



Barriers to movement: Modelling energetic costs of avoiding marine wind farms amongst breeding seabirds

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ABSTRACT

Proposals for wind farms in areas of known importance for breeding seabirds highlight the need to understand the impacts of these structures. Using an energetic modelling approach, we examine the effects of wind farms as barriers to movement on seabirds of differing morphology. Additional costs, expressed in relation to typical daily energetic expenditures, were highest per unit flight for seabirds with high wing loadings, such as cormorants. Taking species-specific differences into account, costs were relatively higher in terns, due to the high daily frequency of foraging flights. For all species, costs of extra flight to avoid a wind farm appear much less than those imposed by low food abundance or adverse weather, although such costs will be additive to these. We conclude that adopting a species-specific approach is essential when assessing the impacts of wind farms on breeding seabird populations, to fully anticipate the effects of avoidance flights.

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1. Introduction

In response to climate change, the EU has set targets to achieve 20% of energy from renewable sources by 2020 (House of Lords European Committee, 2008). Consequently, the UK wind power industry has grown rapidly, with associated concerns over adverse effects of wind farms on wildlife populations, particularly birds, and our ability to assess these impacts (Masden et al., 2010). The potential impacts of wind farms on bird populations can be grouped into three major types: direct mortality due to collision with turbines/infrastructure; physical habitat modification and/or loss due to the footprint of turbines and associated structures; and avoidance responses of birds to turbines (Fielding et al., 2006; Fox et al., 2006; Masden et al., 2009).

Birds exhibit avoidance responses to wind farms; whilst these vary within and between species (Hötker et al., 2006), concern remains over the extent and impact of these responses. Wind farms may act as barriers to movement, increasing distances travelled and so increasing energy expenditure. Reproductive success is often related to parental body condition at the time of breeding amongst provisioning birds (Wendeln and Becker, 1999), so any reduction in mass due to increased flight costs may be detrimental and may impact reproductive output. Masden et al. (2009) showed that for common eiders *Somateria mollissima* migrating over 1400 km, the additional energy required to divert around the

Nysted wind farm off southern Denmark (a medium-sized wind farm: 72 turbines covering an area of approximately 60 km²) was trivial; responses equivalent to avoiding 100 such wind farms would be necessary to cause detectable reductions in bird body mass. However, breeding season impacts may be different and greater for other species. Seabirds typically have altricial offspring and during the breeding season the parents become central place foragers, commuting daily between breeding colonies and foraging sites to provide food for their offspring. Therefore, seabirds could potentially interact with a wind farm located within their foraging range several times a day throughout much of the breeding season.

To date, there has been no consideration of the potential energetic costs to such birds that are forced to commute around offshore wind farms on a regular basis. This is particularly relevant for the breeding seabirds in the Firth of Forth, Scotland. The Scottish Offshore Wind Exclusivity agreements have identified four areas in the Firth of Forth for possible development and close by there is also another offshore site outside 12 nautical miles (The Crown Estate, 2009). All of these areas are within the foraging range of seabirds breeding on Bass Rock (of international importance for northern gannets *Morus bassanus*) and the Isle of May National Nature Reserve. Therefore it is quite possible that a breeding seabird may interact with, and be affected by, one or more wind farms.

This study is the first of its kind to model the likely impact of wind farms on a range of breeding seabirds due to the birds' avoidance responses. Using an energetic model parameterised with values from the peer-reviewed literature, we examine the extent to

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which wind farms of differing sizes impact different species of seabirds through increases in energy expenditure. We hypothesise that species will be differentially sensitive to wind farms due to their contrasting morphologies (body mass, wing span and wing area) and foraging characteristics (foraging distance and trips per day). Although set in the context of the Firth of Forth wind power developments, the concepts are globally applicable to the renewable energy sector for cases where central place foragers are concerned.

2. Methods

2.1. Species

Nine species of seabird were considered in this analysis (shag *Phalacrocorax aristotelis*, great cormorant *Phalacrocorax carbo*, Atlantic puffin *Fratercula arctica*, common guillemot *Uria aalge*, black-legged kittiwake *Rissa tridactyla*, lesser black-backed gull *Larus fuscus*, common tern *Sterna hirundo*, northern fulmar *Fulmarus glacialis*, and northern gannet). The choice was motivated by the need to capture a full range of contrasting morphologies, flight characteristics and foraging ecologies (see references and Table 1) when evaluating the potential impacts on different species, but balanced by the availability of empirical data.

2.2. Calculating energy requirements: the intrinsic cost of flight

The energy required for flight was estimated using aerodynamic principles and the modelling software Flight 1.19 (<http://www.bio.bristol.ac.uk/people/pennycuick.htm>). Model input parameters are presented in Table 1. An extensive literature review was

conducted and parameter values were sourced from the peer-reviewed literature; mean values of those reported in the literature were used to parameterise the model. Values for body mass were sourced from the British Trust for Ornithology (<http://www.bto.org/birdfacts/>) except for northern gannet (Cramp and Simmons, 1977). When considering foraging distance, some studies only provided maximum foraging distance; these references have been highlighted (Table 1). Variation in distance to foraging site and foraging trips per day are shown in Fig. 1. Unless stated otherwise, foraging trip refers to the return journey to a foraging site and back. We assumed that birds would fly close to V_{mp} (minimum power speed) (C. Pennycuick, personal communication) and then estimated the power required to achieve this speed. It was assumed that ground speed was equal to air speed to make the analyses more general, as predominant wind direction and speed will undoubtedly be case-specific.

2.3. The energetic cost of barriers to movement

To estimate the cost associated with wind farms (when perceived by birds as complete barriers to movement) we increased the distance the bird had to fly to reach its foraging area. The additional distance (Δd) we considered ranged from 100 to 10,000 m per single trip as a consequence of the potential different combinations of sizes, shapes and numbers of wind farms that might be avoided. This range of distances would incorporate a very minor shift in orientation, to completely circumventing a large wind farm. For example, the worst-case scenario for birds travelling around the Danish Nysted wind farm would be an additional 4000 m. The energy required for flight (Δe) was calculated on a daily basis as follows:

Table 1
Input parameters for energetic model. Superscripts denote references.

Species	Scientific name	Mean mass (g)	Mean number of trips per day	Mean distance to foraging area (km)	DEE (kJ d ⁻¹)
Shag	<i>Phalacrocorax aristotelis</i>	1860	2 ^{a,b}	12 ^{b,x,c,d}	2249 ^b
Great cormorant	<i>Phalacrocorax carbo</i>	2560	3 ^{e,f}	8 ^{e,g}	2762 ^y
Atlantic puffin	<i>Fratercula arctica</i>	387	3 ^{b,h}	58 ^{b,x,h,i}	848 ^j
Common guillemot	<i>Uria aalge</i>	891	2 ^{b,k,l}	12 ^{d,m}	1641 ^d
Black-legged kittiwake	<i>Rissa tridactyla</i>	368	5 ^{b,n}	45 ^{b,x,d,o,w}	786 ^p
Lesser black-backed gull	<i>Larus fuscus</i>	831	2 ^b	42 ^{b,x,c}	1328 ^y
Common tern	<i>Sterna hirundo</i>	128	12 ^{b,q}	19 ^{b,t,o}	343 ^r
Northern fulmar	<i>Fulmarus glacialis</i>	772	1 ^{s,t}	184 ^{t,x}	1444 ^u
Northern gannet	<i>Morus bassanus</i>	3000	1 ^v	160 ^v	4856 ^w

[n] indicates the number of observations within the reference where data were provided.

^a Wanless and Harris (1992) [n = 15].

^b Pearson (1968)^x.

^c Wanless et al. (1991) [n = 31].

^d Enstipp et al. (2006).

^e Grémillet et al. (2004) [n = 29].

^f Grémillet (1997) [n = 14].

^g Grémillet et al. (1999) [n = 18].

^h Corkhill (1973).

ⁱ Wanless et al. (1990) [n = 14].

^j Ellis and Gabrielsen (2002) [n = 9].

^k Hatchwell (1991).

^l Wanless et al. (1988).

^m Monaghan et al. (1994) [n = 38].

ⁿ Hamer et al. (1993) [n = 99].

^o Daunt et al. (2002)^x [n = 9].

^p Golet et al. (2000).

^q Becker et al. (1993) [n = 91].

^r Klaassen et al. (1992) [n = 7].

^s Phillips and Hamer (2000).

^t Hamer et al. (1997)^x [n = 168].

^u Furness and Bryant (1996) [n = 14].

^v Hamer et al. (2001) [n = 14].

^w Birt-Friesen et al. (1989).

^x Highlights references that provided only maximum foraging range.

^y Indicates where DEE was calculated using the 'All Seabirds' equation within Ellis and Gabrielsen (2002).

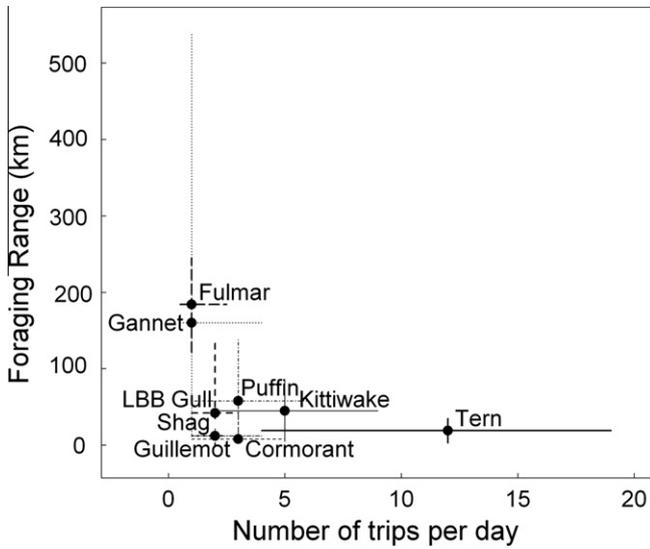


Fig. 1. Variation in the number of foraging trips plotted against distance to foraging site for different seabird species (Shag = shag, Cormorant = great cormorant, Tern = common tern, Guillemot = common guillemot, Puffin = Atlantic puffin, Kittiwake = black-legged kittiwake, LBB Gull = lesser black-backed gull, Fulmar = northern fulmar, Gannet = northern gannet). Dots represent the parameter values used in the simulations. Lines denote the range of values reported in the cited literature. See Table 1 for data sources and samples sizes.

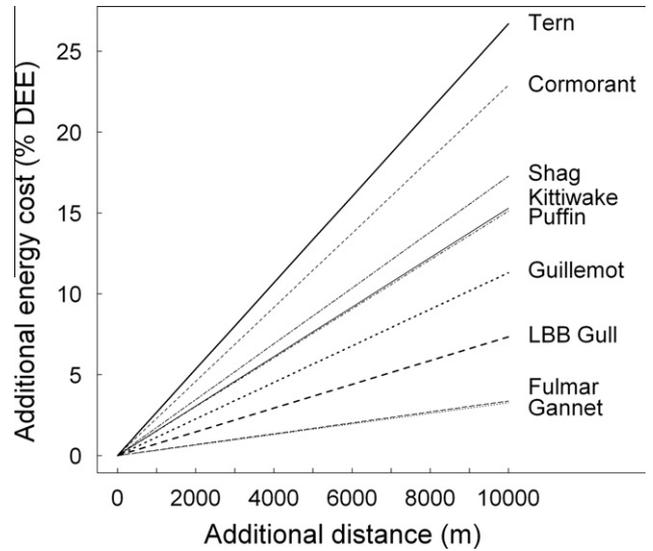


Fig. 2b. The increased energy expenditure (% DEE) associated with increasing additional distance (Δd) for birds foraging based on an "average" individual for each species (for parameter values used see Section 2 and Table 1). Lines represent different species. For complete species names see Fig. 1.

$$\frac{2 \times (\text{foraging range} + \Delta d) \times \text{number of trips}}{\text{Speed}} \times \text{energy}$$

where foraging range and Δd were measured in metres, speed was measured in m s^{-1} , energy was measured in Watts (J s^{-1}), and number of trips refers to return trips completed to the foraging site. The calculations were completed for each species and Δe reported as the percentage of the daily energetic expenditure (DEE) for each species.

Model simulations were divided into three sections:

- (1) To compare differences in Δe between species (due to morphology) we used constant values for foraging range (20 km) and number of foraging trips (4 per day). These values were

chosen because they lie centrally within the possible ranges for all species.

- (2) To examine variation in Δe within species due to foraging characteristics, we varied the number of foraging trips and Δd for each of the nine seabird species. Foraging trips ranged from 1 to 20 trips per day and Δd ranged from 100 to 10,000 m.
- (3) To assess the importance of species-specific analyses we compared differences in Δe due to the overall ecology of species (both morphology and foraging characteristics) and used species-specific values for foraging range and number of foraging trips (Table 1).

Data analyses were conducted using R (Version 2.8.1).

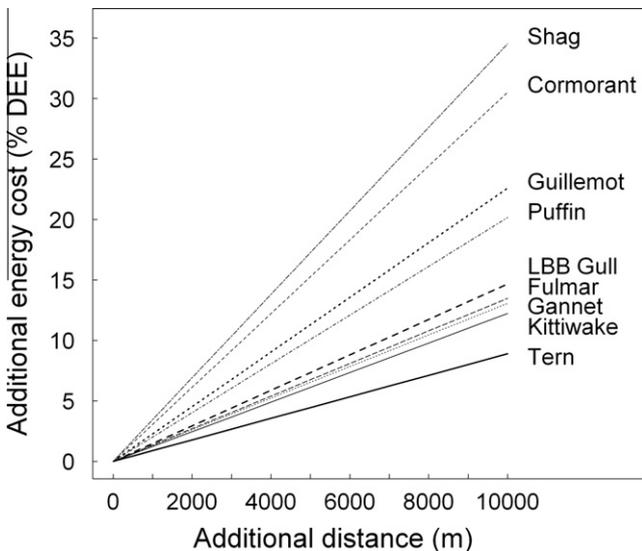


Fig. 2a. The increased energy expenditure (expressed as % DEE) associated with increasing additional distance (Δd) for birds of different species foraging four times per day, at a distance of 20 km from their breeding site. Lines represent different species. For complete species names see Fig. 1.

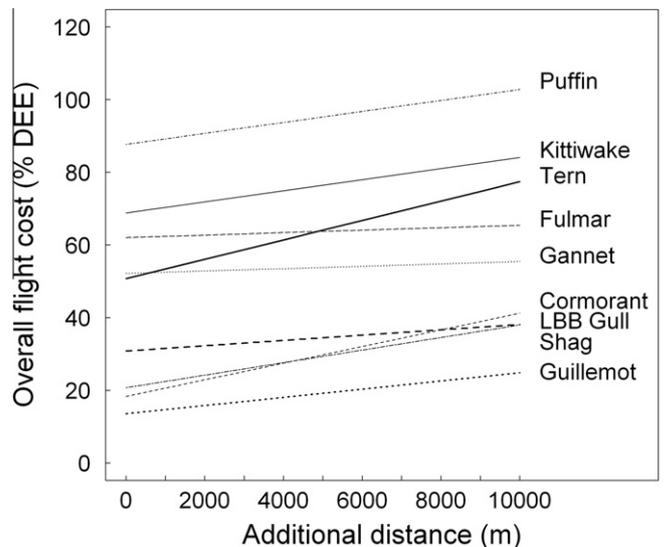


Fig. 2c. The overall energy expenditure (expressed as % DEE) of foraging flight for different seabird species. Lines represent different species. For complete species names see Fig. 1.

3. Results

3.1. Constant values

The increase in energy required (Δe) by different species under the same conditions (20 km, four times a day) is shown in Fig. 2a. Δe increases linearly as Δd increases, although the rate of increase differs between species; the rate of increase in Δe (slope of Δd vs. Δe) required by shag (when represented as a percentage of DEE) is $0.003\% \text{ m}^{-1}$ compared with a rate of $0.0009\% \text{ m}^{-1}$ for common tern. It can also be seen from Fig. 2a that the largest difference in Δe for different species occurs when Δd is greatest. The difference in Δe between shag and common tern is 37 kJ when flying an extra 500 m but increases to 745 kJ when flying an extra 10,000 m.

3.2. Inter- and intra-specific variation

Fig. 2b represents the change in Δe for different species when foraging bouts vary in distance and frequency (as reported in Ta-

ble 1). Great cormorant and shag had high rates of increase in Δe ($0.0023\% \text{ m}^{-1}$ and $0.0018\% \text{ m}^{-1}$, respectively), but the highest ($0.0027\% \text{ m}^{-1}$) was for common tern (Fig. 2b). Northern fulmar and northern gannet had the lowest rates of increase. Greatest differences in Δe between species were again when Δd was 10,000 m.

Considering the overall foraging flight costs (i.e., the complete foraging trip), rather than just Δe (the cost of travelling Δd), there was large variation in the percentage of DEE that was required for flight (Fig. 2c). Although common tern, cormorant and shag, had the greatest rates of energy increase, black-legged kittiwake and Atlantic puffin used a larger percentage of their overall DEE on flight. An Atlantic puffin travelling an extra 10,000 m would require 103% of its normal DEE to fuel this extended flight.

There is variation in foraging range and trips within species (see Fig. 1); the contour plots in Fig. 3 show Δe (% DEE) expended by different species making varying numbers of foraging trips over a range of Δd . We assume that costs remained constant over time, therefore the results are relevant across varying foraging ranges. For all species, Δe required for flight increased as both Δd and

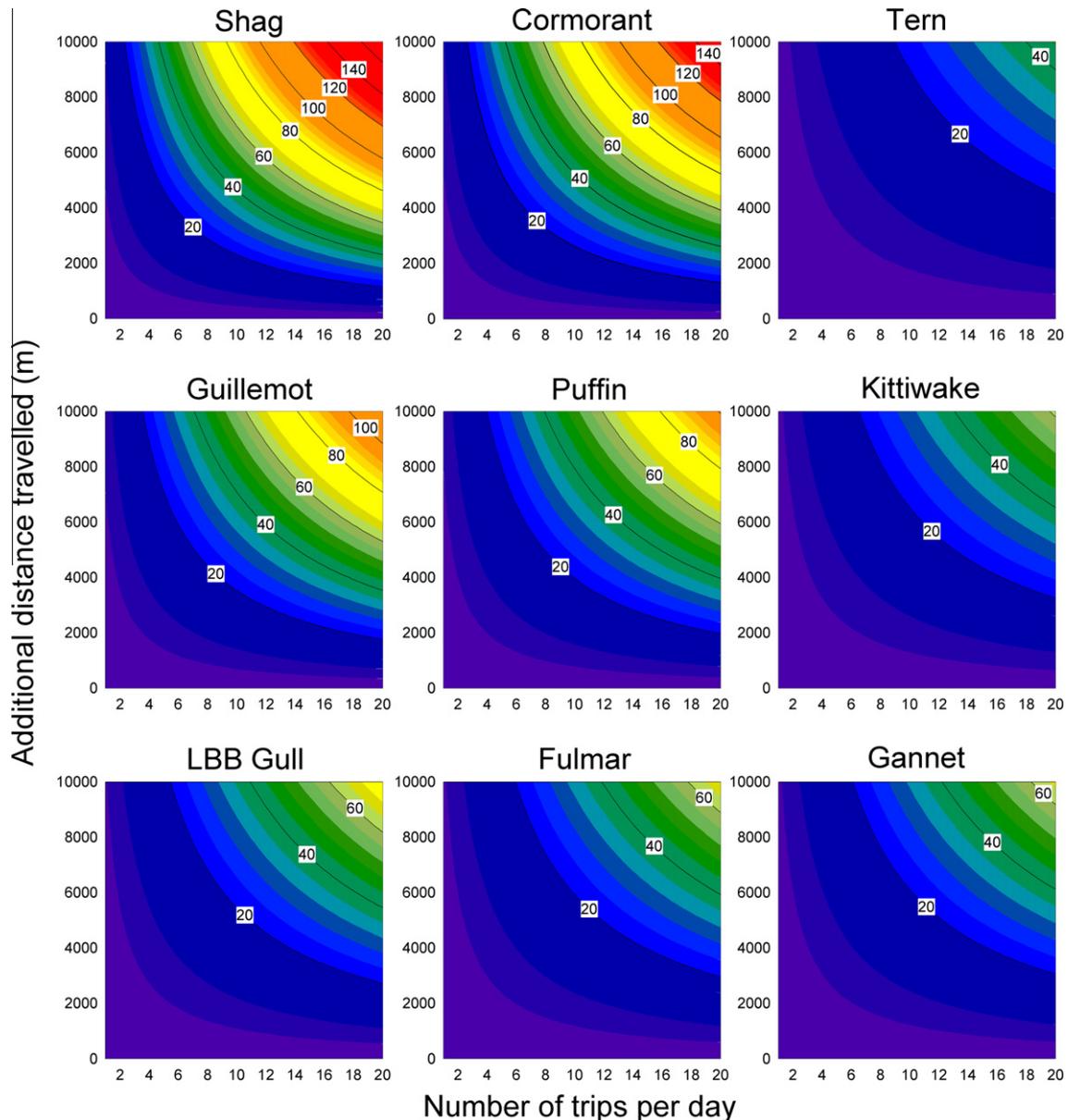


Fig. 3. Energy requirement for flight according to number of trips and additional distance (Δd) travelled for different seabird species. Colours and contours represent energy increase as % DEE. For complete species names see Fig. 1.

number of foraging trips increased. However, the greatest increases in Δe (up to 170% DEE) were for shag, great cormorant, common guillemot and Atlantic puffin (Fig. 3).

4. Discussion

With an increase in the number of wind farm proposals, it is vital that developers, along with the relevant authorities, consider the impacts and consequences of the construction of these potential barriers to animal movements. In this study, we assessed the potential cumulative impacts of wind farms on birds through the energetic costs of additional flight incurred during regular provisioning flights between nesting sites and feeding areas. With increasing numbers of wind turbines in the environment, and increasing observations that many species of birds exhibit avoidance behaviour towards wind turbines (Desholm and Kahlert, 2005), it is likely that individuals will have to fly increasing distances in order to reach their foraging grounds. The increased flight distance has energetic consequences that may impact upon the health of the population. For example, an increased energetic requirement that could not be balanced could lead to a reduction in the condition of a breeding bird, to a reduction in the fitness of its offspring, or both.

Bird species differ intrinsically in their morphology (e.g., variations in wing span and wing area in relation to body mass) so flight costs can be expected to be species-dependent. Variations in the energetic costs of flying an additional distance (Δd) beyond a constant 20 km, four times a day were species-specific, with shag and great cormorant requiring the most additional energy, followed by the auks (common guillemot and Atlantic puffin, Fig. 2a). The high cost of flight for these species is likely associated with large body mass and relatively small wing area, resulting in a high wing loading and hence relatively high cost of faster flapping flight (Calder, 1984; Benowitz-Fredericks et al., 2007; Pennycuick, 2008). The cost of flight will also vary depending on the mode of flight for example, flapping flight vs. gliding flight (Videler, 2005) and birds may alter the mode of flight according to the priority of minimizing flight costs versus minimizing time spent in travel.

For a given distance, species have different levels of basic energy expenditure for flight and thus different species suffer proportionally more or less energetic penalties for each extra kilometre of flight caused by avoidance of objects such as wind turbines (Fig. 3). Cormorants and auks undertake a few short provisioning flights (Fig. 1), and hence experienced the greatest additional costs when performing many foraging trips per day, and travelling large additional distances as would be expected when avoiding wind farms. In contrast, northern fulmar and northern gannet undertake few but long foraging trips and are adapted to using efficient gliding flight, so the extra costs of additional distance are relatively small, although both species may have difficulty provisioning chicks in low-wind or strong head-wind conditions due to the high energetic cost of flapping flight (Furness and Bryant, 1996). Gulls (lesser black-backed and black-legged kittiwake) show similar patterns despite their shorter and more frequent provisioning trips, suggesting a more energy efficient wing loading in these species. Finally, although common tern required the least energy when ecology and foraging characteristics were assumed constant across all species, it was the most affected by the additional distance when foraging ecology was considered species-specific. A common tern typically completes 12 foraging trips per day and therefore would interact with the wind farm and incur the additional distance, 24 times per day. If the additional distance were 500 m then the increase in energy requirement would be 1% of their DEE. However, 1% DEE may be insignificant when compared to unsuitable wind conditions or changes in prey density (Hamer et al., 1993; Furness and Bryant, 1996). For example, Furness and Bryant

(1996) found that breeding northern fulmars more than doubled their wing-beat frequency and increased at-sea metabolic rate by 100% when mean wind speed decreased from 8 to 3 m s⁻¹.

Although the cost of flying Δd may be small, the overall cost of foraging flights should be considered, and not simply the additional cost incurred due to wind farms. The sensitivity of a bird to any incurred additional energetic costs is likely dependent on how close it is operating to its physiological limit. Fig. 2c shows how the overall energetic cost of flight increases for each species and it can be seen that although common tern, great cormorant and shag have the greatest rates of increase in energy requirement, it is Atlantic puffin and black-legged kittiwake that incur the greatest energy costs relative to their DEE. If an Atlantic puffin were to travel an additional 10,000 m due to the presence of wind farms then it would expend 103% of its DEE on the extended flight activity alone. Should an individual be unable to acquire this additional energy without extra costs, it would soon be in deficit and the condition of the bird would decrease, potentially affecting the fitness of itself and its offspring.

Species show variation in their foraging characteristics as demonstrated in Fig. 1. Some of this variation may be associated with environmental conditions, with birds having to travel further in bad years due to low food availability. Hamer et al. (1993) reported black-legged kittiwakes travelling 5 km to foraging areas in a good year but 40 km in a bad year, with the frequency of foraging trips decreasing from 9 to 2 times a day. Their study indicated that variations in prey abundance from year to year can have a marked effect on seabird energy expenditure and breeding success; it is against this background of strong variation in natural conditions that we must assess the impact of extra flight by seabirds commuting past and around wind farms at sea. In this situation, based on additional energy requirements of flying greater distances, birds in good years would be impacted more by the development of wind farms and the consequent increase in foraging trip distance (Fig. 3). Although, on the whole, individuals during a bad year would experience a greater impact despite lower absolute energy costs, because they would be closer to their physiological capacity in terms of energy balance if prey availability is low. Individuals may also forage further from a breeding colony as colony size and therefore competition for food resources increases. Such competition may deplete food around a colony (Ashmole's Halo: Ashmole, 1963; Birt et al., 1987; Gaston et al., 2007) forcing birds to travel further to meet their foraging demands, especially later in the breeding season. Additional distance and energetic costs associated with increasing numbers of wind farms may therefore impact individuals in smaller colonies to a greater extent than those in larger colonies. This is because these birds will be travelling shorter distances to forage and potentially passing the wind farm more times each day, therefore the additional cost will be a larger proportion of their daily energetic budget. Although it is possible that the consequences may be more severe for seabirds in large colonies if competition is already requiring them to work at their physiological limit (Lewis et al., 2001).

In this analysis we have only assessed the impact in terms of energy costs; however, it may be the case that there would be additional impacts associated with changing foraging ecology. For example, a bird travelling further to a foraging location, if travelling at a constant speed, will be away from the nest for longer. Therefore, during any given day, the time available for nest defence and pair-bonding between the two adult birds will be reduced and this may impact upon the success of the breeding attempt (Caldow and Furness, 2000). However, there are many factors which can lead to variation in the proportion of time when both adults are present at the nest, for example poor weather conditions (Finney et al., 1999). If birds are travelling further and there is no change in the speed of flight, there will be a reduction in the number of

foraging trips that can be made within a day. If an individual is limited to carrying single prey items, then the amount of food brought back to the nest will be reduced. Compensation for this may involve travelling with more or bearing larger prey items which may also carry an energetic penalty; both of these are mechanisms which may also contribute to deterioration in the condition of the offspring. Birds can increase flight speed to compensate for travelling the additional distance, but only with an associated energy cost, which if not recovered, may lead to a decrease in adult body condition and ultimately fitness.

The results generated by this study are based on several assumptions that should be considered in relation to our conclusions. All species included in this study were assumed to exhibit complete avoidance of wind farms. There is limited information available on the avoidance of wind farms by birds (Desholm and Kahlert, 2005), and particularly for seabird species, therefore in this study we investigated the worst-case scenario. If this assumption were relaxed then the distance travelled, and thus the energetic cost, would be reduced. It was assumed that the cost of flight remained constant over time. We included neither variation in the mass of the bird during foraging trips nor varying wind conditions. The mass of a bird and the associated energetic cost of flight will increase when carrying prey items and probably decrease with flight activity. Therefore it was assumed that this variation would balance over the period of a day. The effects of wind were excluded from calculations of energy expenditure since wind speed and direction will inevitably vary in space and time. Generally, during a foraging trip and over the course of a day an individual will experience both head winds (increased energy expenditure) and tail winds (decreased energy expenditure) so net energy expenditure due to wind is likely to be low. Another assumption made was that birds fly at minimum power speed (V_{mp}), the speed at which less power is needed to fly than at faster or slower speeds (Pennycuik, 1989). If this assumption is not met, then the absolute values for overall energy expenditure will vary from those reported within this study however the relationships between energy expenditure, additional distance and number of trips, and between species would remain the same. Similarly, if another method other than aerodynamic theory was used for energy calculation, for example allometry (Castro and Myers, 1988), then the absolute values for energy expenditure would probably have varied slightly from those reported, although the general relationships would hold true. Finally, we only included foraging in the day time period because the majority of studies report only data collected during daylight hours. If birds continue to forage during the night then the number of trips per day will increase and there will be an associated increase in energy expenditure (Fig. 3). However, it should be considered that the avoidance response of birds to wind turbines, and the consequent energy expenditure, may differ between night and day (Desholm and Kahlert, 2005).

5. Conclusions

The energetic costs of flying around one wind farm may be insignificant for the range of breeding seabirds considered in this study. Nevertheless, as the number of wind farms increases, so too will the cost of reaching foraging grounds as birds will have to fly further on each journey. This also confirms the need to study the potential mitigating effects of varying wind farm geometric design and inter-turbine distances as a means of reducing such potential additions to breeding seabird energetic expenditure. The results clearly show that it cannot be assumed that the effects will be similar across seabird species. Due to the differences in ecology of seabirds there is variability in the effects of wind farms and therefore a species-specific approach should be taken when assessing the barrier effects of wind farms on birds.

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