Modelling Barrier Effects of Offshore Wind Farms on Birds

Incorporating the current knowledge on barrier effects in a quantitative assessment framework

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Preface

The Dutch Framework for Assessing Ecological and Cumulative Effects (Dutch name for the framework: Kader Ecologie & Cumulatie; or in short KEC) aims to predict and evaluate the cumulative ecological effects of all existing and planned Dutch and foreign wind farms in the Central and Southern North Sea. A key effect that is in the current version of the KEC (5.0) not yet addressed is the barrier effect. In this report we investigate this knowledge gap through reviewing the current literature on barrier effects, specifically discussing the current model by *Bos et al. (2025)* and proposing a generalised framework for assessing barrier effects in the KEC framework. We also identify specifically knowledge gaps and data needs currently hindering the implementation of said framework.

The work is commissioned by Rijkswaterstaat. Martine Graafland and Meik Verdonk coordinated the project and provided valuable feedback on an earlier version of the report.

The original model conceptualisation was carried out by René Bos from Eneco, with support from Marin van Regteren (Eneco), Jacco Leemans and Abel Gyimesi (both Waardenburg Ecology). René Bos also carried out the original coding. Furthermore, the following people from Waardenburg Ecology (WE) and Wageningen Marine Research (WMR) participated in the work described in this report:

Gerben IJntema (WE)	Conceptualisation, coding & reporting
Maarten Japink (WE)	Conceptualisation & coding
Abel Gyimesi (WE)	Project management & quality control report
Vincent Hin (WMR)	Quality control report

Synthesis

Based on the definition of Drewitt & Langston (2006), we define the barrier effect as: "*The effect of birds adjusting a specific travel path as a reaction to a wind farm area, which causes an increase in energy expenditure, potentially disrupting commutes between locations.*"
To disentangle this definition from habitat loss and displacement effects, we propose to strongly adhere to the effects on windfarm areas as a commuting site.

Assessments or research into barrier effects can regard three different types of barrier effects:

- to local breeding birds,
- to local non-breeding birds
- and to migrating birds.

In the Dutch "Kader Ecologie & Cumulatie (KEC)" assessment for displacement and collision impacts on local birds are not specified for breeding and non-breeding birds, but for barrier effects the effects could differ for these two groups of birds. Depending on the overlap between foraging range of breeding birds, and (future) wind farms this discrepancy needs to be explicitly addressed in the modelling.

The literature review suggests that vulnerable species to barrier effects strongly overlap with species vulnerable to displacement. In the literature, we found species often associated with barrier effects to be concentrated in the species groups Sea Ducks, Divers and Alcids. Additionally, other species to consider according to literature are the Sandwich Tern (Thaxter *et al.* 2024) and species in the group Geese/Swans (Krijgsveld *et al.* 2011).

Building on the original MATLAB scripts of Bos *et al.* (2025), we have successfully developed an R version of this model. Based on the initial modelling exercises, we concluded that the assumption of birds always flying the most efficient route when avoiding wind turbines should be thoroughly revisited. Future versions of the model could also be expanded to include stochasticity of the input parameters. Based on the literature review of other available models, we currently deem the Bos *et al.* (2025) as the most promising model to assess barrier effects in the KEC. In cases of large data availability, we recommend revisiting the usability of the model by Masden *et al.* (2010).

We see possibilities for building an assessment framework around (subsequent versions) of the Bos *et al.* (2025) model or barrier effect models in general as a five-step modelling approach (see Figure 4-1). However, multiple developmental steps would be needed to implement this five-step approach into an EIA. Besides the further development of the newly built model, development of the framework should also focus on 1) the pre-processing and assumptions needed to prepare source data for the barrier effect model, and specifically the drawing of flight paths 2) converting a predicted change in travel route to additional energy energetic expenditures and 3) translating additional expenditures into their effects on demographic parameters, such as fecundity and survival. For 1) we foresee much work on investigating the available data and the discrepancies needed to test different types of barrier effect assessments and a strong data need for GPS logger data to estimate flight paths and the frequency of occurrence for these flight paths. A large knowledge gap, requiring more consideration, specifically for non-breeding birds is the definition of flight paths and frequency of use of said paths. For 2) we see possibilities in applying the model by Pennycuick (2008) or literature values for flying birds, but to develop a similar module for swimming commutes requires more in-dept research. For 3) we see possibilities in adapting parts of the SeaBORD framework from Searle *et al.* (2018). However, here we strongly recommend integrating the approach with the energetic model developed for a displacement approach in the Wozep project ZV4-5-6 *(Complexe vogelmodellen)* and the KEC. This integration becomes even more so needed when implementing the loss of potential destinations due to energy budgeting.

Considering comparing with thresholds, we see only minor adaptations needed to connect the framework to the Acceptable Levels of Impact (ALI) approach (Hin *et al.* 2024), as is commonly applied in the KEC assessments.

Consequently, we conclude that many ingredients for an assessment framework are present, but much further development and the integration of these ingredients is necessary to be able to apply a comprehensive barrier effect impact assessment. We recommend starting with a small concise scope (only horizontal avoidance; no loss of destinations) to have a fist version of the assessment available. Subsequent versions should then expand this scope to arrive at a full extensive assessment of the barrier effect.

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1 Introduction

1.1 Background

In the Netherlands, offshore wind energy is considered a key sector to facilitate the transition to green energy and continuous growth of the sector is intended by the government. Offshore wind energy, however, is not without effects on the natural environment and marine life. One of the species groups impacted by wind energy developments is birds, specifically local seabirds and birds migrating over sea. In the Netherlands, in the Framework for Assessing Ecological and Cumulative Effects (in Dutch: ‘Kader Ecologie & Cumulatie”; abbreviated to KEC) the expected impacts on different species groups, including birds, of existing and planned wind farms are assessed in cumulation for the Dutch Continental Shelf in the North Sea. The effects currently specifically assessed within KEC are displacement (Soudijn *et al.* 2025) and collisions (IJntema *et al.* 2025). However, an often mentioned, rarely assessed, third effect is barrier effects (Drewitt & Langston 2006). In the most recent version of the KEC (5.0), barrier effects are not specifically assessed.

1.2 Objective

In preparation for later versions of the KEC, Rijkswaterstaat (RWS) has commissioned Waardenburg Ecology to execute a first investigation on barrier effects of offshore wind farm developments on birds. This study will therefore first focus on describing how barrier effects may impact local seabirds and birds migrating over the North Sea, specifically identifying bird species to which a substantial effect might be expected. A second objective of this study will be to provide a first reasoning on how to assess barrier effects in the KEC framework. Based on a literature review, we will describe if and how other countries currently assess barrier effects. Finally, the usability of a previously developed conceptual model, developed by Eneco in collaboration with Waardenburg Ecology (Bos *et al.* 2025) will be investigated.

This study therefore aims:

- to provide an overview of the nature of barrier effects,
- to provide an initial line of reasoning on how to assess barrier effects,
- to highlight the potential role of the existing model and further developments hereof might play in future assessments.

2 Current knowledge on barrier effects

2.1 Definitions & typologies of barrier effects on birds

Key to properly assess barrier effects is to have a proper definition. For this reason we choose the widely cited description of Drewitt & Langston (2006) as basis for our scope and definition of barrier effects of wind farms. Drewitt & Langston (2006) describe barrier effects, as a specific form of displacement, through:

“The effect of birds altering their migration flyways or local flight paths to avoid a wind farm is also a form of displacement. This effect is of concern because of the possibility of increased energy expenditure when birds have to fly further, as a result of avoiding a large array of turbines, and the potential disruption of linkages between distant feeding, roosting moulting and breeding areas otherwise unaffected by the wind farm.”

Based on the description of Drewitt & Langston (2006) we can infer several key components of any definition of the barrier effect:

1. The focus of the effect is on flight paths, which implies that floating or swimming birds are not included in their view of barrier effects.
2. The effect is on an (adjusted) travel between two locations outside of the windfarm.
3. The effect only considers changes in the use of the area (to be) designated as a windfarm site for commuting.
4. The effect is expected if the presence of the wind farm results in an increase in energy expenditure needed to travel between two points.
5. The effect may result in the travel between two locations no longer being possible. The travel route be disrupted through several effects, such as for instance the increase in energy expenditure not being affordable within a birds energy budget. Hence, barrier effects may cause disruption of linkages between feeding, roosting, moulting and breeding areas.

While Drewitt and Langston (2006) focus on only flight paths (component 1 above), we propose to not only include travel by flight, but to include any mode of travelling. Hence, we suggest including swimming birds as well, as for example common guillemots, razorbills and divers may be impacted by barrier effects while swimming. Additionally, we propose to focus on the effect of energy expenditure following much of the published literature on barrier effects. Except for adjustments to component 1 and 5 mentioned above, we suggest adhering to the three other components above.

Finally, it is good to mention that this definition does not explicitly discriminate in which dimension (horizontal or vertical) the change of travel path may occur. In our definition we make this more explicit for clarity. Consequently, we define the barrier effect here as:

"*The effect of birds adjusting a specific travel path as a reaction to a wind farm area (in either the horizontal or vertical plane), which causes an increase in energy expenditure, potentially disrupting commutes between locations.*"

2.1.1 Disentangling the barrier effect from habitat loss and displacement

In literature, varying definitions of barrier effects occur, which may even overlap with other effects on birds. For instance, as also mentioned above, Drewitt & Langston (2006), define barrier effect as a specific form of displacement. To avoid confusion, we therefore also have to make the definition explicit in relation to displacement and habitat loss. To achieve clarity in our definition, we strictly adhere to the key components of the barrier effect mentioned above.

The key distinctive element of barrier effect, when compared to habitat loss or displacement is that barrier effects only consider changes in the use of a windfarm area for passing through. This means that, while an area may have multiple uses for a bird, within the assessment of barrier effects we only consider the effects on their use as a commuting area, to reach other areas, resulting in a change in energy expenditure needed during their travels. Habitat loss and displacement specifically address other uses of the area, such as for instance foraging habitat.

However, the effects of habitat loss, displacement and barrier effect may overlap in the extreme case where travel between two locations is adjusted in such a way that the travel route no longer becomes viable to use. The consequence of closing a travel route altogether could cause the loss of other functions in areas down the travel path. Depending on the severity of the barrier effect emerging from assessments, additional energy expenditure may reach a level where birds will need to make energy budgeting decisions and potentially choose to abandon certain flight destinations in favour of others. We propose to initially place such adaptive decision-making outside the scope of barrier effects. This way we keep habitat loss and barrier effects as much separate as possible. Additionally, this follows the precautionary principle, reflecting a worst-case scenario where no alternative travel destinations are present and an adaptive travel destination choice is not possible in light of the barrier effect as defined above: Significant extra energetics costs are always incurred and not mitigated by travel to alternative destinations.

2.1.2 Defining different typologies of barrier effects

In literature and environmental assessments barrier effects are rarely assessed or investigated. However, when assessed, we discern three distinct forms of identifying or assessing the barrier effect of wind farms in literature:

Barriers to migrating birds. Migrating birds from seasonally occupied sites with different functions, such as, for example, breeding sites, wintering sites and moulting sites, may experience the barrier effect of wind farms as an increased travel distance between these two locations (Christensen *et al.* 2004, Kahlert *et al.* 2004, Drewitt & Langston 2006, Hüppop *et al.* 2006, Masden *et al.* 2009, BSH 2013, Bundesamt für Seeschifffahrt und

Hydrographie 2019, DCCEEW 2023). Generally, the barrier effect is then experienced only once or twice every year (back and forth migration between the sites). While the effect is only experienced sparsely, significant extra energy expenditure might have severe effects on the energy budget needed to reach their migration destination. Examples of studies addressing this type of barrier effect are Christensen *et al.* (2004), Kahlert *et al.* (2004), Masden *et al.* (2009).

Barriers to frequent travel routes of birds. Local birds that are known to frequent certain routes (for instance twice a day from specific roosting sites to foraging grounds) may experience barrier effects on these routes. Given the frequency of these trips (one of twice a day), additional energy expenditure may be significant and leave the birds with less energy reserves in-between travel instances. Examples of studies considering this type of barrier effect are known from onshore wind energy development (Radstake & Heunks 2019, Jeninga & Engels 2024).

Barriers to foraging trips of breeding birds. Breeding birds are tied to their specific breeding grounds, such as colonies, during the breeding season. Especially during the chick-rearing phase, trips back and forth between foraging- and breeding grounds are frequent, as food needs to be returned to the chick. Barriers to travel between nesting and feeding locations may decrease the energy budget and reserves of birds (Masden *et al.* 2009, Fox & Petersen 2019, Daunt *et al.* 2020). Reduced body condition of breeding birds may have a multiple effects in 1) reducing the fecundity of animal through increased chick mortality, 2) increasing adult mortality at the end of the breeding season through increased energy expenditure, 3) increasing the adult mortality during the following winter, through carry-over effects of reduced energy budgets during the breeding season (Humphreys *et al.* 2015, Daunt *et al.* 2020). 4) a reduction in productivity as a result of foregoing breeding (Humphreys *et al.* 2015). While not explicitly mentioned in literature on barrier effects of wind farms, it is known that poor body condition of breeding female birds can affect clutch size (Erikstad *et al.* 1993). Hence productivity might also be affected through clutch size as a result of a barrier effect induced reduction in body condition. Examples of studies addressing this type of barrier effect are Masden *et al.* (2010), Searle *et al.* (2014), Searle *et al.* (2018), Thaxter *et al.* (2024).

The key difference between these three types of analyses lies in identifying the flight paths and the frequency of use of these flight paths. For the actual analyses of how a defined flight path changes and what the energetic consequences of changing a single flight are, the typology completely overlaps. For this reason, we regard all three typologies in the rest of the report and only explicitly refer to these typologies when the matter discussed is specific for any one of these types.

2.2 Current evidence for barrier effects in bird species

Currently, several examples of addressing barrier effects are known in literature. However, the definition of barrier effects and displacement are often overlapping. Using our previously determined definition, we focus on literature corresponding to (parts of) our definition.

The current literature often assesses potential effects of a single windfarm. Many of these studies conclude that single windfarms often have little impact. Especially in migratory birds, the detour needed to avoid a single windfarm is often deemed negligible as a very small proportion of the whole flight (Masden *et al.* 2009). However, with the increasing development of the offshore wind energy sector in the North Sea, future scenarios, with increasingly larger wind farms, may no longer be about scarce single wind farms affecting birds. With an increasing amount of wind farms in the North Sea area the travel detours needed due to the barrier effect may prove to be significant (Masden *et al.* 2009, Boehlert & Gill 2010).

2.2.1 Individual sources addressing barrier effects

In this section we discuss the individual studies we found addressing if travel paths are rerouted as a result of the presence of a wind farm. This section does not discriminate between the different typologies mentioned in section 2.1.2, as merely the evidence for a change in travel path is discussed, regardless of the discerning characteristics of the different analysis typologies mentioned above, such as the origin, destination or frequency of a flight path. Furthermore, macro-avoidance behaviour signals that an area is no longer feasible to travel to or through, we have explicitly taken studies into macro-avoidance as studies signalling a potential barrier effect.

Some examples of studies providing evidence for barrier effects in offshore windfarms include Christensen *et al.* (2004), Kahlert *et al.* (2004), Masden *et al.* (2009), Masden *et al.* (2010), Krijgsveld *et al.* (2011), Masden *et al.* (2012), Thaxter *et al.* (2024):

Christensen *et al.* (2004) observed Divers *Gavia spp* (n=13), Northern Gannets *Morus bassanus* (n=28), Common Scoters *Melanitta nigra* (n=28) and Eurasian Curlews *Numenius arquata* (n=1 flock) to adjust their travel routes around (lateral or vertical) the wind farm Horns Rev. Additionally, they also reported altered behaviour of several birds in the windfarm, adjusting their flight behaviour and causing potential additional energy expenditure in their travel around the wind farm. They reported this response for a small numbers of Grebes *Podiceps spp* (n=3), a portion of Great Cormorants *Phalacrocorax carbo* (n=4 flocks) and Geese *Anser sp.* (n=1 flock). In Horns Rev, they found (almost) no altered flight behaviour in Gulls *Larus spp* & *Rissa spp.,* Terns *Sterna spp.* and Arctic Skuas *Stercorarius skua* (n=27), Golden Plovers *Pluvialis apricaria* (n=11), Oystercatchers *Haematopus ostralegus* (n=15) and Whimbrels *Numenius phaeopus* (n=1).

Kahlert *et al.* (2004) investigated the tracks of birds around Nysted offshore windfarm in related to tracks from before the windfarm was operational. They observed that migrating waterbirds in general showed a response at 3,000 meters distance from the windfarm, and at less than 1,000 meter the response was clearly visible, even during the night. The number of tracks passing the transect on the Eastern border of where the windfarm is situated also significantly declined after the turbines were erected, showing a barrier effect for migrating waterbirds. As Fox & Petersen (2019) pointed out, the data by Kahlert *et al.* (2004) also showed clear changes in flight paths between the pre- and post-construction situation, specifically for the Common Eider *Somateria mollissima*.

Masden *et al.* (2009) assessed potential impacts of barrier effects on multiple birds species. They explicitly also assessed the Common Eider, a species known to be cautious when migrating. They found that the overall relative effect of a single wind farm (Nysted offshore wind farm) was likely trivial, with the Eiders requiring an extra travel distance of 500 meter on a 1400 km migration route, estimating that to achieve a significant effect one would need a 100 times the Nysted wind farm. However, they considered the Nysted wind farm to be relatively small compared to other planned wind farms and explicitly warn for future wind farms in cumulation. Additionally, they warn for related birds executing daily foraging trips, such as the Common Scoter and the Long-tailed Duck *Clangula hyemalis*.

The modelling exercise by Masden *et al.* (2010) predicted that, theoretically, breeding Great Cormorants and Shags *Phalacrocorax aristotelis* would experience the most impact from a barrier effect, when avoiding a wind farm that would be placed on their foraging route. Followed by the Common Guillemot *Uria aalge* and the Atlantic Puffin *Fratercula arctica.*

Based on radar data, Krijgsveld *et al.* (2011) showed particularly high macro-avoidance for several seabirds (within a range of at maximum 5.5 km) around the offshore wind farm Egmond aan Zee (OWEZ). Specifically, the seabird species groups Divers (macro-avoidance = 0.68), Gannets (0.64), Sea Ducks (0.71; mostly Common Scoters) and Alcids (0.68) and of the migrating landbirds species group of Geese/Swans (0.68; mostly Brent goose *Branta bernicula*) showed high macro-avoidance in OWEZ.

Thaxter *et al.* (2024) addressed potential effects of windfarms on Sandwich terns *Thalassesus sandvicensis* during the breeding season. Their data suggested that when the quality of foraging area is large enough Sandwich terns tend to enter wind farms, but for other reasons the birds tend to funnel their movements around the edges of wind farms. Given that the barrier effect specifically addresses the effect on travel and not foraging behaviour, this study suggests the presence of a barrier effect in Sandwich terns. However, the authors suggested that the changes in travel behaviour perceived may not be due to avoiding the wind farm, but as a response to changes in the prey landscape within wind farms.

2.2.2 Reviews addressing species risks from barrier effects

Humphreys *et al.* (2015) provided an overview of species expected to be susceptible to barrier effects in Scottish territorial water, based on Langston (2010). Species that show a moderate risk of barrier effects are found in representatives of ducks (Greater Scaup *Aythya manila*, Common Eider, Long-tailed Duck, Common Scoter, Velvet Scoter *Melanitta fusca*, Common Goldeneye *Bucephela clangula* and Red-breasted Merganser *Mergus serrator*), divers (Red-throated Diver *Gavia stellata*, Black-throated Diver *Gavia arctica* and Great northern Diver *Gavia immer*), petrels (Northern Fulmar, Manx Shearwater, Balearic Shearwater, European Storm-petrel and Leach’s Storm-petrel), cormorants (Great cormorant and Shag) and alcids (Common Guillemot, Razorbill *Alca torda*, Black guillemot *Cepphus grylle*, Little Auk *Alle alle* and Atlantic Puffin).

Alternatively, species susceptible to displacement are likely to be susceptible to barrier effects as well (Searle *et al.* 2018). We therefore propose also to look into sources identifying the displacement risk when identifying the birds affected by barrier effects. For instance, Birdlife International (Pigott *et al.* 2021) identified species at risk for displacement in the whole North Sea and Baltic. They pose that the species greatest at risk in the North and Baltic Sea for displacement are the Greater Scaup, the Common Goldeneye, the Common Scoter, the Goosander *Mergus merganser*, the Red-throated Diver, the Black-throated Diver and the White-billed Diver *Gavia adamsii*. Furthermore, they proposed that species with moderate risk of displacement effects are Velvet Scoter, Red-breasted merganser *Mergus serrator*, Common Eider, Great Northern Diver, Great Crested Grebe *Podiceps cristatus*, Long-tailed Duck, Black Guillemot and Slavonian grebe *Podiceps auritus*. However, it is important to realise this risk analysis was done 1) for displacement, not barrier effects specifically and 2) for the whole North Sea and/or Baltic Sea, which may not accurately reflect the smaller scales, such as for instance the Dutch Continental Shelf (DCS).

2.2.3 Conclusion on species affected by barrier effects

In conclusion, based on the current literature, we see that the species groups Divers and Sea Ducks are almost always mentioned in studies investigating barrier effects and could potentially be species groups of interest for future assessments of barrier effects. Another group of interest often mentioned in literature are Alcids. For migrating birds that are not covered under the previously mentioned groups, we suggest considering geese/swans as well, given the strong avoidance found by Krijgsveld *et al.* (2011). Finally, despite the ambiguity of the barrier effects suggested by Thaxter *et al.* (2024), we suggest considering breeding Sandwich terns *Thalassesus sandvicensis* as a precautionary approach.

Finally, if we look specifically at the risk analysis by Humphreys *et al.* (2015) on birds in Scottish waters, we see all the species currently considered for displacement in the Dutch assessment framework KEC 5.0 (Soudijn *et al.* 2025), and its predecessor KEC 4.0 (Soudijn *et al.* 2022), also being mentioned for barrier effects, showing that the species affected by displacement and barrier effects are expected to strongly overlap. Species from displacement should therefore also be considered in light of barrier effects when known to be travelling at sea as well. It should, however, be noted that this is a literature review into the published literature on barrier effects and studies that identified a barrier effect. Other species or species groups may or may not be affected, but we did not find any published evidence of this.

3 The current redeveloped model

Eneco and Waardenburg Ecology have developed a first conceptual model to assess barrier effects. One of the goals of this study is to assess the broader usability of the existing model (Bos *et al.* 2025). In this chapter, we first describe the model conceptually (§3.1), after which we describe the technical details (§3.2) and a proof of concept exercise (§3.3).

3.1 Model description

The aim of the model is to determine how large the detour is (in distance, e.g. meters) that must be made to avoid a wind farm during a travel from a possible starting point to a possible destination. See Figure 3-1 for a schematic representation of the conceptual basis of the model.
To determine the additional distance travelled, the model starts with a starting coordinate to start the travel from. First, the unobstructed distance (straight line) from a starting coordinate to an ending coordinate (destination) is determined.

The model then draws a boundary line around the windfarm at a distance that represents the first moment a bird may perceive the presence of the wind farm. The point where the unobstructed path first crosses the boundary around the wind farm is where avoidance behaviour starts. Then, the model draws secondary boundaries around each of the turbines considered at a defined avoidance distance. Roughly on the boundaries surrounding the turbines, the model discerns a set of points with specified resolution (e.g. every 200 meters along all above-mentioned boundaries). Consequently, the model holds information on four types of geographic points:

- **Starting point:** where the bird starts flying from
- **Ending point:** where the bird tries to fly to
- **Wind farm discerning point**: point where the bird can first perceive the wind farm and avoidance behaviour starts
- **Turbine boundary points:** points at exactly the avoidance distance away from a turbine

Any of the points that are located within the avoidance boundary of a turbine are then excluded from the analysis. Then, all of the points now remaining in the model are connected with each other with straight lines. Any of the travel lines crossing the boundaries of a turbine are now deemed an impossible travel path and excluded from the further analysis. Using the remaining (possible) travel paths between points, the model now identifies the shortest path (in distance) to get from the starting point to the ending point.

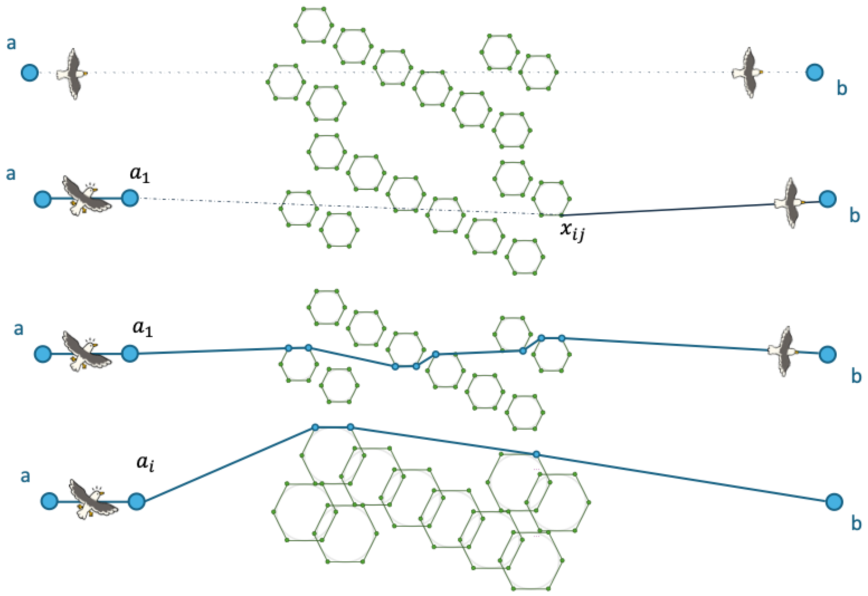


*Figure 3-1: Visual representation of the barrier model. A bird from the starting point (a) reaches a specified distance from which it can discern the wind farm (a_1). The green hexagons represent no-fly areas that are closer than the avoidance distance to a turbine, located in the center of a green hexagon. At point a_1 the bird starts adjusting its flight path as to ensure not flying closer than the avoidance distance to the first turbine it would encounter. The bird then looks for a flight path possible point to reach far enough away from a turbine (at a distance equal to the avoidance distance), represented by the points on the hexagons, eventually reaching their end destination (b). **Top**: the bird wants to fly unobstructed from a to b. **Second**: a bird considers traveling to a point x_{ij} that requires it to come closer to a turbine than the avoidance distance (through any of the hexagons surrounding the turbine). The direct travel between these two points is deemed impossible and excluded from the further analysis. **Third**: the bird finds a travel path between points that does not require it to come closer to any turbine than its avoidance distance. This full path is considered as a possibility. If this path is the shortest path of all possible paths, this will be the path the model identifies as the detour the bird will take. **Bottom:** for some birds, the avoidance distance may be larger than half the distance between turbines, making travel in-between turbines impossible, in this case the bird will try to find the shortest path along the edges of the windfarm. Edited from the original by René Bos/Eneco.*

The difference in travel distance between this newly found path and the straight, unobstructed path is defined as the impact of the barrier effects and forms the output of the model.

It is important to notice the model holds three key assumptions that need to be touched upon:

- **A bird is able to find the shortest way of crossing the wind farm**. This does not represent a worst-case scenario. While this first model has clear use for comparing wind farm layout scenarios (Bos *et al.* 2025) and windfarms, future modelling of worst-case scenarios should reconsider the algorithm used to find a path through the windfarm. Examples of alternative approaches could include a bird that always avoids the whole wind farm or scenarios where a bird has no perfect method for choosing the shortest path. However, it should be noted that in the case of many of the birds that are considered susceptible to barrier effects the avoidance distance exceeds the half of the distance between the turbines, making travel in-between the turbines impossible. As a result, the model will try and find the shortest round along the edges of the wind farm for these species. Nevertheless, even in this case the assumption that a bird can find the shortest path around the wind farm should be reconsidered.

- **The bird exhibits no vertical avoidance.** Evidence for vertical avoidance is patchy and often ambiguous with some studies finding vertical avoidance and other studies finding no or ambiguous evidence (Madden in prep.). Consequently, we choose not include vertical avoidance in the model. Future versions of the model could consider vertical avoidance as well.
- **Uncertainty in input parameters is not yet supported** (e.g. a probability distribution for avoidance distance). Relatively simple adjustments to the underlying code should make this possible in future versions

3.2 Technical description of the model

Table 1: Notation and description of input parameters in the current redeveloped version of the (Bos et al. 2025) barrier effect model.

Parameter	Description
a	starting point
b	destination to travel to (ending point)
O	Set of coordinates of all wind turbines in the analysis
$d_{avoidance,max}$	Maximum distance to start avoiding from (point of first discerning the wind farm)
$d_{avoidance}$	Radius of avoidance around wind turbines
d_j	Resolution (in distance) of travel nodes along turbine avoidance buffers around wind turbines
$J_{i,min}$	Minimum number of travel nodes on each boundary around a turbine
$\boldsymbol{J_{i,max}}$	Maximum number of travel nodes on each boundary around a turbine

Table 2: Notation and description of calculated measures in the current redeveloped version of the Bos et al. (2025) barrier effect model.

Parameter	Description
O_i	turbine index ($i = 0, \ldots, i = length(O)$), represent the different turbines considered in the model
J_i	Number of travel nodes on any boundary around turbine O_i
a_1	Travel node defined as the first location a bird can start avoidance behaviour from. Defined as the location where an unobstructed travel path between starting point a and end point b cross a boundary around the wind farm at $d_{avoidance,max}$
x_{ij}	Travel node j on boundary around turbine i
D	Distance matrix for physical distances between any two points (Starting point **a**, end point **b** and travel nodes, a_1 and x_{ij}) of the possible travel routes only.
d_{impact}	Distance of the shortest path, when incorporating the barrier effect, from the beginning point A to the end point B
d_{null}	Distance of the shortest unobstructed path from the beginning point **a** to the end point **b.**
$\boldsymbol{d_{barrier}}$	**Additional distance travelled due to barrier effect**

The model was originally programmed in MATLAB. As part of this study, we have translated the model from its original programming language, MATLAB, to the language R. MATLAB is generally used very little among ecologists and we deemed it necessary for the accessibility to and applicability by other ecologists to have an R version.

The model considers a geographically explicit starting point a and a destination point b. The goal of the model is to determine the additional distance travelled $d_{barrier}$ because of the wind farm barrier experienced. First, the model determines the unobstructed distance d_{null} (straight line) from point a to a destination point b.

Using a maximum avoidance distance $d_{avoidance,max}$, the model draws a boundary around the outer turbines of the wind farm. $d_{avoidance,max}$ represents the maximum distance from which the bird species considered can discern the wind farm. Crossing this boundary indicates that the bird can now discern the wind farm and adjust its travel path in reaction to the wind farm. The point where the straight line between starting point a and destination point b is then defined as point a_1 This point represents the actual location the bird starts avoiding in our model.

Then, the model defines avoidance buffer zones around each separate turbine in the model. The avoidance buffer zones are constructed as circles around the coordinates of any turbine O_i considered, with a radius $d_{avoidance}$ as representation of the avoidance distance of a bird.

On the boundaries of the turbine avoidance buffers, the model then draws a number of evenly spaced points x_{ij} along the perimeter of each avoidance buffer. The spacing distance (in meter) between points on the turbine buffer is gained using resolution d_j along the perimeter. By dividing the perimeter of the avoidance distance, the number of travel nodes around each turbine is gained. This number is then rounded up to the nearest whole number, yielding the amount of travel nodes a bird can travel to on each turbine buffer J_i. By rounding the number of travel nodes up, the actual resolution distance between travel nodes along a turbine avoidance buffer is always lower then defined in d_j.

However, the number of travel nodes J_i along a turbine avoidance boundary is constrained by a maximum J_{max} and minimum J_{min}. If d_j necessitates a number of travel nodes on a given boundary outside of the range $[J_{min}, J_{max}]$ the model redefines J_i to the nearest value satisfying $J_{i,min} \leq J_i \leq J_{i,max}$. The number of nodes is constrained by an upper limit to control computational time and constrained by a lower limit to ensure travel along the avoidance buffer is not simplified too much.

Any points x_{ij} that are located inside the avoidance buffer of any turbine are then identified as unreachable and excluded from the analysis.

By directly drawing travel lines between two points x_{ij} on a single turbine perimeter, the flight path between these two points will always cross the buffer, because a straight line is always below an arc between two points. Hence, if not corrected for this effect, a bird is never able to travel along an avoidance buffer only from buffer to buffer. To counter this effect the model corrects every point x_{ij} to a position slightly outward of the buffer using the secant.
The model then excludes all points x_{ij} situated within any turbine buffer, as these are never reachable for a bird.

The model then identifies if direct (straight line) travel between which of the points in a, b, and the travel nodes a_1 and x_{ij} is viable: any direct travel between any of these points crossing any of the boundaries is considered inviable (a part of the travel occurs closer to a wind turbine then the avoidance distance $d_{avoidance}$.), and excluded from the analysis.

The model constructs distance matrix D, containing the physical distances between each of the remaining coordinates a, b, and the travel nodes a_1 and x_{ij}. The model then optimises for the minimum travel distance between the avoidance starting point a_1 and ending point b. This optimisation occurs using Dijkstra's algorithm through the r package *igraph* (Csárdi & Nepusz 2006, Antonov *et al.* 2023, Csárdi *et al.* 2025). The length of the shortest route from a to b through avoidance starting point a_1 is than defined as the length of an impacted travel route d_{impact}.

Based on the shortest resulting route d_{impact} the model then outputs the additional distance travelled because of the barrier effect as:

$$d_{barrier} = d_{impact} - d_{null}$$

All coordinates are expected in WGS84 coordinate reference system, but translated to UTM in the model to be able to calculate distances with.

A full overview of the input parameters and their meaning is given in Table 1. Similarly, a full overview of the calculated measures described, and outcomes gained is given in Table 2.

3.3 Proof of concept

3.3.1 Input data

In order to demonstrate the functionality of the model we have executed a proof of concept using real world data:

We assessed the effect all plots of Borssele wind farm (plot 1 through 5) have on Sandwich terns (*Thalasseus sandvicensis*) breeding on the Dutch North Sea coast.
As potential starting points we chose six locations on the Dutch North Sea from which a Sandwich tern attempts to travel to a location on the other side of the Borssele wind farm roughly corresponding to sites with some concentration of breeding Sandwich terns as displayed on the Vogelbescherming website accessed on the 17th of October 2025. These are chosen to be our starting points a, and we chose a set of points on the far side of the Borssele wind farm as destinations b. These destinations are not based on real world data and simply chosen to ensure we generate flight paths directly through the wind farm as to provide a clear example of how flight paths would be rerouted. Additionally, these destinations were chosen without considering maximum distances a bird might travel, such a foraging range, again simply to illustrate how a flight may be changed. The physical locations of all the turbines i in windfarm Borssele form the set of coordinates I in our case study. In accordance with the original model by Bos *et al.* (2025), we assumed the distance to start avoiding behaviour at 5,000 meter. 5,000 meter was chosen as this is generally considered as the distance of the horizon at sea, meaning that visual observation at sea is up to 5 km, before the curvature of the globe obscures the view. We based the avoidance distance of the sandwich tern of the value used in the KEC 5.0 displacement analysis (Soudijn *et al.* 2025) at 1,500 meter. We chose 200 meters of resolution d_j between each travel point x_{ij} along turbine buffers. The minimum number of travel points $J_{i,min}$ along a turbine avoidance buffer was set at 6. To control for computational time, we set the maximum number of travel points $J_{i,max}$ along a turbine avoidance buffer at 20. An overview of the input data is given in Table 3. A visual overview of the points of origin, turbines locations and destination used in this proof of concept is given in Figure 3.

Table 3: Input parameters for the theoretical case study considered here

Parameter	Description	Value
a	starting point	Six locations on the Dutch North Sea coast, roughly representing breeding bird colonies as displayed by the Vogelbescherming website (Accessed on 17th of october 2025)
b	destination to travel to (ending point)	Points directly on the other side of the Borssele wind farm
I	Set of coordinates of all wind turbines in the analysis	Coordinates for turbines in the Borssele wind farm as downloaded from Windstats.nl (accessed on: 16th October 2025)
$d_{avoidance,max}$	Maximum distance to start avoiding from (point of first discerning the wind farm)	5,000 Meter (assumption)
$d_{avoidance}$	Radius of avoidance around wind turbines	1,500 meter (Soudijn *et al.* 2025)
d_j	Resolution (in distance) of travel nodes along turbine avoidance buffers around wind turbines	200 meter
$J_{i,min}$	Minimum number of travel nodes on each boundary around a turbine	6 travel nodes per turbine buffer
$\boldsymbol{J_{i,max}}$	Maximum number of travel nodes on each boundary around a turbine	20 travel nodes per turbine buffer

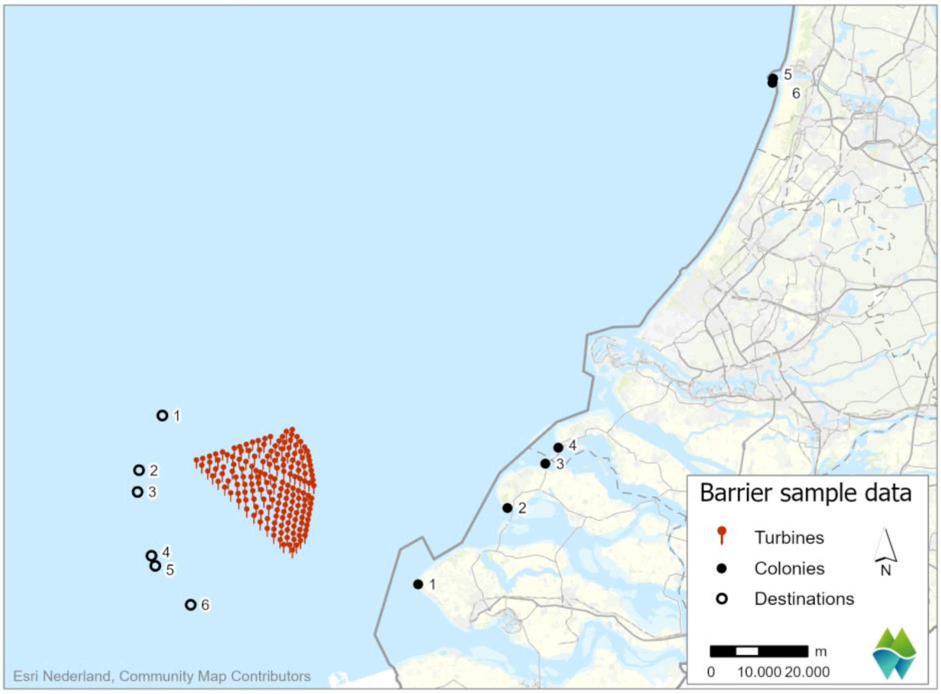


Figure 2: Visual overview of the locations of the points of origin a (closed dots), turbines in Borssele windfarm (red pins) and destinations of each bird (IDs mentioned next to the points correspond to the IDs in the results section (Table 4)

3.3.2 Results

Using our model, we modelled the necessary detour needed for six theoretical Sandwich terns from the Dutch coast to travel to a theoretical foraging ground exactly on the other side of the windfarm. We found a detour between 8,912 and 29,605 meter to be necessary, dependent on the departure site on the coast. This number represents the extra distance that a bird must travel, when experiencing a barrier effect, when compared to a straight-line travel between departure and destination as defined here. A full overview of the departure site and destination site coordinates is given in Table 4. Each of the detours are also visually represented in below. For this proof of concept, we see the distance between turbines is smaller than twice the avoidance distance, making travel in-between the turbines impossible.

Table 4: Proof of concept results for five birds travelling from five separate locations on the Dutch coast to the other side of the Borssele wind farm. All coordinates are in WGS84 coordinate reference system.

Bird ID	Travelling from (latitude; longitude)	Travelling to (latitude; longitude)	Detour necessary (meter)
1	51.52769859, 3,4380081	51.84285567, 2.67144528	15,509.26
2	51.66899503, 3,70842026	51.74053806, 2.60220717	8,912.38
3	51.75045364, 3,82352813	51.70000267, 2.59813389	29,569.58
4	51.78029643, 3,86281098	51.58094224, 2.64077229	11,250.3
5	52.46256944, 4,53256068	51.56225419, 2.65231732	29,605.08
6	52.45476616, 4,52969239	51.48979319, 2.75874248	9,687.16

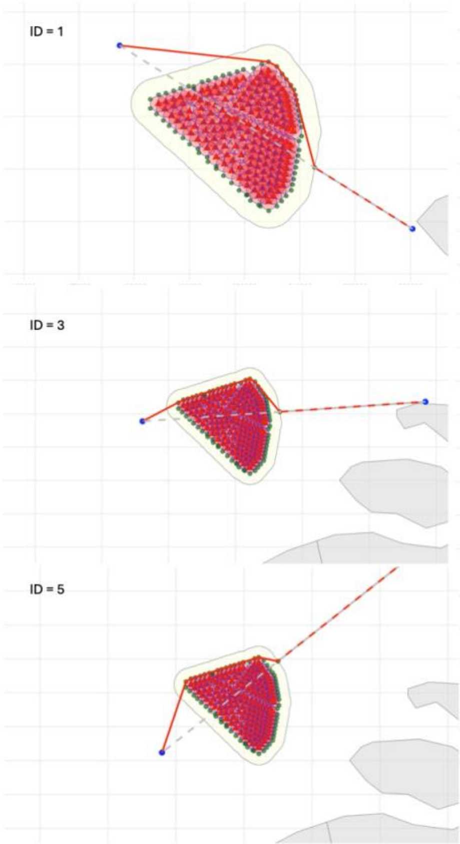


Figure 3: Detours taken as predicted by our model for 6 birds due to Borssele wind farm. IDs correspond to the values mentioned in Table 4. The dotted line represents a direct unobstructed path to each destination. The solid line represents the predicted new path by our model. Green dots represent the travel nodes each bird can travel along. Red circles represent areas around a turbine within avoidance distance of the bird.

4 A generalised assessment framework

One of the primary goals of this study is to develop a reasoning on how a barrier effect model could make lead to an assessment in the Kader Ecologie & Cumulatie (KEC) assessment framework and Environmental Impact Assessments (EIAs) in general. In this chapter we lay out our thoughts on how a barrier effect model could be integrated in an analysis framework to get to an assessment of the environmental impact.

Given the variety of birds using the Dutch Continental Shelf in all three barrier effect assessment typology categories (breeding birds, non-breeding local birds and migrating birds; see section 2.1.2), we recommend a general framework applicable to all three assessment typologies. Whenever applicable, the differences in executing the framework for each typology is discussed within the chapter.

To assess barrier effects in the future EIAs, we propose an approach of five steps (section 4.1) in which we discuss the literature relevant for each step and our personal knowledge of the current Dutch EIA system.

Additionally, we highlight some overlap in the analysis framework of barrier effects with assessing habitat loss or displacement. We therefore discuss the potential to assess these effects within a single integrated framework in section 4.2 for species that require an assessment for both effects simultaneously.

4.1 The suggested framework

We propose the first version of an assessment framework to have five sequential steps:

- Pre-processing Data
- Modelling Barrier Effects
- Converting Barrier Effects into Additional Energy Expenditure
- Energetics Modelling to Assess Effects
- Assessing the impact of increased energy expenditure using population effects and policy thresholds

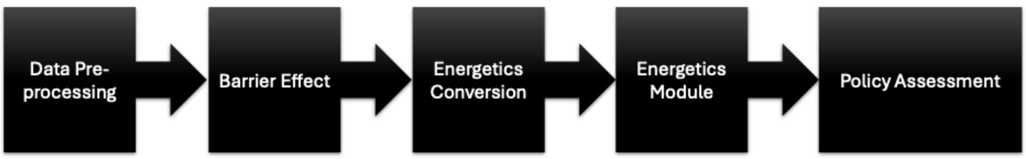


Figure 4-1: Schematic overview of the discrete steps proposed in the framework

In this chapter we specifically also describe models that could cover the steps discussed here. While this study explicitly focuses on the usability of the Bos *et al.* (2025) model (chapter 0), we also discuss any other models available in literature and models that could fulfil the requirements of the assessment steps Bos *et al.* (2025) do not yet assess. Some of the modelling frameworks discussed here may cover multiple steps of the proposed approach (Searle *et al.* 2018) , in this case we discuss the relevant parts of these modelling frameworks in the relevant steps.

4.1.1 Data pre-processing

Data analysis or assumptions on the translation of the underlying data into the parameters needed for any barrier effect model could have a great influence on the outcome. Proper considerations on these translations, need to be consistently formulated in any future assessment framework. For the purpose of clarity, this step is presented as a single step in the framework. However, this step likely encompasses several different parallel and sequential data preparation steps.

Data needs and pre-processing to estimate barrier effects can vary with the model used. Here we attempt to summarise the core of data and data pre-processing needed in each barrier model found in literature. We consider the different models found in literature more in-depth described in section 4.1.2 and here we focus on the data and data pre-processing needs:

All barrier effect models need to be fed with a predefined preferred flight path of birds. Identifying where a bird leaves from, what the destination of a flight path is and how often this flight path occurs is at the core of understanding and predicting how flight paths will be modified by barrier effects. To estimate the flight paths of birds geographically explicit and species-specific data on bird movement is needed. At a small scale, within of near wind farms, pre-construction tagged radar data could generate some understanding of the current flight paths in the area. At every scale GPS-logger data can generate understanding of points of origin and (intermediate) destinations of birds. It is in this aspect that the three types of birds described earlier show clear differences:

- **Breeding birds** generally tend to display relatively consistent movements from colonies to foraging grounds and back, making the estimation of flight paths relatively easy. For instance, Searle *et al.* (2018) build local density maps of breeding birds as proxy of food availability using GPS-loggers, and then apportion the birds from colonies to each of the found foraging locations, generating likely flight paths between colony and foraging location.
- For **migrating birds**, flight paths are likely spaced sparsely, highly directional and occur only in a set short time window. GPS-logger data on these species could show us clear migration paths, points of origin and destinations.
- **Non-breeding birds** are the most difficult to estimate flight paths from. These birds are free to roam the North Sea without clear points of origin and destination. Key to understanding the movement of these birds will be GPS logger data outside of the breeding season or on non-breeding floaters specifically. Given the diversity of

flights for species unbound to colonies, single windfarms are expected to have little effects on these birds. However, with increasing offshore wind farms, also this groups diverse movement patterns are expected to be affected. With the increase in wind farms, clear new ways of summarising the movement of non-breeding birds at sea need to be developed. Promising initiatives for modelling movement of non-breeding are currently being developed in the DisNBS ORJIP project R package (Donovan & Caneco 2026) and in an individual based model in Norway (Buckingham *et al.* 2026).

Parameters to model behavioural responses are needed in every barrier model currently found in literature. This can be:

- composing the distance a specific species avoids a single turbine (Bos *et al.* 2025), with or without the inclusion of uncertainty, on several loose estimates
- composing the distance a specific species avoids a whole windfarm (Searle *et al.* 2018) based on expert elicitation.
- modelling the response much more intricately directly from bird GPS tracks interacting with windfarms (Masden *et al.* 2012) (see section 4.1.2).

Finally, all models require assumptions on the future windfarm layout. Either only the positions of the outer turbines need to be clear (Masden *et al.* 2012, Searle *et al.* 2018) or assumptions on the location of every separate turbine is needed (Bos *et al.* 2025).

The bird data mentioned above can be available in a multitude of forms, such as for instance originating from bird radars, GPS loggers, surveys, bird density maps and ringing. Each data form may prove its unique challenges to obtain the data needed for a barrier effects model. Even GPS-loggers, while it may seem to be directly usable from the text above, require cleaning of low quality data or conversion into density maps (Searle *et al.* 2018). A thorough inventory of the available data and the required pre-processing steps would be necessary to accurately assess the effort needed to incorporate this step.

In conclusion, data availability will have to be thoroughly identified to understand the data pre-processing needs. In general, three types of data general need to be collected or estimated: 1) Flight paths, 2) avoidance behaviour and 3) Future windfarm layouts. Key data to be collected and assessed in barrier models is GPS logger data. Flight paths are most difficult to estimate in non-breeding birds due to their unbound free roaming on the North Sea.

4.1.2 **Modelling barrier effects as a reroute of travel paths**

After preparing the data, the next step will be to determine the change in travel route a bird would take as a result of the barrier effect. An example of such a model is the Bos *et al.* (2025) model addressed in section 0.

Given that a primary goal of our current study is to investigate how the model from Bos *et al.* (2025) would function in an assessment, we explicitly discuss the role of the model here as well. The model takes travel start points, travel ending points and an avoidance distance.

Based on this data the model determines the shortest possible distance between the starting and ending points, given the avoidance distance. The model then calculates the difference to a situation where the barrier effect is absent. Hence the outcome is the added travel distance caused by the barrier effect (see chapter 0 for an extensive description of the model).

In addition to the Bos *et al.* (2025) model, we found four other models in literature assessing barrier effects, which we describe here in short.

Masden *et al.* (2010) executed a theoretical modelling exercise to investigate how much additional energy expenditure occurs when making a detour of between 100 and 10,000 meters of flying. Using the tool *flight* (Pennycuick 2008) they estimated which of nine birds would use the largest additional energy expenditure. Given that this exercise only modelled energy expenditure in sensitivity exercise to given detour distances, we do not deem this model directly usable in environmental impact assessments (EIAs).

Masden *et al.* (2012) developed a model based on real-world GPS data from Common eiders in the Nysted offshore wind farm. This model divides a measured GPS track in 100 meter interval travel nodes along the path. At each node the model determines what direction the bird has to fly to get to the next node on the track and therefore effectively has to travel for the next 100 meter. The model assumes that the direction of flight is a result of two separate forces pushing the bird, representing their motivations: one force pushing the bird towards its destination and one force pushing the bird away from a windfarm, depending on the distance to the windfarm. Based on the direction of flight and the distance to the wind farm, the model then attempts to estimate (a mathematical function to describe) the opposing forces acting on the bird. As a result, the model generates a mathematical function that describes how to draw a likely travel route around a wind farm. This function could then be used to draw a new travel path and find the additional distance travelled due to the barrier effect.

Searle *et al.* (2014) and its subsequent update SeaBORD (Searle *et al.* 2018) focus on the assessment of displacement and barrier effects for breeding birds only. Here we only discuss the parts relevant for the currently considered step of assessing barrier effects. Using an intricate Individual based model (IBM) to predict the condition of each bird in considered colonies, the authors attempted to estimate fecundity and mortality of breeding populations. Based on pre-construction densities, constructed using locally sourced GPS track data, they estimated flight paths from each colony to potential foraging grounds. Specifically, Searle *et al.* (2018) developed a user interface to make the model accessible for a broad spectrum of environmental consultancies. Barrier effects are modelled using two cognitions of a bird: either 1) the bird has a good spatial memory of the windfarm and already corrects its flight path very early in its flight or 2) the bird is completely naïve to the existence of the wind farm and only starts its avoidance behaviour very close to the wind farm. Corrected flight paths are then converted to additional flight costs and incorporated in an energetics model to get estimates for changes in demographic parameters.

Finally, several sources in literature (Brookes 2009, Boehlert & Gill 2010, Humphreys *et al.* 2015) mentioned an assessment of the additional energy expenditure due to wind farms in Speakman *et al.* (2009). However, we were unable to find the original text of this resource to assess the usability of this model as a barrier effect assessment.

To assess which of these models can best cover the proposed modelling step, we need to weigh some of the assumptions, qualities and weaknesses of each of the three available models identified from literature. In section **Error! Reference source not found.**, we discuss the assumptions of and remarks on the current Bos *et al.* (2025) in detail, while here we only highlight those that are relevant to weigh the different models that could model barrier effects:

Masden *et al.* (2010) only execute an analysis on which bird will expend the most additional energy to fly a number of additional meters, not considering any spatial data, avoidance distances or estimating an actual detour of a flight path. Therefore, we see this model as not suited for an assessment of barrier effects in an environmental impact assessment (EIA).

Masden *et al.* (2012) pose an interesting model suited for broad applicability and robust analysis of barrier effects for any bird interacting with wind farms. The method of constructing barrier effect assessments from real-world GPS-tracks shows great promise. However, the model has three aspects that need to be considered in light of useability:

1) The model is very data hungry and requires the availability of a good number of reliable species-specific tracks passing through windfarms. For many of the birds considered in Dutch EIAs this data pre-requisite is unfortunately not met. Even for the birds that do have reasonable amounts of GPS tracks available, many do not yet cross any existing wind farms. With increasing wind farm development, chances of birds encountering wind farms at sea may increase and more data on behavioural responses to wind farms may be generated.
2) As the result of this model is a mathematical/statistical equation to correct flight paths, a translation to the additional flight distance due to barrier effects should still be developed. Therefore, the model would require an additional development step to provide the output needed for the proposed framework. Nevertheless, Masden *et al.* (2012) also conducted a case study. Further discussions with Masden may highlight ways this development step could be executed and if this development step may already be executed.
3) The model is a complex statistical exercise. Properly understanding the inner statistics/mathematics of the model is a daunting task, requiring time.

In light of these three considerations we recommend not using the Masden *et al.* (2012) model in EIAs on the short term. However, we strongly recommend periodically reassessing the data availability and the potential to apply this model given the broad applicability and strong basis in real-world data.

Finally, the **SeaBORD framework** (Searle *et al.* 2018) is a promising model currently becoming the standard for barrier model assessment in the United Kingdom. In light of its applicability to the Dutch North Sea, there are several aspects to consider:

1) The model is tailored to the United Kingdom context. In the United Kingdom many assessments of birds and wind farm impacts are geared towards breeding birds. In the Dutch North Sea, however, the birds are a string mix of breeding birds, non-breeding residents and migrating birds. Additionally, assessments in the United Kingdom are generally project- or groups of projects based, consider rarely large scale cumulative impacts. To adapt SeaBORD to the Dutch context would require a thorough investigation of the source code of the model and all its complex intricacies. Furthermore, the user-friendly tool attached focusses entirely on the United Kingdom context, and hence irrelevant for the Netherlands.
2) SeaBORD is a very intricate and complex model requiring a great deal of different data sources. At the project level one might assemble data with thorough pre-construction surveys and bird tracking, but it is not realistic to collect such data at a North Sea scale.
3) SeaBORD is a very integrated framework covering almost all of the steps described in our proposed framework. When this is coupled with the high specificity and focus on the context of the United Kingdom, this would require much development time to disentangle the parts of the framework that are UK specific and the parts that are more generally applicable.

Consequently, we currently see several issues with the direct application of the SeaBORD framework in Dutch EIAs. We therefore currently do not recommend using the SeaBORD framework in an assessment framework of barrier effects in the Netherlands.

The **Bos *et al.* (2025)** model is the model specifically considered in this report. The model is being developed in tandem with the framework proposed here, ensuring its usability in the framework. However, also for this model at least one consideration is of key importance to assess the useability: the model by Bos *et al.* (2025) assumes that:

- the bird is beforehand naïve in not knowing where the windfarm is
- and when the windfarm is reached it has perfect knowledge of the layout of the wind farm and the fastest way to navigate this windfarm.

These strong assumptions need to be thoroughly considered and revisited in future developments, especially given the juxtaposition between the unknowing naïve bird at one point in time and the perfect all-knowing the next moment in time. Any future updates of the model would need to either adjust the pre-flight naïveté or the perfect knowledge of the wind farm layout. Currently, the knowledge of a perfect path through the wind farm does not reflect a worst-case scenario, where EIAs normally consider a worst-case scenario. We recommend that any future developments of the model should look into alternatives. Examples of alternatives are for instance:

- tools that allow the bird to progressively find a path through the windfarm rather than know the perfect way beforehand. To accurately understand these models future development would need to execute a wide review of all models of movement under constriction within and outside of the field of ecology. A specific field of research that could provide valuable future insights in such a review would for instance be human travel models relating to traffic conditions such as construction obstructions and traffic jams.

- an assumption that birds will always avoid the whole wind farm rather than try to fly in-between turbines. It should be noted however, than in the instances where the avoidance distance of a bird is larger that the distance between turbines the model already aligns with the assumption.

Consequently, while we see that the Bos *et al.* (2025) is currently the most applicable to fulfil the needs this framework step has, it currently does not reflect the assessment of a worst-case scenario and any assessments based on this model should be treated as such by policy makers. To match the need for worst case assumption, the model would need to be further developed.

4.1.3 Converting barrier effects into energetic consequences

Given that barrier effect is primarily defined to work through a change in energy expenditure, the next step in the assessment framework should be to translate the change in travel route to additional energy expenditure. In literature we found one model that may be suited to cover this step of the assessment framework:

When Masden *et al.* (2009) assessed barrier effects, they employed the modelling tool *Flight* by Pennycuick (2008) to calculate the increase in energy expenditure resulting from an increase in flight time. This model takes several characteristics of a bird (such as bird mass and flight speed) and the environment the birds live in (such as air density) to calculate flight costs. Also Searle *et al.* (2018) employed earlier work of Pennycuick (1997) combined with published values from literature to gain estimates of energy expenditure.

Consequently, the models by Pennycuick (2008) may in the future be used to translate additional travel time to additional energy expenditure due to barrier effects. An earlier version of this model is also found to be used outside of barrier effects; for example Warwick-Evans *et al.* (2018) used this model to estimate foraging and flight energy expenditures to model Northern Gannet wind farm displacement and collisions effects. Next to flight costs, for specific bird species also the costs of swimming need to be modelled. In case of assessing barrier effects on predominantly swimming birds, such a model should compute the additional swimming costs due to barrier effects.

In summary, we see that the model of Pennycuick (2008) and earlier versions thereof are more or less the standard and are currently suitable as a theoretical model to translate flight costs. It should be noted that Pennycuick (2008) is a theoretical model based on aerodynamics, future versions of this framework should review studies into actual flight costs of birds with the theoretical prediction and adjust if necessary. To translate additional swimming costs, however, a thorough broad review on the energy expenditure of swimming is needed.

4.1.4 **Incorporating energetic consequences into energetic models**

Finally, an increase in energetic expenditure should be translated into demographic impacts. For instance, Daunt *et al.* (2020) stated that additional energy expenditure in birds can have an effect on fecundity and adult survival (in or after the breeding season). To identify the impact of increased energy expenditure, models would need to explicitly compute the energetics of the birds considered. In literature pertaining to barrier effects, we found one source that has an energetics module to incorporate energy expenditure in general energetic modelling:

Searle *et al.* (2018) integrated the additional energy expenditure in an energetics module. They obtained energy expenditure from literature sources on different activities of a bird (flying, resting at sea, foraging, time spent in colony, after Daunt *et al.* (2002)) and daily energy expenditure, both for adults and chicks, which were modified by the perceived effects of displacement and barrier effects.

Additionally, also the Dutch governmental program Wozep (project ZV4-5-6: *Complexe vogelmodellen)* includes the development of energetic models for seabirds, specifically to model energetic effects of displacement on demographic processes due to offshore wind energy. Given our current understanding of the future workings of this model, we foresee that future integration of added energy expenditure due to barrier effects in these models may be possible.

A key consideration that should not be forgotten in this step of the modelling framework, is the feedback mechanism of behavioural adaptation. In order to reflect a worst-case assessment, we initially do not recommend including such behavioural feedback in the first version of the modelling framework. However, when a travel detour due to barrier effects will cause the energy expenditure to be too much, birds may choose to abandon a certain destination in favour of another, causing a shift in energy expenditure. For instance, if the energy budget is so drastically altered, a bird may choose not to frequent an affected travel route. Therefore, we recommend future versions of the framework to include such feedback mechanisms in the energetics modelling step (see specifically sections 0 and 4.1.2).

In short, no ready-made energetics model is currently available to easily include the need of this assessment framework step. Development of such a model could lean on insights gained from the energetics module as applied Searle *et al.* (2018) and the current developments on the energetics model being developed in the Wozep research program.

4.1.5 **Assessing the impact of increased energy expenditure to policy threshold**

After integrating the impact of barrier effects into an energetic model, the result should yield some degree of change in demographic parameters, such as survival and/or reproduction. Using these adjusted parameters, the next and final steps should be to define the effects at a population level and assess whether legal or policy threshold violations occur.

In the context of the Dutch policy for assessing the effects of offshore wind on birds, the current thresholds are set in accordance with the Acceptable Level of Impact (ALI) framework. In this framework stochastic matrix population models are used to test for the difference between unaffected and affected populations using a government set unacceptable threshold (Hin *et al.* 2024). Conceptually, there seems to be no concern why this framework would not support testing for the effects of barrier effects as well. Therefore, we propose using the same framework to assess barrier effect impacts. Currently, the underlying programming code of the ALI framework, as applied in KEC 5.0 (IJntema *et al.* 2025, Soudijn *et al.* 2025), can only assess added mortality from these collisions and habitat loss. If we consider the different potential effects of increased energy expenditure as suggested by Daunt *et al.* (2020), mortality effects should already be possible to include in the population models underlying the ALI framework. However, if we were to model a reduction in fecundity as a result of energy budgeting, the underlying R code would have to be adapted to facilitate fecundity changes.

4.2 Combining an assessment of barrier effects and habitat loss/displacement

Several of the steps described in 4.1 overlap with potential assessments for displacement and habitat. Generally, displacement effects and habitat loss also deal with energetic consequences. Similarly to barrier effects, the impact is not direct mortality, such as by collisions, but often emerges as delayed mortality- or fecundity effect (Daunt *et al.* 2020). This similarity allows us to consider including both the energetic consequences of barrier effects and displacement/habitat loss in a single energetics model (see section 4.1.4) and to evaluate its impact (section 4.1.5). However, when combining these effects, it is essential to consider the first three steps of the assessment as well. Before integrating the energetic consequences into one model, the key assumptions of each step need to be made explicit and consistent throughout the analysis of the different effects causing an increase in energy expenditure. Additionally, species susceptible to displacement and barrier effects tend to overlap and to avoid double counting of these effects integration is essential (Humphreys *et al.* 2015).

We therefore recommend that specifically the development of an energetics model should for species that are also assessed for habitat loss and displacement be aligned with the displacement analysis in the “Kader Ecologie & Cumulatie (KEC)” (Soudijn *et al.* 2025) and the developments within the Wozep research program. It is key to realise, however for species that are not assessed for habitat loss in the Netherlands and do not yet have a energetics model being developed, these would need to be developed using a similar methodology as the energetic models being developed for habitat loss.

5 Conclusions & Recommendations

5.1 Conclusions

The aim of this study was to execute an initial reasoning of how barrier effects of wind farms affect bird species, specifically in a context of how to assess the effect in Dutch assessment policy framework “Kader Ecology & Cumulatie (KEC)” and environmental impact assessments (EIAs) in general. To answer this question, this study posed three sub-goals:

1. To provide an overview of what is understood by the term “barrier effect” and what evidence there is for the barrier effect;
2. To provide an initial line of reasoning of how to assess barrier effects and to draft a conceptual modelling framework;
3. To assess the potential role of the existing Eneco-Waardenburg ecology model and how further developments hereof might play in assessing the barrier effect within Dutch environmental impact assessments.

5.1.1 Overview and Definition of Barrier effects

Given the varying definitions of barrier effects in literature, we find it necessary to pose our own definition, based on the problem description of Drewitt & Langston (2006): “*The effect of birds adjusting a specific travel path as a reaction to a wind farm area, which causes an increase in energy expenditure, potentially disrupting commutes between locations.”* To keep the barrier effect clearly defined this means the barrier effect only considers changes in a flight path and additional direct energy expenditure this may cause. In this way any assessment of the effect will also minimise the overlap with habitat loss assessments.

In current assessments and studies into barrier effects, three types of flight paths are assessed:

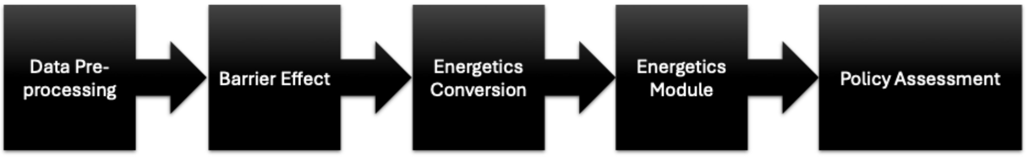
- migrating birds on long distance routes from one functional location to another
- birds frequenting certain travel routes
- breeding birds on foraging trips to and from their nest

The key distinction between these assessments is in defining the travel paths of birds, the frequency and the timing of these travel paths. Further conceptual steps of how the flight path changes are the same.

Vulnerable species to barrier effects strongly overlap with species vulnerable to displacement. In the literature, we found species often associated with barrier effects to be concentrated in the species groups Sea Ducks, Divers and Alcids. Additionally, other species to consider according to literature are the Sandwich Tern (Thaxter *et al.* 2024) and species in the group Geese/Swans (Krijgsveld *et al.* 2011).

5.1.2 Assessing the barrier effect

This study concludes that a five-step approach would provide a clear conceptual framework for any future assessment of the barrier effect:



Schematic overview of the discrete steps proposed in the framework

In this five-step approach an assessment would need to:

1) define travel paths and the frequency of use, as well as acquire other parameters needed for the model;
2) model how the identified travel paths will be changed;
3) model how the change in travel path results in additional energy expenditure;
4) model how additional energy expenditure will affect the energy budget and resulting demographic parameters;
5) identify the population level effects and test policy set thresholds.

Out of these five steps, this study sees that only step five currently has a readily available, immediately applicable model to accommodate an assessment of our definition of the barrier effect: the Acceptable Levels of Impact (ALI) framework (Hin *et al.* 2024) could fill the last step of the approach, if the steps beforehand are adapted towards this framework.

When only considering travel routes by flight, step 3 can be filled using the theoretical model by Pennycuick (2008) to provide a first theoretical framework to translate additional flight time into energy expenditure. However, for additional swimming time further examination would be needed for an adequate framework.

This study also concludes that the other steps of this approach currently do not have a readily available, immediately applicable model. In these steps existing models will need to be further developed, or entirely new models will need to be developed: implementing the proposed framework requires significantly more model development.

5.1.3 The role of the Eneco-Waardenburg Ecology Model

In this study we investigated the use of the existing Eneco-Waardenburg model to fill step 2 the proposed framework (a model how identified travel paths will be changed). As part of our study, we successfully translated the model to an R version. However, the model does currently not operate under worst-case assumptions. A thorough reconsideration of the model assumptions or the adaptation of another model is needed before the model is able to fill step 2 in the proposed assessment framework.

5.2 Recommendations

Based on the conclusions, this study defines several recommendations for future research and development in service of assessing barrier effects in the Dutch policy context. This study recommends further development and research on two key areas of the framework:

- Recommendations on the initial scope of the assessment framework.
- Recommendations on the development needed to implement the modelling framework proposed.

5.2.1 Scoping an initial assessment

A key issue with barrier effects remains defining a clear scope of the effect. In this study, we have attempted to provide a concise and well-delineated definition, in order to focus (the development of) any assessment and disentangle the barrier and habitat loss effects of wind farms. Apart from the definition set as only considering changes in travel paths and only the direct energetic consequences of this change, other effects may come into play. Effects that may also be relevant are for instance found in the altered environmental conditions a bird may encounter during its alternative travel path, such as sub-optimal wind conditions or altered predation pressure. While for some effects we may widen the definition formulated in this study, others may prove to have significant overlap with habitat loss assessments. For each of these expansions, we recommend clearly separating in which assessment the considered effect should be assessed (habitat loss or barrier effects) and to what degree each effect is already considered in either assessment.

Furthermore, given that this study is to our knowledge the first ever study to attempt to assess barrier effects of wind farms in the Dutch policy context, we strongly recommend starting the implementation of an assessment framework using a small, focused scope and iteratively expand the scope in the further development of the framework. Because of this, we recommend future development of the conceptual framework posed here to start with the following scope:

- Only considering the result of horizontal avoidance as barrier effect. While vertical avoidance is certainly of interest, including this in the models will add another layer of intricate complexity and we recommend to first implement assessment framework without. However, after the first version of the assessment framework has been successfully developed and implemented, the assessment should be expanded with vertical avoidance.
- Initially disregarding the potential effects of travel routes no longer being viable due to barriers. While this effect is relevant for barrier effects, the current or potentially future models available do not regard this effect. Considering how to model the loss of habitat behind barriers and keeping this disentangled from habitat loss assessment is a complex matter and requires further consideration and elaborate

model development. Therefore, we recommend not including this effect in the initial assessment framework. We do recommend including this effect in later subsequent versions of the framework.

Finally, the scope of this project was within the Dutch offshore wind energy development. However, conceptually, the essence of the model is to identify the effect of a deterring geographically explicit barrier on the travel path of an animal. Further research could investigate the use of this conceptual framework in assessing other geographically explicit human infrastructure on the movement of birds or animals in general, if data on avoidance and behavioural changes in relation to said infrastructure is available. However, for this initial assessment, we recommend keeping the development focused within the scope of offshore wind energy development and the impact on birds.

5.2.2 Further development of the modelling framework

Four out of five steps of the model currently do not have a readily available model for use in environmental impact assessments:

Step 1

A key issue in assessing barrier effects is how to model movement of birds at sea and therefore generate travel paths. For breeding birds and birds frequenting certain travel routes generating travel paths is mostly relatively straightforward. However, for non-breeding free roaming birds defining travel paths requires much conceptual work.

For breeding birds and birds frequenting certain travel routes for other reasons, examples of drawing flight paths are known and development can lean heavily on adapting existing models to fit the Dutch policy context. In case of developing the framework specifically for breeding birds, we recommend adapting existing frameworks.

For migrating birds, flight paths are difficult to estimate. For an initial assessment we recommend looking into adapting the crude assumptions used in the assessment of collisions mortality in the Kader Ecologie & Cumulatie (KEC) framework (IJntema *et al.* 2025). However, for subsequent versions of the assessment, we recommend a further investigation into the paths used by specific species of migrating bird using GPS data analysis of migrating birds when possible. Based on the findings from these studies, we recommend replacing the crude assumption with more informed drawing of migration routes as travel paths in subsequent versions of the assessment framework.

For non-breeding local seabirds, drawing travel paths is a complex exercise. New movement models would need to be developed before being able to draw certain travel paths. These models would have to be strongly coordinated with the assessment of habitat loss to properly align the models and integrate the effect at later stages of the assessment. Currently, there are no readily available techniques to model movement and consequently travel paths of non-breeding birds. However, there are continuous international efforts to develop such models (e.g. Donovan & Caneco, 2026; Buckingham et al., 2026). We recommend closely following these international developments that could be adapted to fill this modelling step.

Step 2

For modelling barrier effects investigating the use of the current Eneco-Waardenburg Ecology model showed that currently the assumptions do not reflect a worst-case approach, which may prove problematic. We recommend further developing the model, such that the assumptions better reflect a worst-case approach. In species with relatively abundant data-availability of GPS data on the interaction between bird and wind farms, the model by Masden *et al.* (2010) could also be revisited and parts of it used to study how flight paths change. However, in the initial development of the model, we recommend further adapting the existing Eneco-Waardenburg model to reflect worst-case assumptions.

Step 3

To translate a change in travel path into an energetic cost, only one theoretical model is currently available for travel through flight (Pennycuick 2008). An initial assessment of birds predominantly travelling through flight could include this model. However, for travelling through other means (such as swimming), and for subsequent assessment frameworks, we recommend an additional review into the energetic costs of both flying and swimming.

Step 4

To incorporate the additional energetic consequences into step 4 of the approach (an energetics module) models would need to be developed for all species that will be assessed to estimate the demographic consequence of additional energy expenditure. For the assessment of habitat loss, such energetics models are in development in the Dutch policy context (Wozep project ZV4-5-6: *Complexe vogelmodellen*). We foresee that these models may fulfil the need of the proposed modelling framework. However, for species for which the Wozep project does not develop energetics models, such as species not assessed for habitat loss in the Dutch policy context, additional models would need to be developed. Therefore, we recommend identifying the species that will need to be assessed for the barrier effects and, subsequently, the species for which an energetics model is not developed within other projects.

Additionally, future versions of the modelling framework could include that certain travel destinations become unavailable due to too much energy expenditure altogether. If additional energy expenditure would prove to be too much, the flight paths would need to be redrawn in the first step of the modelling framework. However, identifying if an additional energy expenditure proves to put too much of a strain on the energy budget would need to be considered within the full analyses of the energy budget, as is done within an energy model. Hence, a feedback loop from the energetics model to the drawing on initial flight paths will be necessary to implement potential losses of destinations in future versions of the framework. However, identifying if a single activity is using too much of the energy budget requires a complex development step on energy models, which we do not foresee being currently implemented in any of the existing or in development models. Therefore, we recommend that future developments of the model supporting the adaptive feedback loop of disregarding a destination entirely, would require strong collaboration between with the developers of such an energetics model.

Step 5

To assess policy threshold for population level effects we recommend the existing Acceptable Levels of Impact (ALI) framework. Only minor changes to the underlying R code are foreseen to make this possible.

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