate modelling for the national scenario using nocturnal activity rates of 3% and 8% only for wind farms within the foraging range of northern gannets and during the breeding season as described in 2.2.2.

Wind farm name	Collisions	SD	KEC Mean	Difference
Borssele 2	96	44	98	-2
Borssele 3	84	39	85	-1
Borssele 4 - Blauwwind	83	39	85	-2
Borssele Site V -Two towers	5	2	5	0
Egmond aan Zee	30	14	30	0
Prinses Amaliawindpark	73	35	73	0
Eneco Luchterduinen	32	15	32	0
Gemini Zee energie	46	23	46	0
Gemini Buitengaats	24	12	24	1
Hollandse Kust Zuid Holland IV	36	17	37	0
Hollandse Kust Zuid Holland III	51	24	52	-1
Hollandse Kust Zuid Holland II	43	20	44	-1
Hollandse Kust Zuid Holland I	43	20	43	0
Borssele 1	105	48	107	-2
Hollandse Kust Noord (Tender 2019)	65	28	65	0
Ten noorden van de Waddeneilanden - (Tender 2022)	29	15	30	0
IJmuiden Ver	242	120	244	-3
Hollandse Kust West - (Tender 2020 2021)	84	43	85	0
Hollandse Kust West zuidelijke punt	32	16	32	0
Zoekgebied 1 Noord	152	69	154	-2
Zoekgebied 5 Oost origineel	176	88	176	-1
IJmuiden Ver Noord	107	54	109	-1
Zoekgebied 1 Zuid	79	36	81	-2
Zoekgebied 2 Noord	188	86	190	-1

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