BIRD CURTAILMENT IN OFFSHORE WIND FARMS

Towards a coherent sea-basin approach to mitigate collision risk for birds

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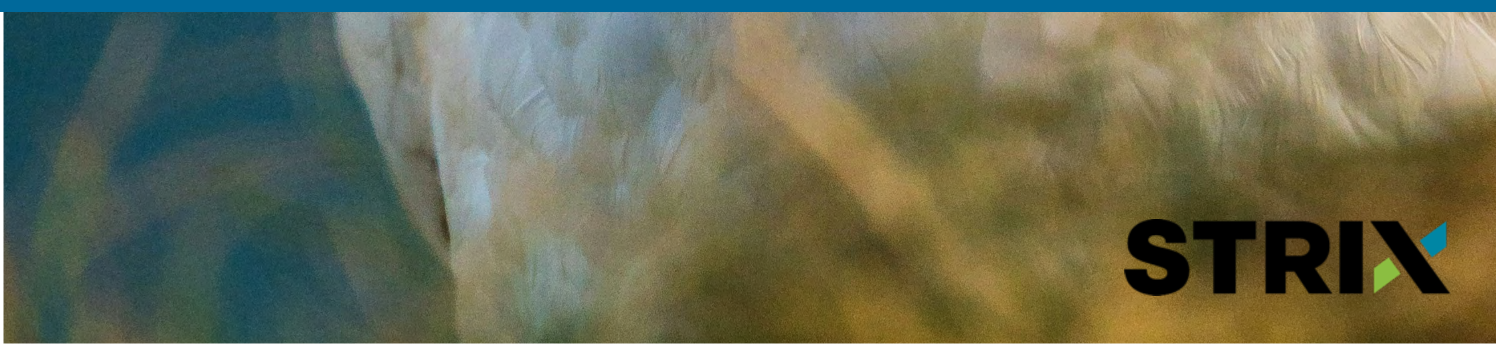

Bird Curtailment in Offshore Wind Farms:

Towards a coherent sea-basin approach to mitigate collision risk for birds

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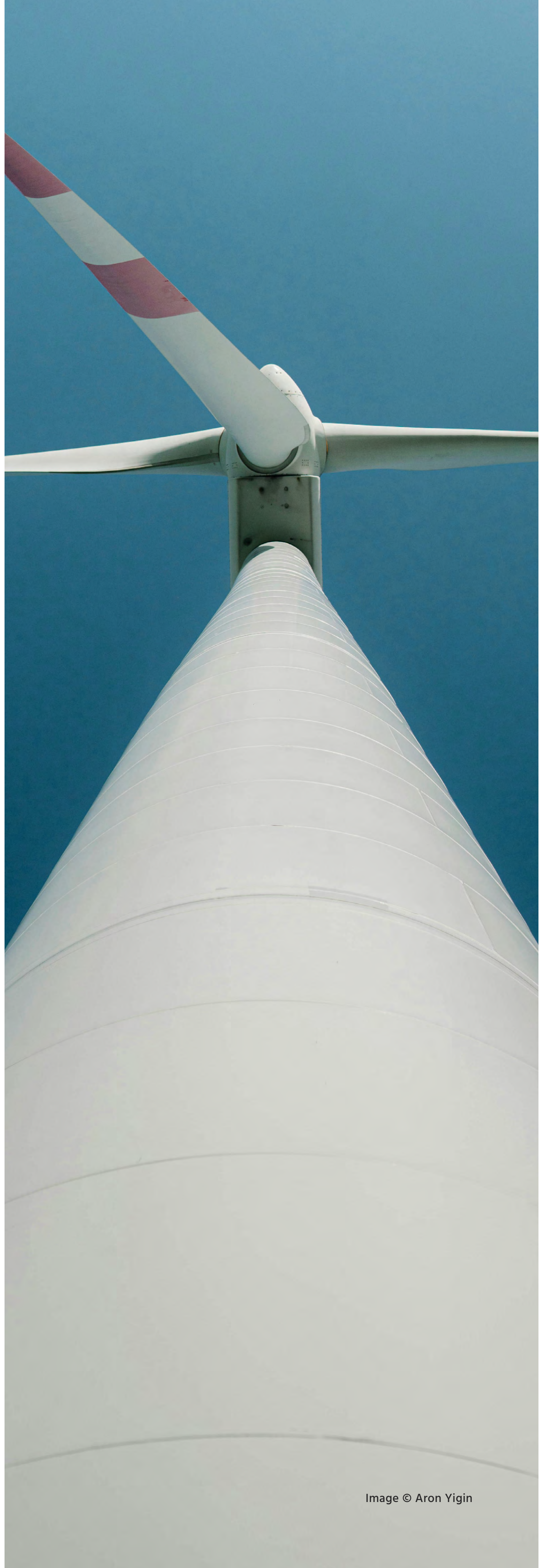

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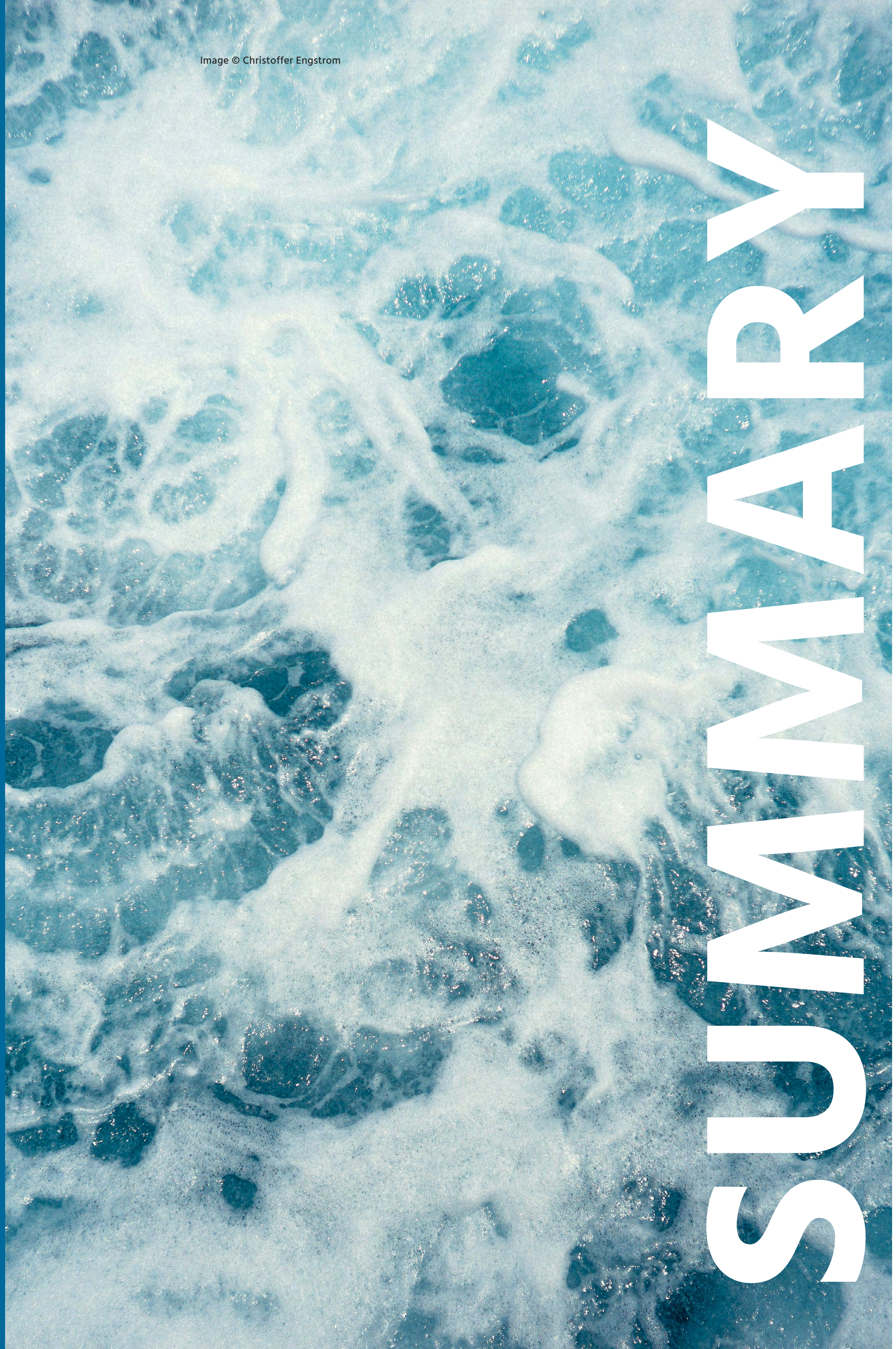


Image © Christoffer Engstrom

Scope and Aim

Offshore wind farms are essential for countries to meet climate neutrality goals and address the growing demand for electricity. The EU has set ambitious targets for offshore renewable energy, aiming for at least 120GW by 2030 and 300GW by 2050. However, as offshore wind areas expand, concerns about their impact on bird populations grow.

Bird curtailment and turbine shutdown are among the currently available options to mitigate collisions, but they can result in energy production losses. Curtailment measures involve reducing or stopping wind turbine operation during periods of high collision risk, determined by previous monitoring studies, real-time monitoring or model-based predictions of bird activity.

Approaches to curtailment aim to identify critical periods of collision risk with the objective to minimize energy production losses while maximizing the avoidance of collision. To achieve this objective, it is essential to identify and utilize existing technology effectively. This enables the identification of the most suitable curtailment strategy and ensures its successful implementation. Additionally, implementing monitoring protocols, leveraging the best available technology, is critical for assessing the effectiveness of curtailment strategies.

This study, prepared by STRIX, aims to identify and review the currently available approaches for the development, implementation and monitoring of bird curtailment in offshore wind farms, and explore how bird curtailment strategies could be implemented at a local and regional scale, considering the implications for power generation losses.

Key Findings

The information gathered and compiled in this report resulted from a comprehensive literature review on the impacts of offshore wind farms on bird species, bird monitoring in the offshore environment, and curtailment strategies aimed at preventing collisions of birds with offshore wind turbines.

The following key findings were identified:

1. Technology used for Development, Implementation and Monitoring

The successful implementation of a curtailment strategy in offshore environments depends on current technological capabilities. Various technologies, including radar and video-based systems, play a crucial role not only in informing the development of curtailment strategies but also in their implementation and for monitoring their effectiveness.

Despite significant progress, there remains a critical knowledge gap in understanding the true impact of offshore wind turbines on bird species due to collisions. Deploying monitoring technology, such as radar and digital cameras, is essential for assessing migration patterns and offshore bird activity, particularly in relation to distance from the coast. This information is vital for gaining insights into how offshore locations influence bird behaviour and understanding temporal-spatial variations in order to refine and advance curtailment procedures. One important parameter that can be gathered by available technology is the Mean Traffic Rate, which measures the number of individuals per kilometre per hour passing through an area. This data is crucial for determining or predicting key periods for curtailment, with the goal of maximizing avoidance of collision while minimizing energy production loss.

Additionally, the expenses associated with monitoring technology should be considered, as some equipment may be costlier but may also provide insights that other technologies cannot offer.

2. Curtailment Strategies

Bird curtailment strategies in offshore wind farms may be categorized into two main groups: predictive curtailment and real-time local curtailment. These strategies offer the possibility to tackle and reduce collision casualties of large groups of migratory birds and specific target species (both migratory terrestrial species and seabirds), respectively. The development and execution of these strategies should consider the ecological characteristics of the species or groups they aim to protect and will determine the technological infrastructure that will need to be deployed at the site.

Species-specific curtailment, which focuses on reducing collisions of target species with offshore wind turbines, requires real-time identification of the target species, among other factors. In contrast, species-generalist curtailment, primarily targeting migratory bird species, relies on a comprehensive understanding of their migration patterns and the determination or prediction of critical periods of bird activity. The Mean Traffic Rate serves as a crucial parameter to inform the implementation of this curtailment strategy. For the implementation of species-specific curtailment, the accurate identification of the target species is paramount, often facilitated by digital cameras.

3. Bird Migration Predictive Model

The predictive model plays a crucial role in shaping the development and execution of a bird curtailment strategy by identifying peak migration periods requiring curtailment measures. In the Netherlands, project Start/Stop aims to identify critical periods of bird migration during autumn and spring, implementing curtailment on selected nights with elevated collision risk.

This project relies on a predictive model that determines the Mean Traffic Rate by analysing avian radar data from a proxy offshore area and environmental/weather data from migration departure areas and along migration routes. The goal is to accurately identify periods of high-intensity migration.

In the Netherlands case study, the timing of predictions is vital for national authorities responsible for ordering curtailment to ensure that curtailment periods are communicated promptly to the national grid operator, allowing for the maintenance of electricity supply in the market.

4. Large-scale Grid Stability

It is crucial to adopt strategies that reduce the impact of energy loss on grid stability while safeguarding birds from collisions with wind farms. An example of a measure is the distribution network reconfiguration (DNR), which helps regulate active power losses in the network.

5. Regional Curtailment Implementation and International Cooperation

Implementing predictive species-generalist bird curtailment strategies at a sea basin level holds potential for mitigating bird collisions at offshore wind farms. Essential considerations encompass various factors such as employing site-specific monitoring technology, continuously refining predictive models, improving curtailment procedures, researching grid stability and integration, addressing regional implementation challenges, and promoting international collaboration and oversight.

Of particular significance is the need for effective international cooperation and supervision. Harmonizing curtailment procedures, sharing best practices, and maintaining consistent standards across borders are vital for ensuring the success of these strategies.

Image: Atlantic Puffin © Ray Hennessy

SECTION ONE
INTRODUCTION

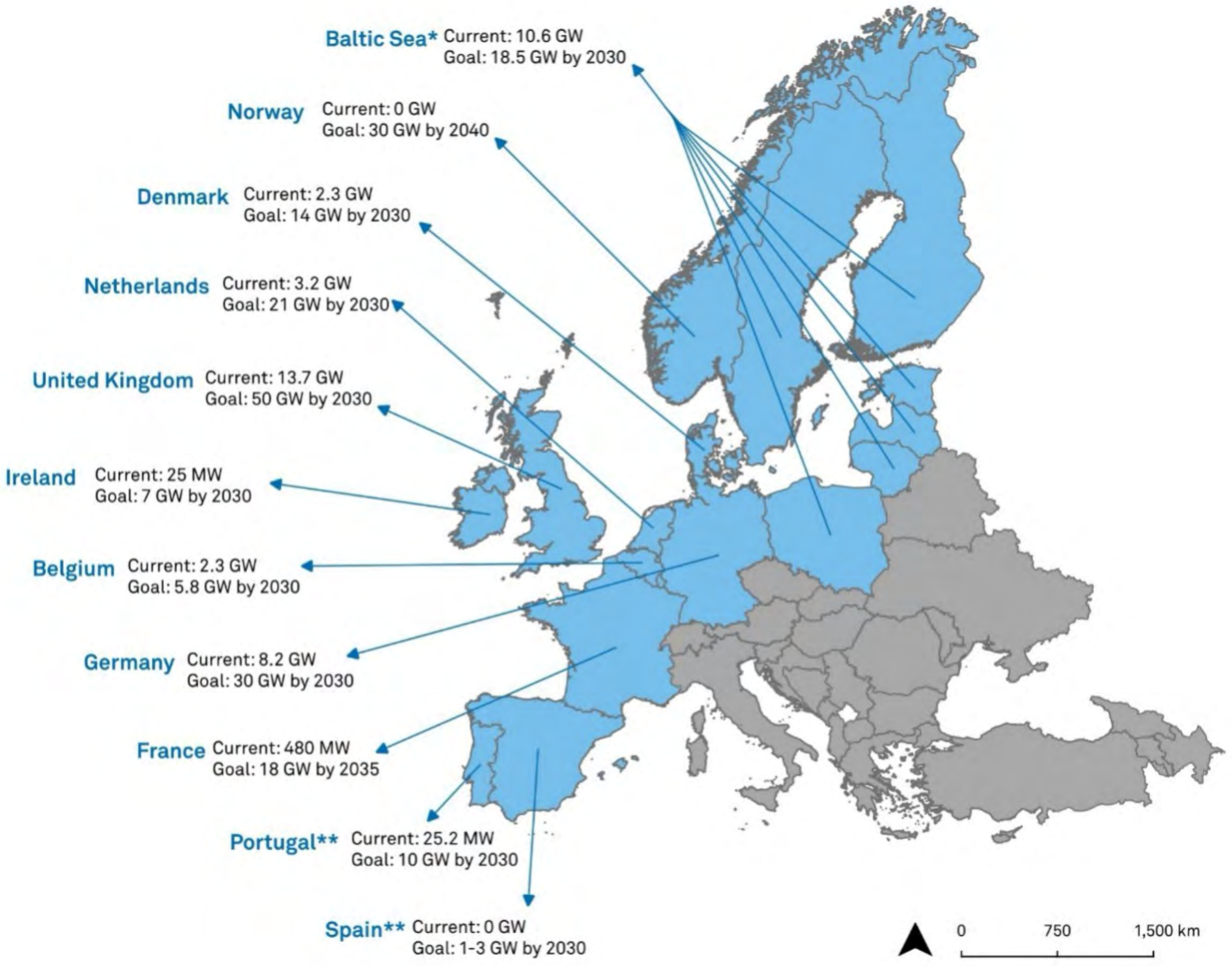


Figure 1 – Status and goals for offshore wind in Europe's Atlantic, North and Baltic seas. *Includes values for wind farms in the German and Danish parts of the Baltic Sea. ** Floating offshore wind.

Offshore wind farms play a pivotal role for numerous countries as they strive to meet both national and global climate neutrality objectives, while also addressing the escalating demand for electricity in the market. At the EU level, ambitious offshore renewable energy targets have been set, with a goal of reaching at least 120GW by 2030 and 300GW by 2050 (van der Kamp *et al.*, 2023) (Figure 1 and Figure 2). These targets are aligned with the European Climate Law, which aims to achieve climate neutrality within the EU by 2050. Despite ongoing technological advancements, including the development of 20MW turbines, achieving these energy production milestones will necessitate a significant expansion of offshore wind farms, particularly in the North Sea and Baltic Sea. As of 2023, the current offshore wind capacity in Europe stands at 32.3GW (Marques *et al.*, 2023; Ministry for the Ecological Transition and the Demographic Challenge, 2022; van der Kamp *et al.*, 2023; Wind Europe, 2022).

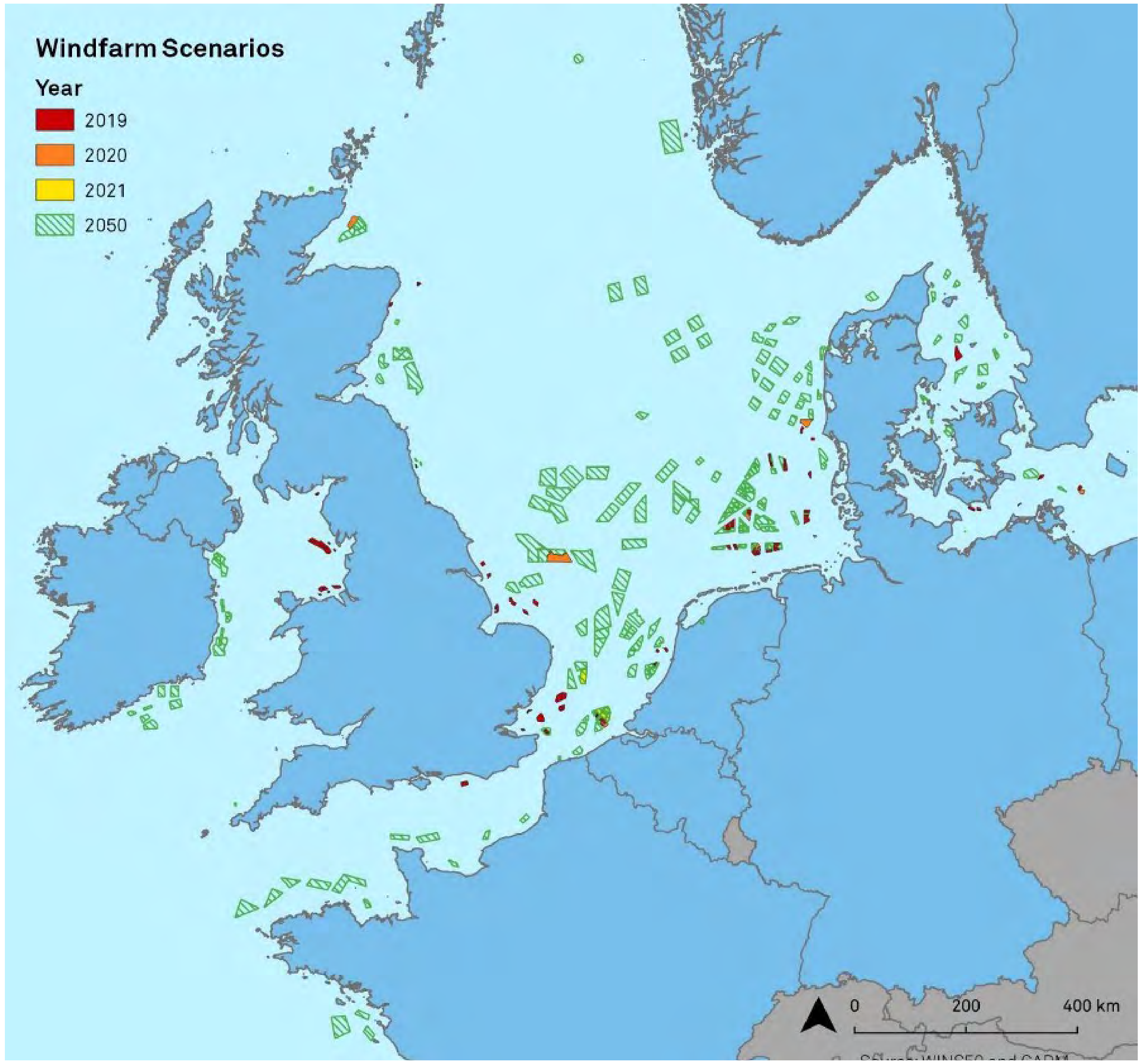


Figure 2 – Current (red, orange and yellow) and planned (green) offshore wind farms in the North Sea in 2050 (Baas 2022) – https://wins50.nl

As offshore wind areas expand, so do concerns regarding their impacts on bird species and populations. Offshore wind farms have the potential to affect bird populations through various mechanisms, including displacement due to disturbance, the barrier effect, habitat change or loss and collision mortality (Drewitt & Langston, 2006). While each of these impacts alone can have negative implications for bird populations, the cumulative effects arising from the presence of multiple wind farms can exacerbate these concerns, potentially leading to population reductions (Langston, 2010).


Image: Black-legged Kittiwake © Jerry Cassidy

The application of the mitigation hierarchy is fundamental to limit, as far as possible, the negative impacts of project developments on biodiversity. It identifies four sequential steps aiming to achieve no net loss: 1) avoidance; 2) mitigation; 3) restoration; and 4) offset. Additional measures that go beyond the mitigation hierarchy may be further considered to achieve a net gain for biodiversity. During the avoidance step, actions should be undertaken in order to identify and implement measures aiming to avoid the creation of impacts from the project development. Particularly for wind energy developments, the identification and selection of areas for project development, firstly at a plan level, which will result in the least impact, such as selection of areas away from sensitive or protected areas, or migratory routes, is key for avoidance.

Despite the possibilities offered by a careful application of the avoidance step, mitigation will be needed to achieve the goal of no net loss of biodiversity. The strategies identified in this report fall within this mitigation step of the mitigation hierarchy.

Bird curtailment and turbine shutdown stand as viable options to mitigate bird collisions with wind turbines, both offshore and onshore (Cook *et al.*, 2011; Garcia-Rosa & Tande, 2023; Hoge, 2021). Nevertheless, curtailment periods inevitably entail losses in energy production, posing potential challenges to the financial viability of wind farms and their contribution to the transition to sustainable energy production. This concern has spurred the development of smart strategies aimed at identifying periods with heightened collision risks and tailoring the application of curtailment to instances where it can offer a more cost-effective solution, aiming to minimise energy production losses while maximizing the avoidance of collision (Cook *et al.*, 2011).

The implementation of curtailment measures to prevent, or minimize, bird collisions with wind energy infrastructure is integral to broader efforts to balance renewable energy generation with nature conservation. This endeavour seeks to safeguard bird species from potential harm resulting from the expansion of renewable energy production. The effectiveness of these measures hinges on continuous research, advancements in monitoring technologies and the implementation of adaptive management strategies.

Curtailment measures aimed at preventing bird collisions in offshore wind farms involve temporarily reducing, or halting, the operation of wind turbines during periods of heightened collision risk. This can be determined either by predictive models or through on-site, real-time detection of significant bird presence at risk of collision. In accordance with current practices in offshore wind farms, bird curtailment is implemented by reducing the rotation speed of wind turbines to less than two rotations per minute. The main objective of this curtailment strategy is to mitigate the collision risk of birds flying through or within the wind farm area, which might include migratory bird species or local seabirds. Additional strategies or measures may be necessary alongside curtailment to mitigate collision impacts.

This study aims to address the following questions:

1. **What approaches are available for implementing bird curtailment in offshore wind farms and what are the associated benefits and limitations of each approach?**
2. **What monitoring is necessary (or desirable), both within and outside offshore wind farms, to develop, implement and assess the effectiveness of a curtailment strategy and its associated rules?**
3. **What are the potential implications for power generation losses resulting from the application of bird curtailment measures and how can a curtailment strategy strike a balance between minimizing potential bird collisions and minimizing power losses?**
4. **What are the key considerations for the design and implementation of a coordinated approach to bird curtailment at the level of a sea basin?**

1.1 Approach

The information in this report stems from a comprehensive study involving a systematic literature review on the impacts of offshore wind farms on bird species, including collision incidents, bird species monitoring in the offshore environment and curtailment strategies aimed at preventing bird collisions with offshore turbines. Additionally, input was gathered from relevant stakeholders within the offshore wind energy sector, categorized into three groups: 1) offshore wind energy developers; 2) national grid operators; and 3) national environmental agencies (see Section 9 – Annex).

Vogelbescherming Nederland (VBN), an environmental NGO, was consulted to contribute insights into the implementation of nocturnal curtailment during peak bird migration over the Dutch part of the North Sea.

The participation of these stakeholders involved responding to questionnaires and, where necessary, engaging in online interviews to clarify certain aspects. Their contributions not only aided in identifying and characterizing the current status of bird curtailment development and implementation, but also helped pinpoint knowledge gaps and underscored additional considerations crucial for implementing bird curtailment strategies at a sea basin level, namely the North Sea basin.

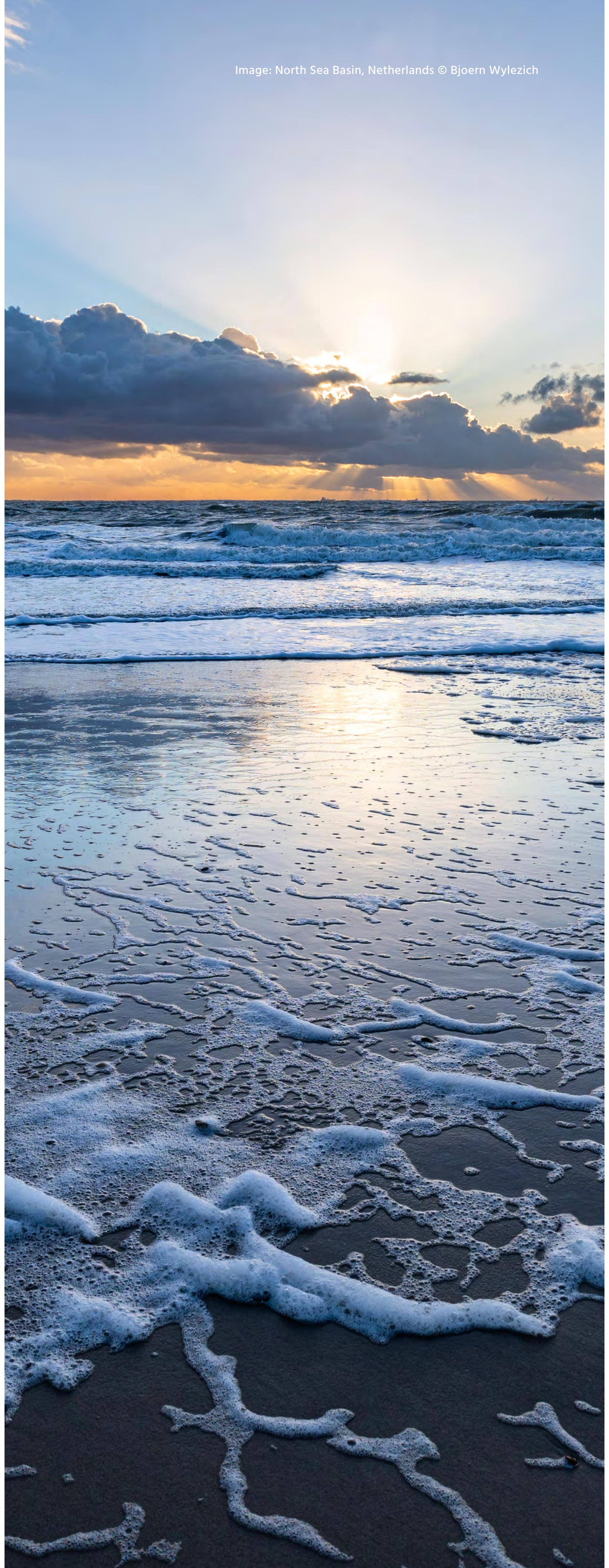


Image: North Sea Basin, Netherlands © Bjoern Wylezich

SECTION TWO

CURTAILMENT STRATEGIES

Various curtailment strategies can be explored with the aim of mitigating the impact of bird collisions with offshore wind turbines. These curtailment strategies are intrinsically linked with pre-existing baseline studies that will follow a risk assessment and determination phase (addressed in more detail in Section 2.1. – Baseline studies). Additionally, they are contingent upon the characteristics and limitations of available technologies required for successful curtailment implementation, spanning from local to regional scales.

It is imperative to recognize that the efficacy of these measures is subject to variation based on the specific attributes of the wind farm, the local bird populations and prevailing environmental conditions. Each strategy may present a distinct set of advantages and constraints.

For an informed decision on curtailment implementation at offshore wind farms, the following information should be considered:

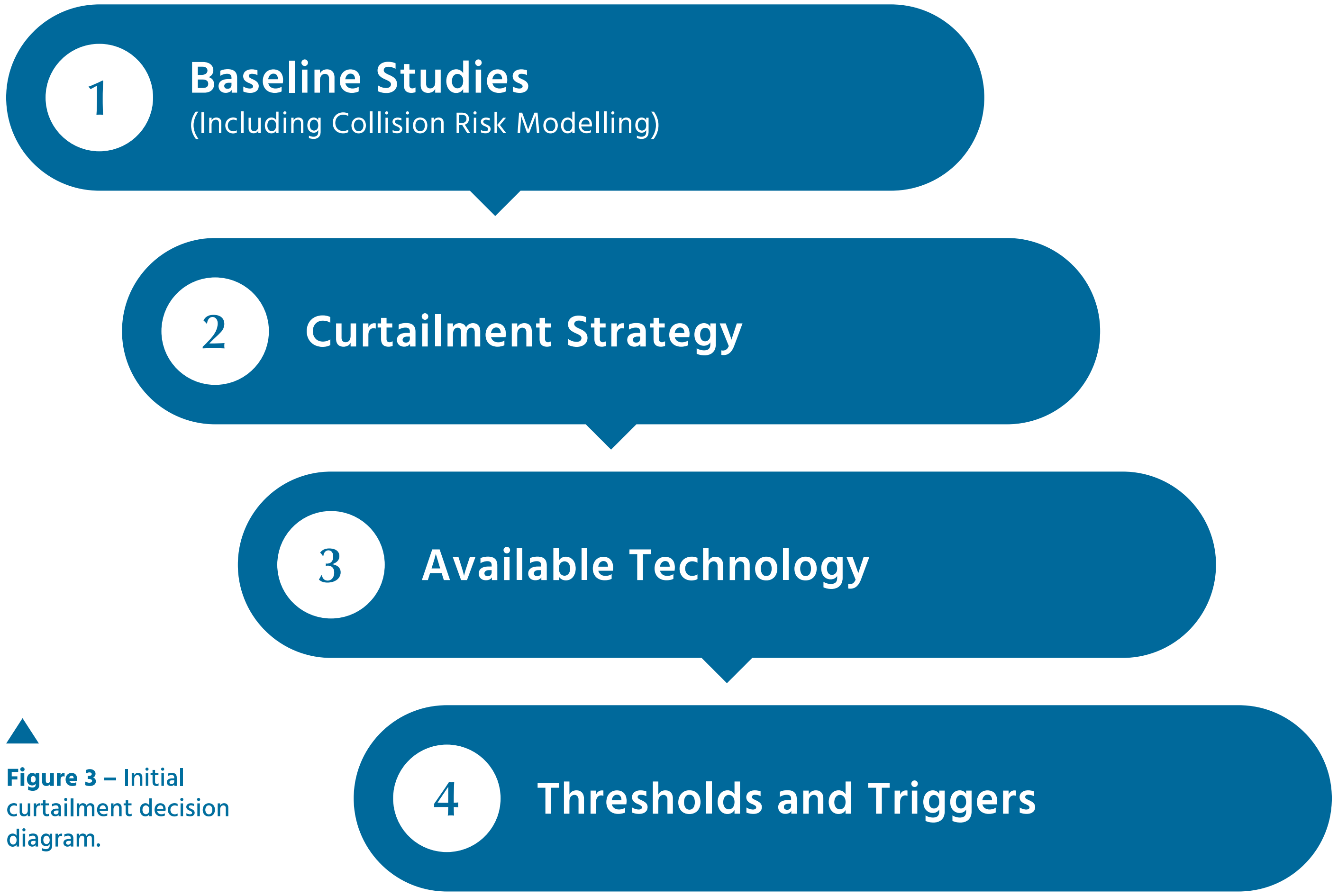


Figure 3 – Initial curtailment decision diagram.

2.1 Baseline Studies

The availability of baseline monitoring studies regarding the ecological impact of offshore wind farms, particularly on bird species, is prevalent in North Sea countries (van Der Kamp *et al.*, 2023). Environmental impact assessment legislation mandates the completion of studies to identify and characterize the environmental risks associated with wind energy developments. The findings from some of these studies and monitoring programs are publicly available and can be used by developers and national authorities for the formulation of mitigation plans and measures, including the implementation of bird curtailment.

Site-specific baseline studies play a crucial role in informing and guiding decision-making processes regarding the most effective approach to curtailment. These studies serve as vital references, aiding in the determination of tailored curtailment measures aimed at mitigating the collision risk associated with an offshore wind development in a particular location.

In the Netherlands, the government has established a comprehensive process for spatial planning and the attainment of good environmental status. This process encompasses the consideration of cumulative ecological effects resulting from existing and planned offshore wind farms across the country. These cumulative effects are addressed within the Framework for Assessing

Image: Great Black-backed Gull © Schrempf2

Ecological and Cumulative Effects (KEC), which identifies bird species vulnerable to collision impacts and estimates the collision-related fatalities among species, including seabirds and migratory species. In addition, the Wozep Ecological Programme, initiated by Rijkswaterstaat, conducts a centralized and long-term research to expand the knowledge about offshore wind farms' impact on protected species, including the impact of collisions on birds.

Therefore, conducting a thorough evaluation of site and region-specific information on collision-sensitive species — those most likely to be affected by collisions — while also considering population-level effects, is crucial for accurately assessing collision risk. This process will facilitate the identification of the species most sensitive to collisions with offshore wind farms at a local level. It enables the development of site-specific curtailment strategies tailored to mitigate the impact on these species. Moreover, it allows for the identification of the most vulnerable periods, such as migration seasons, thereby aiding in the determination of the curtailment approaches to be adopted. These may include species-specific curtailment measures or period-specific curtailment strategies, depending on the identified sensitivities and temporal patterns of species' activities.

In the Netherlands, significant studies have been conducted to evaluate the cumulative impacts of collisions with both existing and planned offshore wind farms in the southern North Sea region. These studies provide estimates of annual collision victims among seabirds and migratory birds (Potiek *et al.*, 2022). By comparing these findings to the species-specific Acceptable Levels of Impact (ALI) established by the Ministry of Agriculture, Nature and Food Quality, it becomes possible to assess the population-level impacts on species affected by collisions.

Detailed information and data of this nature are indispensable for evaluating which species are most likely to experience population-level impacts due to collisions with offshore wind farms. This knowledge allows for the precise targeting of mitigation measures aimed at reducing collision impacts, such as the implementation of curtailment strategies. By leveraging such comprehensive assessments, authorities and stakeholders can effectively prioritize conservation efforts and minimize the ecological impacts of offshore wind energy developments.

The conclusions resulting from baseline studies may determine the need for curtailment measures to be species-specific or species-generalist/period-specific.

Collision Risk Modelling

A critical aspect in assessing and evaluating the impacts of bird collisions is Collision Risk Modelling (CRM). CRM aims to estimate the potential number of bird collisions likely to occur at a given wind farm (Masden, 2015). This modelling framework relies on input parameters related to species-specific biometrics, behaviour, activity, as well as wind farm and turbine-specific information.

The "Band Model", initially developed in 1995 and established in 2012, has become the standard collision risk assessment tool in most European countries for predicting collision risk mortality associated with wind farms. Since its inception it has undergone several modifications and expansions to make it more realistic, flexible and user-friendly. Notably, Johnston *et al.* (2014) proposed an extension to incorporate flight height distributions into calculating collision risk (Extended CRM). Masden (2015) further advanced the approach by incorporating parameter uncertainty and variability into collision estimations, developing the stochastic CRM (sCRM). This approach was made accessible through a user interface application, the Avian Stochastic CRM Shiny App (McGregor *et al.*, 2018). More recently, Caneco *et al.* (2022) expanded on the sCRM framework through the development of the peer-reviewed R-package stochLab: Stochastic Collision Risk Model. This version offers increased computational efficiency compared to the Shiny App and extends the sCRM framework to estimate the collision risk of migratory birds flying through offshore wind farms (mCRM). These advancements in CRM contribute significantly to enhancing our understanding of collision risks associated with offshore wind energy installations and aid in the development of targeted mitigation strategies.

2.2 Curtailment Strategy

The selection and definition of any curtailment strategy should be guided by the preceding step, which involves baseline studies aimed at identifying and characterizing species sensitivity and vulnerability to collisions with offshore wind farms. Ultimately, the implementation of bird curtailment measures should be tailored to the specific circumstances and risks they aim to mitigate.

By first understanding the ecological dynamics and identifying the species most at risk of collision, developers and authorities can make informed decisions regarding the approach and scope of curtailment measures to implement. This approach ensures that resources are allocated effectively and that mitigation efforts are targeted where they are most needed, since collision of bird species with offshore wind turbines may result in population-level impacts on threatened species and tailoring the curtailment approach will achieve the most efficient results.

Information regarding collision-sensitive species identification and their phenology is essential for determining an effective curtailment strategy. Bird curtailment measures can generally be targeted towards specific species or periods, particularly during migration seasons.

During migration periods, there are peak migration intervals when significant numbers of migratory birds traverse offshore wind farms at rotor height, greatly increasing the risk of collision (Hüppop & Hill, 2016; Smallwood & Bell, 2020). In the East Atlantic Flyway, large populations of migratory songbirds and shorebirds cross vast expanses of open sea during migration seasons, often benefiting from supportive tailwinds. This scenario presents a collision threat when offshore wind farms intersect their migratory routes (Bradarić, 2022; Bradarić *et al.*, 2020).

In this crucial flyway, hundreds of millions of birds from, approximately, 250 species migrate across the North Sea. Their migratory paths include routes from north to south, spanning from Scandinavia to southern Europe and Africa, as well as from east to west, crossing from continental Europe to the British Isles. Many of these migrations occur during night-time (Bradarić *et al.*, 2020; Hüppop *et al.*, 2006).

If baseline information suggests a collision risk to specific threatened or sensitive species, either at the national or regional level, then the proposed curtailment strategy must address the species' characteristics, including individual traits, presence in the offshore wind farm area and phenology (Figure 4).

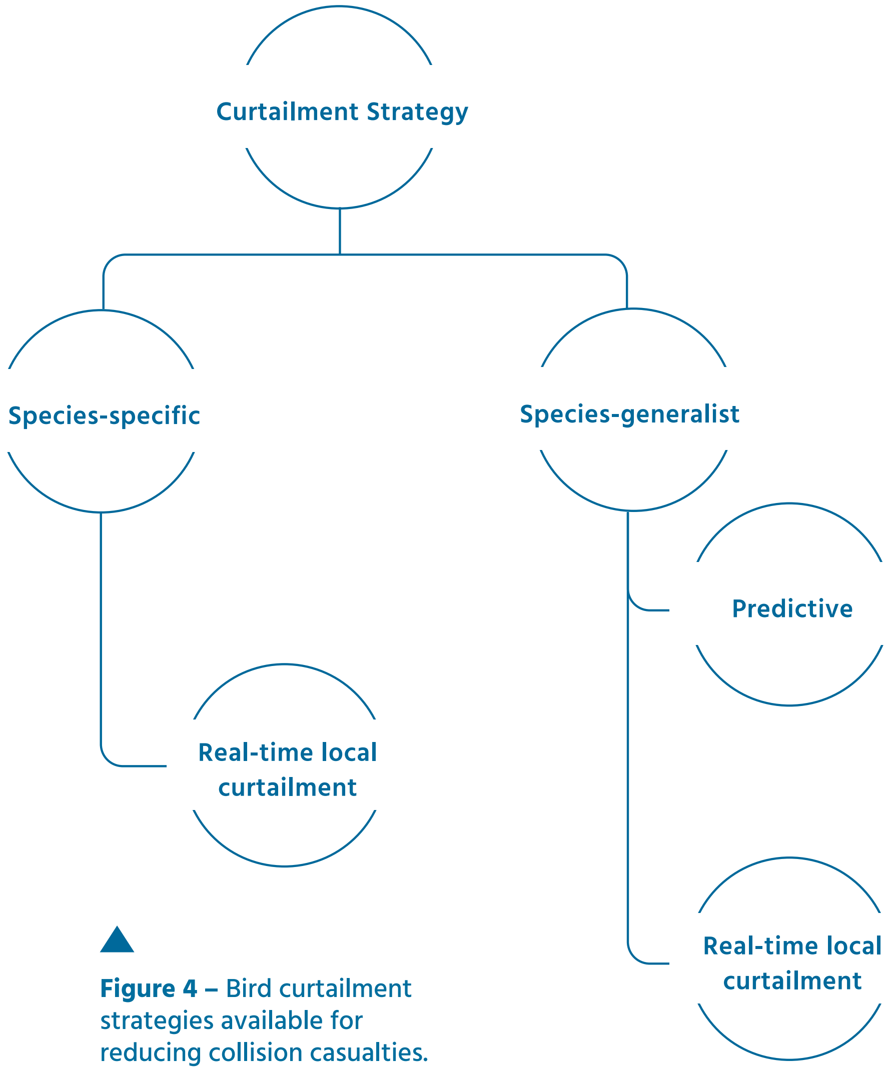


Figure 4 – Bird curtailment strategies available for reducing collision casualties.

2.2.1 Species-specific Curtailment

Species-specific curtailment, as an approach to reduce collisions of target species with offshore wind turbines requires, above other information, the real-time identification of the target species. Further information from baseline studies is required to accurately identify the most vulnerable species within an area and thus determine the best curtailment strategy to reduce this risk.

Further detailed in Section 2.2.3 Available Technology and Chapter 3 Monitoring Technologies, we identify the available technology and parameters gathered that provide essential information to determine and implement a species-specific curtailment or shutdown on demand. This approach requires, most importantly, the identification of real-time collision risk of target species, given by the species identification firstly and later from the determination of flight height and direction in relation to the rotor swept area.

Species-specific curtailment requires the implementation of an array of cameras to enable real-time species identification and radar systems to determine the target species individual's position in relation to the wind turbine and ultimately allow the order to shutdown turbines. Information such as Mean Traffic Rate (MTR) is not particularly useful in this approach as the current technology does not allow the determination of species-specific MTR.

This approach has been implemented most typically in onshore wind farms, either based on automated technology, such as cameras and radars, or a combination of technology and human observers.

Empirical data regarding the impact of wind farms on local seabirds and migratory birds due to collision is limited; operational and technological limitations contribute to this knowledge gap. Further technological developments are required to achieve a better comprehension of how birds interact with offshore wind farms. Presently, a seabird study is underway at the Neart na Gaoithe Offshore Wind Farm in Scotland that aims to provide valuable insights into the interaction between birds and offshore wind infrastructure. Its objective is to monitor the flight patterns of two target species - the Northern gannet and the Black-legged kittiwake - to gain a deeper understanding of their behaviour in the vicinity of offshore wind turbines as well as to track and document actual collisions of seabirds with turbines. However, studies have been conducted on the avoidance behaviour of various species, resulting

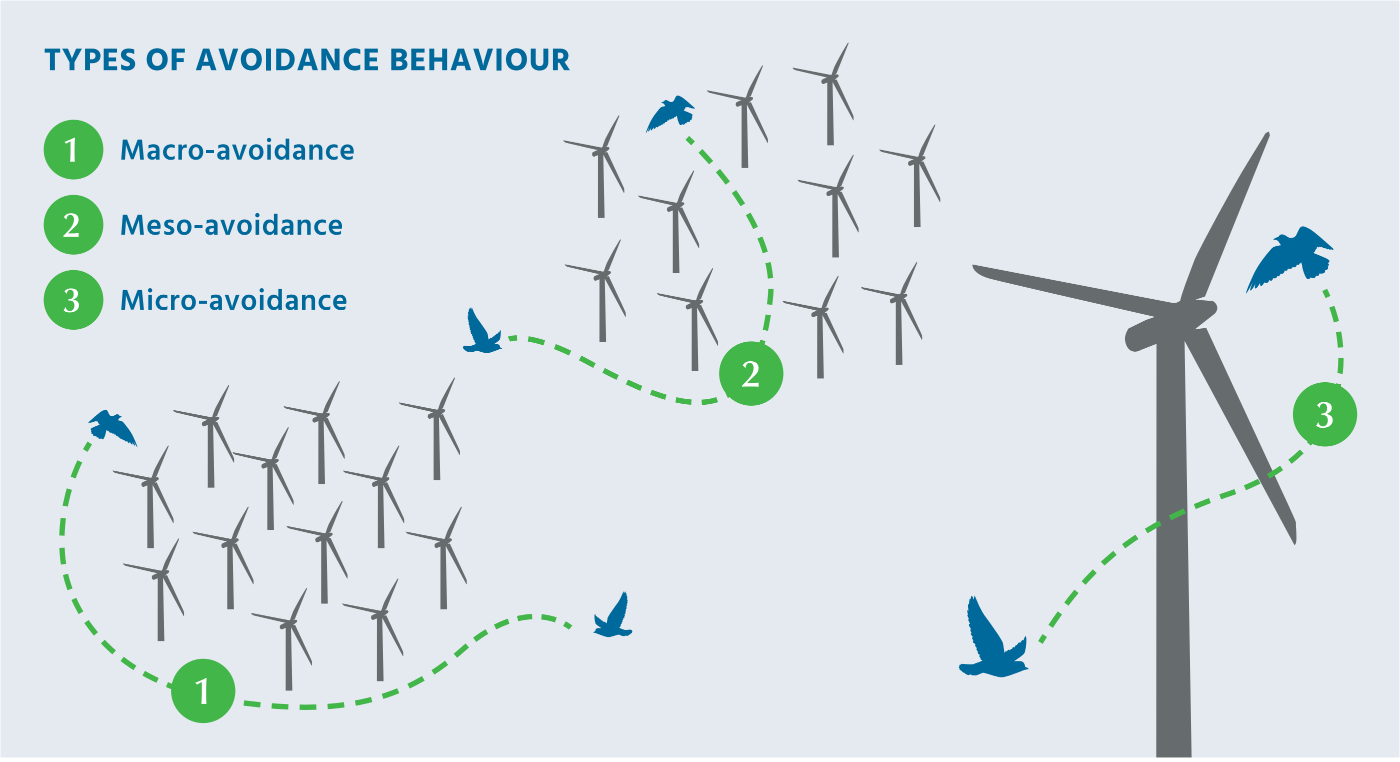


Figure 5 – Types of avoidance by birds in the vicinity of wind turbines

in species-specific avoidance rates categorized into macro-, meso- and micro avoidance types (Leopold *et al.*, 2011; Peschko *et al.*, 2020; Tjørnløv *et al.*, 2023). Macro-avoidance refers to avoidance of wind farms as a whole, meso-avoidance pertains to avoidance of individual wind turbines, or turbine rows, within the wind farm and micro-avoidance involves "last-second" actions to avoid collision by adjusting flight paths vertically and/or horizontally (Woodward *et al.*, 2023).

Empirical studies on bird collisions with offshore wind turbines are limited due to operational and technological constraints, related with the challenges of i) monitoring collision events in harsh offshore environments and ii) gathering evidence of collision without remote-operated technology, as carcasses are unlikely to remain detectable when they fall in the water. However, data from a 2-year study in a Scottish offshore wind farm recorded zero collisions during the survey period for five target seabird species: Northern gannet, Lesser black-backed gull, Herring gull, Great black-backed gull and Black-legged kittiwake (Tjørnløv *et al.*, 2023). In the Netherlands, the WOZEP research program has identified several research goals for the period 2024-2030, including studies on the use of the North Sea as a migratory corridor to inform nocturnal migration prediction models (van Nieuwpoort *et al.*, 2023).

Studies comparing wind farms with different layouts have shown variations in avoidance behaviour among species. Divers, great crested grebes, common scoters and common/arctic terns exhibited significant avoidance behaviour, while other species such as common gulls, lesser and great black-backed gulls, black-legged kittiwakes and herring gulls showed little to no effect from wind farms (Leopold *et al.*, 2011, 2013). Likewise, research conducted during the breeding season of the Northern gannet and Common guillemot revealed that both species primarily avoided wind farms. However, those northern gannets that forage within wind farms were more prone to collisions due to flying at rotor blade height (Peschko *et al.*, 2020, 2021).

Increased avoidance behaviour may result in displacement and loss of foraging habitat, whereas species with poor avoidance will be more vulnerable to collisions. Species at higher risk of collisions in offshore environments include seabirds, especially those that fly at higher altitudes, those associated with the marine environment, waterfowl, shorebirds and other terrestrial species such as raptors and common cranes (Furness *et al.*, 2013; Leopold *et al.*, 2013; Piggott *et al.*, 2021).

Based on studies prepared for the North and Baltic Sea and the Portuguese coast, a summary of most sensitive species to collision is compiled in Table 1 (Guilherme *et al.*, 2023; Piggott *et al.*, 2021):

TABLE 1

Summary of collision risk (vulnerability) for bird species in the North Sea, Baltic Sea and Portuguese coast, as defined by Guilherme *et al.* (2023) and Piggott *et al.* (2021). (V.HIGH – very high collision risk; MOD – moderate; V.LOW – very low; N.A. – not assessed in the respective study; Collision Vulnerability in Portugal was represented as a figure from 0 to 1, with 1 representing the maximum vulnerability).

Common name	Species	North Sea and Baltic Sea (Piggott *et al.*, 2021)	Portuguese coast (Guilherme *et al.*, 2023)
Common Scoter	*Melanitta nigra*	LOW	0.35
Common Goldeneye	*Bucephala clangula*	LOW	N.A.
Goosander	*Mergus merganser*	LOW	N.A.
Greater Scaup	*Aythya marila*	LOW	N.A.
Red-throated Loon	*Gavia stellata*	LOW	N.A.
Arctic Loon	*Gavia arctica*	LOW	N.A.
Yellow-billed Loon	*Gavia adamsii*	LOW	N.A.
Wilson's Storm-petrel	*Oceanites oceanicus*	N.A.	0.4
European Storm-petrel	*Hydrobates pelagicus*	Uncertain	0.35
Band-rumped Storm-petrel	*Hydrobates castro*	N.A.	0.4
Sooty Shearwater	*Ardenna grisea*	Uncertain	0.38
Great Shearwater	*Ardenna gravis*	N.A.	0.38
Cory's Shearwater	*Calonectris borealis*	N.A.	0.31
Manx Shearwater	*Puffinus puffinus*	V.LOW	0.28

Common name	Species	North Sea and Baltic Sea (Piggott *et al.*, 2021)	Portuguese coast (Guilherme *et al.*, 2023)
Balearic Shearwater	*Puffinus mauretanicus*	**N.A.**	**0.32**
Bulwer's Petrel	*Bulweria bulwerii*	**N.A.**	**0.45**
Northern Gannet	*Morus bassanus*	**HIGH**	**0.44**
European Shag	*Gulosus aristotelis*	**MOD**	**0.49**
Great Cormorant	*Phalacrocorax carbo*	**MOD**	**0.4**
Red Phalarope	*Phalaropus fulicarius*	**MOD**	**0.25**
Little Gull	*Hydrocoloeus minutus*	**HIGH**	**0.41**
Sabine's Gull	*Xema sabini*	**HIGH**	**0.41**
Black-legged Kittiwake	*Rissa tridactyla*	**HIGH**	**0.27**
Black-headed Gull	*Larus ridibundus*	**HIGH**	**0.27**
Mediterranean Gull	*Larus melanocephalus*	**HIGH**	**0.41**
Audouin's Gull	*Larus audouinii*	**N.A.**	**0.56**
Mew Gull	*Larus canus*	**HIGH**	**N.A.**
Lesser Black-backed Gull	*Larus fuscus*	**V.HIGH**	**0.37**
European Herring Gull	*Larus argentatus*	**V.HIGH**	**N.A.**

Common name	Species	North Sea and Baltic Sea (Piggott *et al.*, 2021)	Portuguese coast (Guilherme *et al.*, 2023)
Yellow-legged Gull	*Larus michahellis*	**Unknown**	**0.45**
Iceland Gull	*Larus glaucoides*	**V.HIGH**	**N.A.**
Glaucous Gull	*Larus hyperboreus*	**V.HIGH**	**N.A.**
Great Black-backed Gull	*Larus marinus*	**V.HIGH**	**0.63**
Little Tern	*Sternula albifrons*	**MOD**	**0.27**
Black Tern	*Chlidonias niger*	**MOD**	**0.27**
Common Tern	*Sterna hirundo*	**MOD**	**0.52**
Arctic Tern	*Sterna paradisaea*	**LOW**	**0.32**
Sandwich Tern	*Thalasseus sandvicensis*	**MOD**	**0.52**
Arctic Jaeger	*Stercorarius parasiticus*	**MOD**	**0.37**
Pomarine Jaeger	*Stercorarius pomarinus*	**MOD**	**0.37**
Great Skua	*Catharacta skua*	**MOD**	**0.25**
Atlantic Puffin	*Fratercula arctica*	**V.LOW**	**0.23**
Razorbill	*Alca torda*	**V.LOW**	**0.2**
Common Murre	*Uria aalge*	**V.LOW**	**0.26**

2.2.2 Species-generalist or Period-specific Curtailment – Migratory Birds

Although there are indications that some migrating birds may avoid wind farms (Larsson, 1994), soaring bird species have been shown to be attracted to offshore wind farms (Skov *et al.*, 2016). Higher collision risks for migratory birds are typically associated with bird species exhibiting attraction behaviour towards offshore wind farms and/or engaging in high-intensity migration (Brabant *et al.*, 2015; Hill *et al.*, 2014; Petersen *et al.*, 2006; Shinneman *et al.*, 2020).

Data collected at various offshore wind farms in the North Sea revealed high fluxes of nocturnal migratory birds during autumn and spring, corresponding to post- and pre-breeding seasons. These migrations predominantly consist of songbirds such as thrushes and small passerines (Degraer *et al.*, 2023; Fijn *et al.*, 2015; Krijgsveld *et al.*, 2011). Consequently, appropriate curtailment strategies aimed at reducing collisions of terrestrial migratory bird species, such as songbirds, should be implemented during periods of predicted peak migration. Other migratory bird species, including divers, gannets, cormorants, dabbling ducks, common eiders, common scoters, oystercatchers, red knots, skuas, auks, terns and gulls, have been observed near or within offshore wind farms, particularly during autumn (Petersen *et al.*, 2006).

Understanding bird migration patterns and predicting intense fluxes necessitates an understanding of birds' reactions to weather conditions. Bradarić *et al.*, (2020) found that seasonal wind regimes over the North Sea influence migratory dynamics, altering headings, timing and intensity of migration. Intense migration nights are characterized by lower wind speeds in autumn (6 m/s) compared to spring (10.1 m/s), with mean wind directions towards the East in spring and towards the Southwest in autumn. Adverse weather conditions, such as dense clouds, persistent precipitation, or fog, can reduce visibility for birds, potentially leading to attraction to light sources and increased collision risk (Aumüller *et al.*, 2011; Hill *et al.*, 2014).

Determining the right timing and spatial extent of curtailment measures is crucial for their effectiveness (Shinneman *et al.*, 2020). This requires understanding migratory movements and how local and regional weather conditions affect them seasonally and hinges on specific data parameters that allow to precisely target curtailment towards particular periods in time where bird movements pose a higher risk of collision. Moreover, it's imperative to consider technology requirements, honed through development and testing in both offshore and onshore settings (these technology requirements are addressed in more detail in Section 3 – Monitoring Technologies).

Following the definition of curtailment strategies grounded in ecological and behavioural insights, a secondary layer of decision-making emerges. This entails determining which turbines are affected by the curtailment measures—whether a subset or all turbines within the wind farm layout. A reactive strategy (real-time local curtailment) may lead to curtailment being applied to a reduced number of turbines in the path of flying birds at risk of collision (but may extend to encompass all of the windfarm's turbines), whereas a predictive strategy may determine the curtailment of all turbines in the wind farm layout, based on migration predictive models.

Image: Turbines on North Sea coast © Bennett Tobias

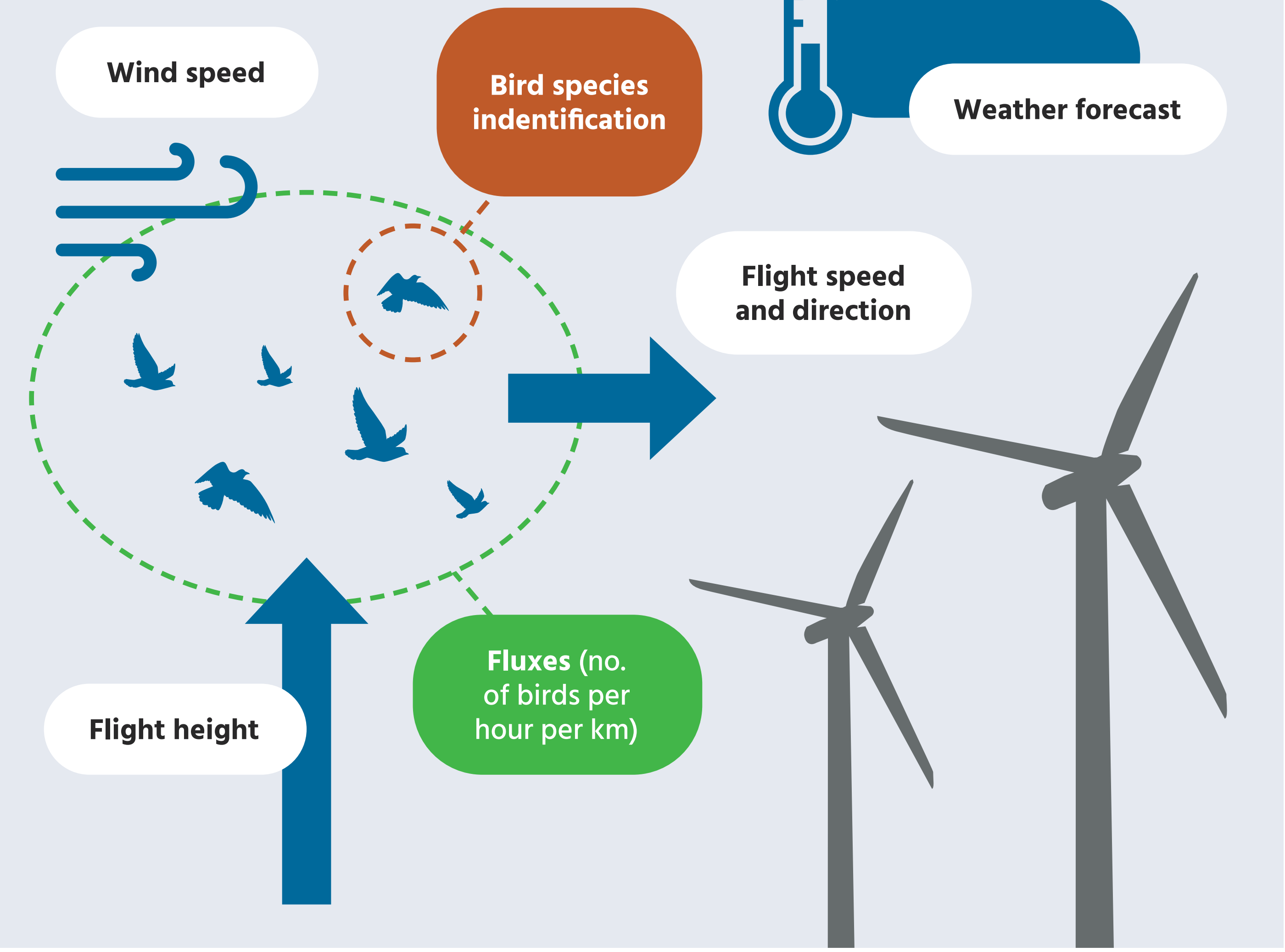
2.2.3 Available Technology

The successful implementation of any curtailment strategy at offshore wind farms hinges on the current technological capabilities, be it targeted at species-specific or species-generalist collision reduction (Skov *et al.*, 2023). Information garnered from various available sensors is crucial not only for predicting peak migration periods (predictive strategy) but also for pinpointing critical periods of bird activity at risk of collision within the offshore wind farm (real-time local curtailment).

The former is associated with a species-generalist curtailment strategy, while the latter pertains to species-specific and species-generalist curtailment strategies. Technology also plays a pivotal role in monitoring the effectiveness of curtailment strategies, particularly in validating the accuracy of predicted periods of peak migration and actual collisions.

The selection and deployment of sensors are intricately linked to the definition and execution of the curtailment strategy and subsequently, to the parameters they capture. Among these, certain parameters are deemed particularly significant: Flight height; Fluxes (number of birds per hour per kilometre); Flight speed; Species identification; Flight direction; Weather forecast; Wind speed.

Figure 6: Key sensor-gathered parameters for informing bird curtailment



To effectively gather this information concerning the temporal and spatial dynamics of bird species within offshore wind farms, the following scheme encapsulates the correlation between the curtailment strategy and its required parameters:

TABLE 2

Summary of sensor-gathered parameters to inform different curtailment strategies: predictive and real-time local curtailment. (* - less important to * - more important).**

Parameter	Predictive curtailment	Real-time local curtailment	Note
Flight height	***	***	Informs of the presence of target species at collision risk height
Fluxes	**	***	Informs the predicted or verified bird flux (birds/km/hour) to determine shutdown or curtailment
Flight speed	*	***	Information on the time predicted for the target to enter a trigger area.
Species identification	*	***	Allows for a species-specific curtailment strategy.
Flight direction	**	***	Allows the risk assessment of a given track either flying towards a turbine or not.
Weather forecast	***	*	Inputs to peak migration predictive model
Wind speed	***	**	Inputs to peak migration predictive model and real-time local curtailment strategy as seabirds flight behaviour is affected by wind speed

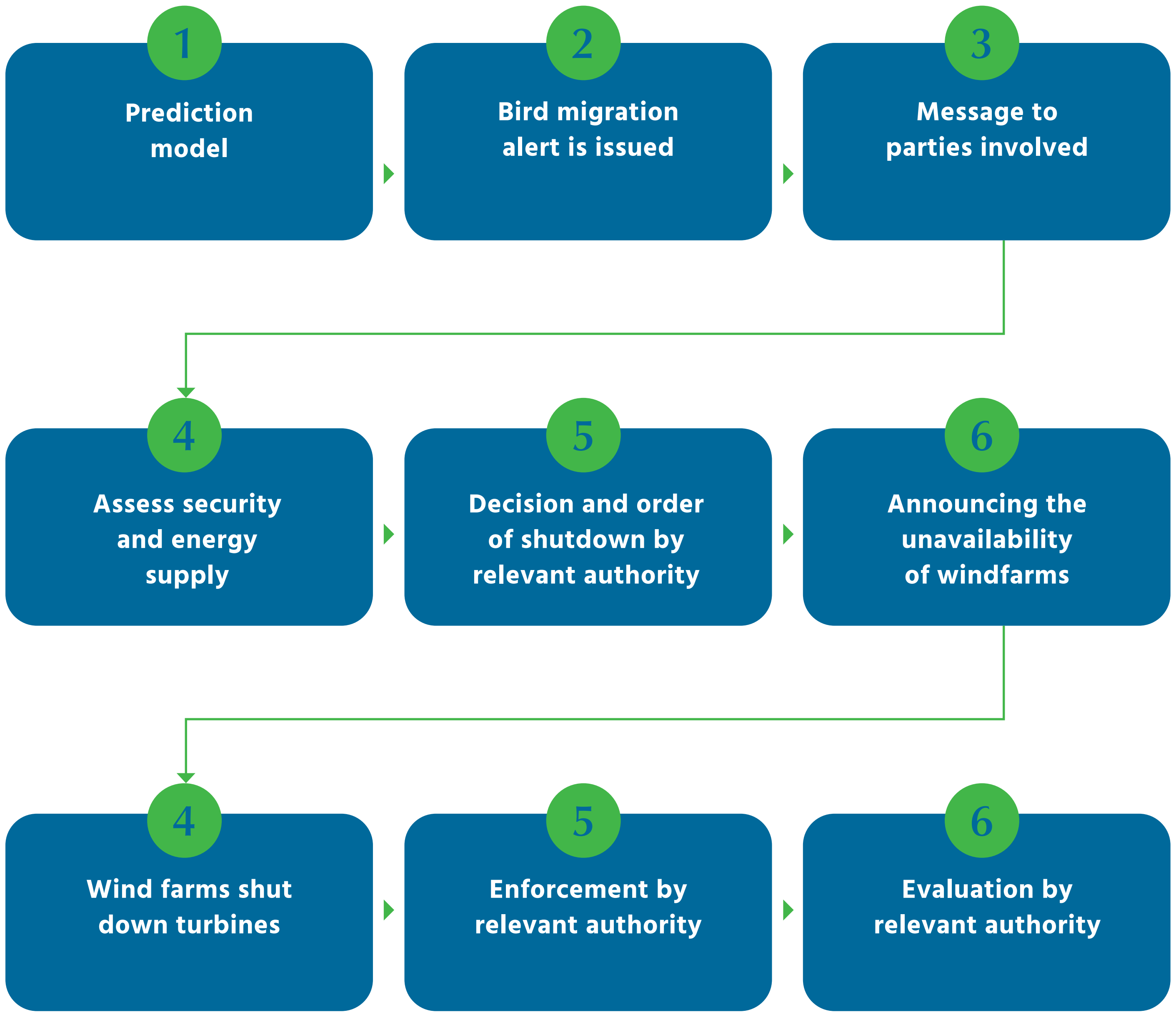


Figure 7 – Infographic of a shutdown process informed by a predictive curtailment strategy (based on the Start/Stop project - https://www.noordzeeloket.nl/en/functions-and-use/offshore-wind-energy/start-stop/).

The operationalization of the curtailment strategy can occur automatically, contingent upon the information collected by sensors. This typically involves the detection of a predefined set of conditions, triggering the issuance of a curtailment order (real-time local curtailment). Alternatively, a second approach entails issuing the curtailment order after results from a prediction model have been assessed and evaluated by various stakeholders involved in the process (predictive), as exemplified by the Start/Stop project in the Netherlands (Figure 5).

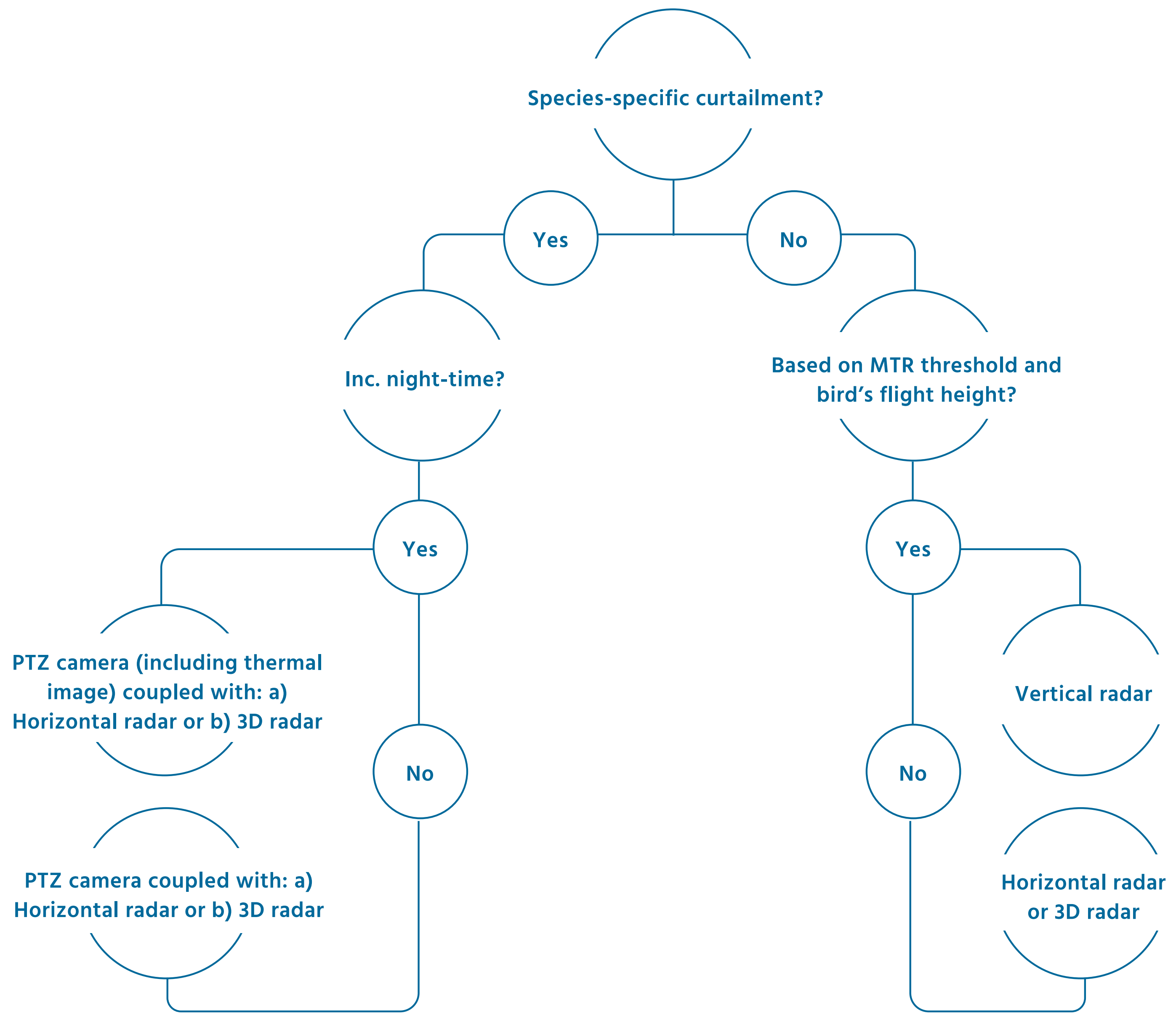


Figure 8 – Schematic visualisation of curtailment strategy in relation to technology requirements (adapted from Skov *et al.*, 2023).

Innovative technological advancements are being pursued to mitigate collision risks associated with wind turbines, including adjusting rotor speeds in response to the presence or detection of specific bird species, thereby minimizing the likelihood of collisions. While this option is currently in the developmental stage, its successful implementation hinges on the integration of monitoring sensors, such as cameras, to detect target bird species approaching the turbines.

Curtailment strategies operate under the assumption of reducing casualties resulting from collisions with wind turbines, achieved through the shutdown or curtailment of turbines when predetermined criteria are met. In the predictive curtailment strategy, turbine shutdown is triggered by a predictive model based on information gathered by sensors (Bradarić, 2022). Conversely, the real-time local curtailment strategy relies on the detection of a target species within the wind farm array or its vicinity, indicating an imminent collision risk. An approach to selecting a curtailment strategy and the associated technology requirements is outlined in Figure 6 (Skov *et al.*, 2023).

2.2.4 Thresholds and Triggers

The definition of thresholds and triggers should be site-specific, ensuring an accurate representation of the ecological conditions within the wind farm area or the broader region, such as the North Sea.

Thresholds are established based on risk assessments, defining conditions under which curtailment measures will be activated. Triggers are set to initiate curtailment when specific conditions are met.

Drawing from the current knowledge available for the Dutch part of the North Sea, exceptional peaks of songbird migration are estimated to exceed a Mean Traffic Rate of 500 birds/km/hour at rotor height. This estimation is derived from vertical radar measurements at the Egmond aan Zee Offshore Wind Farm (OWEZ) (Krijgsveld *et al.*, 2011). This MTR of 500 birds/km/hour was set by the Dutch government and reflects an effort to find a balance between the number of birds saved and the amount of energy production lost. Consequently, the MTR emerges as a crucial parameter for triggering both real-time local curtailment and predictive curtailment measures.

Other triggers, particularly utilized for real-time local curtailment, may encompass the detection of individuals from target species flying at rotor height towards the wind farm. In this scenario, the number of individuals may also serve as a trigger or criteria, subject to evaluation during the curtailment strategy definition phase (Cook *et al.*, 2011).

Deciding on criteria and triggers is a pivotal aspect that hinges uon the chosen curtailment strategy. This decision could be based on various factors, including predictive models for peak migration, the detection of a pre-established MTR at collision height, or the identification of target species at risk of collision.

Considering the currently implemented curtailment strategies in offshore wind farms in Europe, aiming to reduce collision casualties of birds during peak migration nights, the main trigger used to determine curtailment is the MTR (van Bemmelen *et al.*, 2022). This threshold, often established or proposed by governmental authorities, draws from radar studies conducted on offshore wind farms, exemplified by the study at the Egmond aan Zee offshore wind farm. This study revealed higher migratory intensity during autumn and spring nights, with migration fluxes peaking during periods of tailwind and wind speeds of 4 Bft on the Beaufort Wind Scale (Krijgsveld *et al.*, 2011). Krijgsveld *et al.* (2011) reported an average MTR of 80 bird groups/km/hr throughout the year, with peak hours exceeding 3,600 bird groups/km/hour (bird groups defined as number of individual radar tracks). Based on these findings, the Dutch Ministry of Economic Affairs and Climate (EZK) established a threshold of 500 birds/km/hour, equivalent to 3.8% of the total flux over the year (van Bemmelen *et al.*, 2022). Further refinement of curtailment thresholds is recommended to explore the relationship between wind speed, bird migration intensity, power yield and model predictions.

van Bemmelen *et al.* (2022) also proposed the determination of curtailment rules, where curtailment thresholds could be optimized to minimize energy generation loss for varying percentages of collision avoidance, based on the relationship between migration intensity and wind speed. Generally, the results indicate that curtailment during low speeds results in a higher percentage of collisions avoided with relatively low energy production losses. The conclusion suggests adjusting thresholds based on wind speed categories as opposed to the current simple threshold approach.

2.3 Curtailment Implementation

Curtailment implementation in the context of offshore wind farms entails the adoption of measures aimed at mitigating the risk of bird collisions with wind turbines. Various approaches exist, each with its own set of advantages and constraints. It's essential to acknowledge that the efficacy of these measures' hinges on the specific characteristics of the wind farm, local bird populations and environmental factors. Curtailment can be executed at different levels and scales, contingent upon the collision risk assessment:


Image © Dev Kalidhasan

- **Single offshore wind farm** – curtailment can be initiated across all turbines simultaneously or selectively on turbines positioned directly in the flight path of the target species or migration corridor (Cook *et al.*, 2011);
- **Group of offshore wind farms** – curtailment may encompass several offshore wind farms situated along migration routes, akin to the objectives of the Start/Stop project. This approach relies on the development and subsequent validation of site-specific predictive models capable of accurately forecasting peak avian migration across various buffer zones from the coast;
- **Large-scale** – this curtailment method requires additional research and model refinement to accurately forecast peak migrations on a large scale and requires collaboration among wind farm owners, grid operators and environmental agencies across multiple countries. Considerations such as the time delay in implementing curtailment measures are relevant in this context. Enhanced cooperation among nations to facilitate the implementation of consecutive shutdowns, strategically planned to ensure international grid stability, is integral to the curtailment strategy. Prior to considering a large-scale international curtailment strategy, it is essential to refine bird migration predictive models, by expanding existing models to cover larger geographic areas and integrating additional information and measures.

Image © Theodor Vasile

2.4 Relevant Stakeholders in Curtailment

In the context of bird curtailment strategies within offshore wind farms, relevant stakeholders have been identified and classified into three tiers based on their degree of involvement:

1

Tier 1 organizations are directly responsible for the implementation, monitoring and evaluation of curtailment strategies.

a. Offshore wind energy developers & Operators (Developers & Operators)

b. Transmission System Operators (TSO)

c. Regulators (including national environmental agencies)

2

Tier 2 organizations contribute to improving and enhancing curtailment strategies, advocate for their adoption at various levels (national to regional) and conduct complementary research to address knowledge gaps related to bird species' interaction with offshore wind farms.

a. International Financial Institutions (IFI)

b. Non-Governmental Organizations (NGOs) and Research Institutions

c. Political entities

3

Tier 3 organizations are indirectly involved in bird curtailment implementation. They develop and provide the necessary technology for informing and executing bird curtailment measures. They may also need to be consulted regarding any objections or limitations related to technology implementation and curtailment, as is the case with military organizations and wind turbine generator (WTG) constructors.

a. Military

b. Engineering, Procurement and Construction

c. Consultants

Within this study, stakeholders from Tier 1 were contacted in order to collect information on curtailment strategies' development, implementation and limitations.

SECTION THREE MONITORING TECHNOLOGIES


Glaucous Gull © Yves Adams

This section offers an overview of methodologies and technologies currently available for monitoring seabird activity in offshore areas to inform the establishment of curtailment specifications, such as the variables used to set thresholds for curtailment, the implementation of curtailment measures, and the monitoring of their effectiveness. The information presented here results from peer-reviewed articles, publicly available monitoring reports and expert answers to questionnaires.

The technologies identified in this section can inform curtailment implementation across different stages, starting from baseline studies to monitoring curtailment efficiency. The following three stages are considered:

1. **Baseline characterization –** This initial phase is crucial for gathering site-specific data related to species composition, their spatial and temporal patterns of occurrence and behaviour. This information is essential for identifying the necessity of curtailment measures, contributing to the curtailment strategy decision-making process and determining the most suitable curtailment approach. During this stage, technologies and methodologies can provide critical data to ascertain species vulnerability to collision at the specific site and characterize their presence within the area.

2. **Curtailment development and implementation –** In this phase, the focus shifts to technologies that enable real-time determination of curtailment measures. These technologies inform decision-makers regarding the optimal timing for implementing curtailment or shutting down turbines, such as during peak migration periods or in the presence of sensitive species.

3. **Curtailment monitoring –** During this stage, we identify technologies that can provide site-specific information to evaluate the effectiveness of curtailment measures.

TABLE 3

Overview of currently available monitoring methodologies and technologies and their respective use on the different phases of curtailment development, implementation and monitoring.

Technology/Methodology	Baseline Characterization	Curtailment Development and Implementation	Curtailment Monitoring
ESAS	Y		
Radar	Y	Y	Y
Digital Cameras		Y	Y
Acoustic Sensors	Y		Y
Telemetry	Y		
Vibro-acoustic Sensors			Y
Digital cameras – collision detection			Y

Image: Northern Gannet

3.1 European Seabirds at Sea (ESAS)

The ESAS methodology aims to compile offshore monitoring data of seabirds and marine mammals gathered through specific methodologies, such as aerial or ship-based surveys at sea. This approach allows for the determination of georeferenced seabird densities and provides additional information such as flight height and distance, behavioural characteristics and individual traits like age and plumage (Camphuysen *et al.*, 2004).

Digital aerial surveys, which utilize high-definition cameras to monitor seabird and marine mammal activity at sea, have recently become a preferred and standard option (Leopold *et al.*, 2011; Žydelis *et al.*, 2019); in the UK and Germany they have replaced previous methods involving human observers on ships or aerial surveys. This transition has also occurred in other countries bordering the North Sea and the Baltic Sea (Leopold *et al.*, 2021). The main advantages of digital aerial surveys over other methodologies include increased coverage and detectability of individuals, as well as a reduction in disturbance and observer bias (Žydelis *et al.*, 2019).

Data collected using this methodology plays a crucial role in accurately assessing the risk of collision with offshore wind farms for bird species. It helps characterize the impact area in terms of species composition and their temporal variations in occurrence and abundance. This information enables the development of site-specific curtailment strategies to mitigate collision risks.

Image: Strix International, radar © Birdtrack

3.2 Radar

Radar technology has made significant contributions to understanding and characterizing avian movement as it can accurately determine the number and intensity of avian movements over continuous periods of time (Bradarić, 2022; Skov *et al.*, 2023; van Erp *et al.*, 2023). This technology provides crucial information for assessing avian collision risk on a large spatial scale and is independent of seasonal effects, such as time of year or day/night periods (Drewitt & Langston, 2006; Nicholls *et al.*, 2022; Skov *et al.*, 2023).

Radar technology operates by transmitting and receiving radio waves which interact with surrounding objects. These objects can be stationary, like topographic and environmental features, or moving targets, such as birds. The unique characteristics of these objects, along with the time elapsed between the transmission and reception of radio waves, determine the parameters collected by radars (Lagerveld *et al.*, 2020). The choice of radar mode, whether horizontal or vertical, determines the type of data collected. Horizontal surveillance enables monitoring in a two-dimensional spatial pattern, while vertical surveillance gathers altitude and altitude-related data (Table 4). In offshore environments, marine X-band and S-band radars are typically used. The S-band radar is less susceptible to negative influences from weather conditions, such as precipitation and waves (Drewitt & Langston, 2006; Nicholls *et al.*, 2022; Skov *et al.*, 2023).

Radars can operate in horizontal, vertical, or combined modes, allowing the recording of key parameters essential for assessing and determining curtailment measures. These parameters include distance from the radar, flight path, flight direction, flight height, flight speed, flux and size of the target (Table 4; Lagerveld *et al.*, 2020). Depending on the technical specifications of the selected hardware, radars provide solutions to monitor seabird activity ranging from a few hundred meters up to 240 km (Skov, 2023). Typically, the maximum range for horizontal avian monitoring radars is approximately 12 km for larger species (Lagerveld *et al.*, 2020). The detection range of the radar system is closely linked to its capacity to detect and track targets; as radar detection range increases, the capacity to detect and track smaller targets decreases. Definitions settings in radar technology are strictly linked to the equipment capacity to detect and track birds at different range distances (Skov *et al.*, 2023).

The utilization of radar technology in the offshore environment is essential for gathering site-specific data on avian movement. It enables the collection of key parameters necessary to inform curtailment strategies, whether based on predictive models or reacting to real-time conditions in an offshore wind farm.

TABLE 4

Summary of key parameters measured by horizontal and vertical radars in offshore environment. Minimal detection range and height clearance were estimated for World Meteorological Organization sea state code 0-1.

Parameters	Horizontal Radar	Vertical Radar
Mean Traffic Rate (MTR)	Y	Y
Flight direction	Y	N
Flight speed	Y	N
Flight height	N	Y
Distance to radar	Y	Y
Position (coordinates)	Y	N
Minimal detection distance	600 m	-
Height clearance (ASL)	3-5 m	20 m
Range	6-7 km	6-7 km

The deployment of radars in the North Sea for ornithological studies addressing the implementation of curtailment during peak migration periods, indicates that the operation mode of radars, whether vertical or horizontal, differ in their ability to filter out non-bird objects, such as waves and rain. Estimates of MTR based on horizontal and vertical radars result in lower MTRs being estimated when relatively high waves, above 1 meter, are present, whereas the occurrence of rain might pose limitations for vertical radar (Kraal *et al.*, 2023).

Weather radars boast a larger range compared to standard avian radar technology, extending up to 200 km (Cohen *et al.*, 2022; Skov *et al.*, 2023). In the effort to mitigate the impact of bird collisions with wind turbines, weather surveillance radars provide valuable data to pinpoint areas of high-intensity bird activity at rotor height (Cohen *et al.*, 2022). While this information may not always directly trigger real-time shutdowns or curtailment, it serves as a crucial tool to identify sensitive areas and periods prone to avian collisions at wind farms.

Weather radars deployed across wider regions, such as sea basins, can offer detailed insights into avian movement, particularly aiding in the prediction of high-intensity migration periods. This is exemplified by Start/Stop project, initiated by the Noordezeeloket in the Netherlands. In this project, data collected by avian radars are used in bird migration predictive models specific to the Netherlands. These models inform about the expected flux of bird migration at rotor height, leveraging real-time weather forecasts. Consequently, the project enables the prediction of periods (nights), during which high-intensity bird migration is anticipated in offshore areas. This information is crucial for determining the shutdown of turbines during these periods, thereby mitigating collision risks.

Avian monitoring with radar technology, combined with environmental information, such as weather data, provide crucial data to inform bird migration predictive models, such as the one developed by the University of Amsterdam (UvA) (Bradarić, 2022). This model utilizes machine learning techniques to predict bird migration over the North Sea, considering conditions along the migration route from departure to destination areas. This model makes use of actual avian radar measurements in the Luchterduinen offshore wind farm in the North Sea, as well as other environmental and weather data to determine yield predictions of bird migration intensity, typically measured as MTR.

3.3 Digital Cameras

Digital cameras are extensively employed, on both onshore and offshore wind farms, to monitor bird activity and behaviour around the clock, including nighttime observations facilitated by thermal technology (Skov *et al.*, 2018). Often integrated with Artificial Intelligence (AI) algorithms, these cameras enable automatic species identification, facilitating the determination of daytime species composition within wind farms. This technology complements other monitoring tools such as radar, which becomes particularly valuable when curtailment or shutdown measures are tailored to specific species or groups of species.

The ongoing advancements in AI enable more accurate and efficient detection and identification of bird species within images, thereby reducing the time required for species identification. However, it's crucial to acknowledge the importance of targeted identification efforts by ornithologists to further enhance the robustness of the technology and identification algorithms. Presently, operations incorporate a review process by ornithologists of images flagged as birds by AI, ensuring accuracy and reliability in species identification. This collaboration between AI technology and human expertise ensures a comprehensive approach to bird monitoring and conservation efforts.

Real-time determination of the presence of selected species, based on collision vulnerability or conservation importance, may be


Red Phalarope © Lars Soerink

of importance to determine the implementation of curtailment measures and prevent collision of species. Video cameras have the limitation of distance to targets influencing its detection and identification, as distant birds are not always detectable or recognisable. Different setups of cameras available for offshore integration result in variation of detection range from a few meters to hundreds of meters (Nicholls *et al.*, 2022).

The choice between different digital camera technologies, such as fixed versus moving angles of view or fixed aperture versus zoom cameras, significantly impacts the area and distance covered by the technology. Fixed-angle and fixed aperture digital cameras are typically used to cover short distances, whereas those with moving angles can cover larger distances and allow for zooming on specific targets.

Integration of video cameras with radar systems enables the association of radar tracks with video camera images, linking radar-specific data such as flight height, speed, direction and trajectory with species identification. However, operationalizing a large-scale array of video cameras linked to radars at offshore wind farms faces logistical and technological challenges related to data collection, processing and analysis.

Another limitation of digital cameras is their reduced detection range under adverse weather conditions such as fog or precipitation (Lagerveld *et al.*, 2020; Skov *et al.*, 2023). These limitations underscore the need for careful consideration and strategic planning when deploying digital camera systems in offshore environments.

Radar-guided microphone © BirdTrack

3.4 Acoustic

The use of acoustic monitoring technology is well-documented for application on onshore wind farms, even though it is not yet widely employed in this environment (Drewitt & Langston, 2006; Skov ***et al.***, 2018). Like other previously mentioned technologies, acoustic monitoring has the capacity to operate continuously regardless of day or night hours and can detect bird activity through the recording and identification of their vocalizations and even wing-flapping sounds.

While of limited application for implementing curtailment measures, acoustic sensors may be particularly useful for identifying the presence of certain species within wind farms, especially during migration events.

Through sound recording and identification, acoustic sensors can confirm the presence in offshore wind farms of selected species, or groups of species such as thrushes or finches, during the curtailment periods due to high-intensity migration periods predicted by the models. Automated software for species identification based on call characteristics can facilitate quick integration with datasets and contribute to curtailment decisions.

Overall, acoustic sensors contribute to establishing temporal patterns of bird activity, provide data on species identity and, ultimately, can inform the implementation of curtailment or shutdown of turbines (Nicholls ***et al.***, 2022; Skov ***et al.***, 2023).

3.5 Telemetry

Telemetry-based technology provides a valuable opportunity to track and monitor seabird movements, offering detailed insights into the behaviour, phenology and ranges of species of interest. Currently available options on the market include GPS loggers and transmitters, as well as radio-tagging devices. However, the primary limitation for each type of device is the size of the birds. GPS devices are suitable for use on medium to large-sized species only, while radio-tagging may be employed on smaller species (Nicholls ***et al.***, 2022; Skov ***et al.***, 2023).

Radio-tagging devices, in addition to requiring the use of hand-held receivers or fixed base-stations to detect signals, often exhibit relatively low precision and are limited to indicating the presence of the bird at a given location. Conversely, GPS devices offer higher precision in location tracking. Data collected by GPS devices may be transmitted via satellite or GSM, enabling the gathering of information on position, flight height and speed. This data can be utilized for Collision Risk Modelling, facilitating the estimation of the annual number of individuals likely to collide with an offshore wind farm (Nicholls ***et al.***, 2022; Skov ***et al.***, 2023).

The Motus Wildlife Tracking System (Motus) is based on an international collaborative network of research institutions and individuals who contribute to the tagging of individuals with Motus radio devices and the maintenance of Motus stations (Birds Canada, 2024). This initiative enables data collection on migratory patterns of flying species, such as birds, bats and insects and is based on the tagging of target species with uniquely coded radios transmitters, ranging from 0.2g to 2.6g, which are detected by an array of existing Motus antennas (receivers). With this technology, further research opportunities may arise to gain insight into migration patterns of the many small migratory passerine species (e.g. warblers, finches). The extent and quality of information gathered from this tool is intrinsically related to the number of tags and receivers deployed, as well as with the distribution of the receivers. Currently, there are several Motus receivers deployed in Europe, particularly in the North Sea, in the United Kingdom, Belgium, Netherlands, Germany and Denmark.

Image: Gannet with GPS tracker © Edwin Butter

3.6 Vibro-acoustic Sensors

The installation of vibration sensors in rotor blades enables the detection of impact signals resulting from collision events, although this method is limited to detecting impacts of a certain weight of species (Lagerveld *et al.*, 2020; Skov *et al.*, 2023). A combination of accelerometers and digital cameras covering the rotor swept area offers the possibility not only to record collision events but also to identify the species affected (Collier *et al.*, 2012).

3.7 Cameras – Collision Monitoring

Wide aperture, fixed focal length cameras strategically installed on the handrails of turbine jackets, covering the rotor swept volume and equipped with both night vision and daylight capabilities, hold the potential for automatic species identification or subsequent identification by ornithologists through image review. This enables the estimation of empirical collision rates per turbine. The utilization of this technology is crucial for assessing the long-term efficiency of curtailment measures. Further offshore testing and development of these systems, offered by various manufacturers, are necessary to achieve optimal results in detecting and recording collision events. This will enable a comprehensive assessment of curtailment efficiency.

In summary, a diverse range of methodologies and technologies are currently available, at various levels of Technology Readiness Level (TRL), to inform the need for curtailment implementation and monitor its effectiveness. At each stage of curtailment, from establishing the baseline situation and identifying the most sensitive species, areas and periods, to determining curtailment strategies and criteria and ultimately monitoring implementation, several methodologies and technologies should be utilized (Table 3).

Image © Eren Yildiz

SECTION FOUR
NETWORK INTEGRATION

The impact of curtailment as a mitigation measure for bird collision on grid connection remains unclear. Nonetheless, a comparison can be drawn between this form of curtailment and emergency shutdowns.

Among the primary concerns surrounding the application of curtailment in wind farms are reliability, power losses and power quality (Azad-Farsani *et al.*, 2023; Jiang *et al.*, 2013). Furthermore, there is a potential risk that implementing curtailment on a large scale, encompassing multiple wind farms simultaneously, could induce grid energy instability (Kraal *et al.*, 2023; Noordzeeloket, 2024). Given the apprehensions regarding the cumulative effects of offshore wind farms in the North Sea on bird populations (van der Kamp *et al.*, 2023), alongside the interest in implementing basin-level curtailment measures, it is imperative that solutions are sought to reconcile these competing demands.

Energy losses linked to curtailment at offshore wind farms are indeed acknowledged. However, research indicates that these losses are relatively minor. For instance, a study demonstrated that setting cut-in speeds at 5.0 m/s and 6.5 m/s could substantially reduce bat fatalities, with energy losses amounting to only approximately 2% of the total output over 75 days per year (Arnett *et al.*, 2011).

Another investigation illustrated that energy losses attributable to curtailment for birds flying at low wind speeds would be below 1% of the total annual output, as energy generation at lower wind speeds is inherently limited (May *et al.*, 2015). Losses ranging from 0.5% to 2% due to curtailment have been reported for new offshore wind developments, aligning with the figures referenced in these studies.

Curtailment may have considerable costs when the focal species is highly threatened, either at local or regional scale, and has low population sizes: under this scenario, although collisions are likely rare, the loss of even a few individuals will have a population impact (e.g. Singh *et al.*, 2015). Also, curtailment costs may be higher in cases where migratory patterns are poorly characterized and lack a comprehensive understanding. Furthermore, in addition to these expenditures, there may be additional maintenance costs associated with wind turbines and the power grid, as turbine shutdowns can detrimentally impact reliability. Consequently, it is essential to use measures that minimise the effect of energy loss on grid stability, while still affording birds protection from wind farm collisions.

To address the current challenge, the Dutch Start/Stop-project employs a forecast model aimed at detecting potential bird migration within a 48-hour timeframe (see discussion in Section 5 – Case Study – Start/Stop Project). This duration aligns with TenneT's requirements, the Transmission System Operator (TSO) for the Netherlands, to uphold energy supply stability. Nonetheless, the accuracy of the 2-day forecast is contingent upon weather predictions, which introduces uncertainties and may yield inaccurate data (Kraal *et al.*, 2023). Ideally, the model would operate in real-time alongside weather conditions, enabling more precise predictions of bird migration and facilitating real-time turbine shutdowns. However, truncating the curtailment period could jeopardize grid stability (Bird migration predictive modelling, threshold and protocol - Noordzeeloket).

Several studies have suggested systems aimed at mitigating the impact of curtailments on the power grid. Azad-Farsani *et al.* (2023) proposed a novel, cost-effective, tool known as distribution network reconfiguration (DNR), designed to regulate active power losses resulting from curtailment. The DNR system is engineered to minimize disruptions to network reliability and protection during operation. While primarily utilized for other forms of curtailment, this approach may be considered in the future to address the challenges posed by wind turbine shutdowns.

Enslin *et al.* (2003) were pioneers in identifying technologies capable of pre-empting issues such as dynamic stability and achieving balance between wind farms. They advocated for an integrated approach that interconnects pertinent wind farm technologies such as high-voltage direct current, flow-battery storage and direct drives with AC and DC transmission technologies, network load-flow management, dynamic stability mitigation and storage technologies like FACTS. However, they also acknowledged that cost and reliability posed significant concerns.

Utilizing systems equipped with acoustic sensors presents a viable approach for detecting birds near wind turbines and meeting curtailment requirements. A study implementing a similar curtailment system for bats demonstrated a reduction in energy wastage compared to the application of a blanket curtailment during the times of night and periods of the year when bats are known to be active (Ziesler, 2023).

Beyond the direct costs associated with power production losses stemming from curtailment, the costs of monitoring technology to ensure effective curtailment in reducing bird collisions is also significant. Implementation costs for such technology may be variable, contingent upon factors like equipment type (e.g. radars, cameras, drones, microphones) and wind farm characteristics (e.g. area, layout, number of turbines) (Nicholls *et al.*, 2022; Skov *et al.*, 2023). Compared to simpler technologies such as microphones, radar and telemetry systems may have higher costs. However, the data collected by these systems is unique and allows for specific analysis that other technologies cannot provide.

It's imperative to note that the suggestions and evaluations discussed above do not preclude exploration of alternative measures to establish a more efficient relationship between bird curtailment and grid stability, including the refinement of bird curtailment procedures.

SECTION FIVE

Case Study: Start/stop project in the Netherlands

5.1 Context

The North Sea serves as a crucial flyway for migratory birds, with significant numbers traversing this area biannually as part of the East Atlantic Flyway (BirdLife International, 2010; Kraal *et al.*, 2023). Particularly during spring and autumn, terrestrial birds migrating at night face collision risks with offshore wind farms in the North Sea, a region witnessing rapid expansion of such facilities driven by North Sea countries' plans for renewable energy growth (van der Kamp *et al.*, 2023).

The Netherlands, positioned along the North Sea, is experiencing a surge in offshore wind farm development. With current offshore capacity at 3.2GW and plans to reach 21GW by 2030 and 70GW by 2050, the country is implementing measures to mitigate bird collisions with wind turbines during migratory periods efficiently and cost-effectively (Noordzeeloket, 2024; van der Kamp *et al.*, 2023). One such measure involves shutting down or reducing the rotation speed of turbines during expected peaks in bird migration, a method shown to reduce collision incidents (Cook *et al.*, 2011; Garcia-Rosa & Tande, 2023; Hoge, 2021; Tomé *et al.*, 2017).

Following work by the University of Amsterdam, a peak migration prediction model for birds flying between 25- and 300-meters high was developed for the spring and autumn migration periods (Bradarić, 2022). This machine learning model predicts on which nights there will be large-scale bird migration in offshore areas of the North Sea based on weather conditions along the birds' migration route and at their departure locations in mainland Europe. Radar measurements of bird activity at the offshore wind farm Luchterduinen were incorporated into the model, considering offshore weather conditions.

The model produces the predicted bird migration intensity, quantified as the MTR per hour. Weather parameters used in the model to predict bird migration intensity include wind, precipitation, air pressure and temperature (Bradarić, 2022). These parameters are recognized for their influence on bird migration dynamics, with wind speed and direction affecting migration direction and timing, precipitation potentially hindering migration and increasing collision risks, air pressure impacting flight efficiency and speed and temperature fluctuations triggering migration onset, with rising temperatures in spring and falling temperatures in autumn often serving as migration cues (Bradarić, 2022).

5.2 Start/Stop Project

The Start/Stop project utilizes a bird migration predictive model to implement a curtailment approach aimed at reducing avian collisions at offshore wind farms in the Dutch part of the North Sea. This collaborative effort is based on the prediction of large-scale migration nights. The Ministry of Economic Affairs and Climate Policy (EZK) set a threshold value of 500 birds/km/hour, informed by data from Leemans et al. (2022). Leemans et al. (2022) used vertical radars to monitor bird activity and observed exceptionally high fluxes (> 500 birds/km/hour in 1.4% of all measurement hours) particularly during spring and autumn nights.

The Start/Stop procedure entails a collaborative effort between government representatives from EZK and the Ministry of Infrastructure and Water Management (RWS) and wind farm owners/developers. Together, they follow a structured plan to implement bird curtailment during periods identified as necessary based on predictive models. Evaluation of the model's predictions is conducted by a team of external experts, who also forecast large-scale migration nights using weather conditions both offshore and at anticipated bird departure locations (Kraal et al., 2023).

The Dutch Transmission System Operator (TSO), TenneT, plays a pivotal role in the Start/Stop procedure by assessing the risks associated with curtailing offshore wind turbines to maintain electricity supply security in the market during designated curtailment periods. TenneT advises whether to proceed with curtailment based on the potential impact on energy production and grid stability. Given the loss of energy production during bird curtailment periods, TenneT is tasked with implementing measures to compensate for this loss and prevent any instability in the energy grid. Wind farm owners are required to inform TenneT of bird curtailment periods with a minimum lead time of 48 hours, as stipulated by the Start/Stop project.

Following consultation with the external team of bird experts and the TSO, EZK makes the final decision regarding the shutdown of turbines. Upon EZK's decision, the curtailment order is issued and wind farm owners notify the unavailability of the wind farm for the specified curtailment period, including the start and end times.

The monitoring and evaluation of the Start/Stop procedure's implementation are overseen by the RWS. RWS analyses data from offshore wind farms involved in the curtailment procedure to assess actual bird migration patterns compared to the model's predictions. This evaluation process contributes to refining and enhancing the accuracy of the prediction model used in the curtailment strategy (for further details, please check the summary of the Start/Stop procedures available at https://www.noordzeeloket.nl/en/functions-and-use/offshore-wind-energy/start-stop/).

Image: Borssele Offshore Wind Farm © Oscar Bos

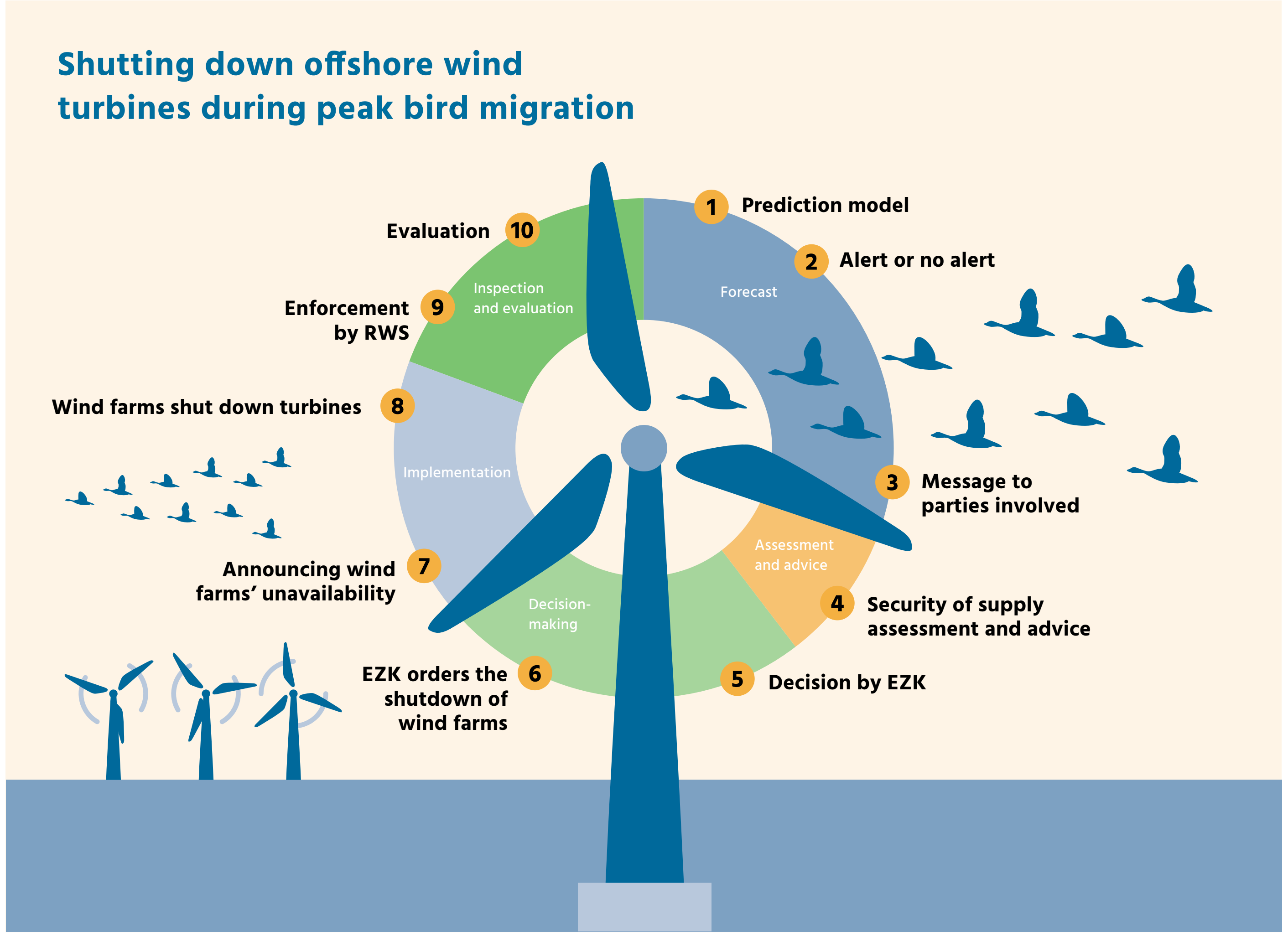


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Figure 7 – Infographic Shutting down offshore wind turbines during peak bird migration (Start/Stop project, Noordeeloket website).

A pivotal aspect of the Start/Stop project is the collaborative engagement of various key stakeholders directly involved in the curtailment procedure, ranging from wind farm owners to the TSO, alongside government representatives responsible for decision-making, enforcement and evaluation of the procedure.

Currently, in the ongoing phase of the Start/Stop project, curtailment measures are being implemented in numerous offshore wind farms located in the Borssele wind farm site and off the coast of the Netherlands. This includes wind farms for which permits were issued from 2016 onwards. These permits mandate wind farm owners to execute bird curtailment protocols during periods of peak migration nights, as per the decision by EZK (Degraer *et al.*, 2023). Future initiatives aim to enhance the prediction model and extend the scope of the curtailment procedure to encompass offshore wind farms situated farther from the coastline.

Information from (Degraer *et al.*, 2023) indicates that, in theory, bird curtailment in the Dutch North Sea should be performed only during 2.5% and 5.5% of the spring and autumn migration periods, representing less than 1% of energy loss, and resulting in a 50% reduction of collision risk.

5.3 Prediction Model Evaluation

The predictions generated by the UvA model underwent validation against actual radar measurements obtained from both horizontal and vertical radar systems installed in the Luchterduinen offshore wind farm, as well as the MTR predictions made by the team of experts (Kraal *et al.*, 2023). This evaluation yielded conclusions and recommendations pertaining to the model's performance, the comparative use of horizontal versus vertical radar data and the output variables of the prediction model.

In summary, the primary finding of this assessment was that the model's predictions consistently underestimated the MTR calculated by both horizontal and vertical radars in Luchterduinen. This discrepancy could be attributed, in part, to the filtering of horizontal radar data necessitated by adverse weather conditions and issues with the vertical radar system (Kraal *et al.*, 2023). Recently, a framework for post-processing bird tracks obtained from automated tracking radar systems has been proposed with the aim of enhancing the quality of radar outputs (van Erp *et al.*, 2023).

This outcome underscores the potential for refinement in the curtailment procedure by adjusting the threshold used to identify peak migration nights. The observed decrease in verified positive matches between the model's maximum MTR predictions and radar data suggests room for improvement. Furthermore, it's notable that the model's predictions for August and September heavily influence the top nights projected by the model, despite these months not being included in the model's training data. Enhancing the accuracy of the MTR prediction model by incorporating data from August and September holds promise for improving performance, particularly given that the curtailment procedure is slated for implementation between August and November. A revision to the curtailment threshold within the Start/Stop procedure can be made by the Dutch government, however, a smooth implementation hinges on the acceptance of key stakeholders involved in the process. It's worth noting that the Dutch government's decision regarding offshore wind farm sites currently dictates a threshold of 500 birds/km/hour. To comply with European and Dutch law it will be needed to either adapt the model or the threshold to prevent unacceptable numbers of collisions of birds with wind turbines.

Image: Flock of Swallows © Light Capturing

Another notable finding from the report suggests that the timing of weather forecast data used in the model may influence its accuracy. Specifically, it was observed that later weather forecast timings resulted in a higher number of agreements between the model's predicted MTR peaks and the predictions made by the team of experts. Further investigation is required to substantiate this hypothesis, particularly considering its implications for the 48 hour-notice required by TenneT to adjust grid energy production in response to downtime during bird curtailment periods.

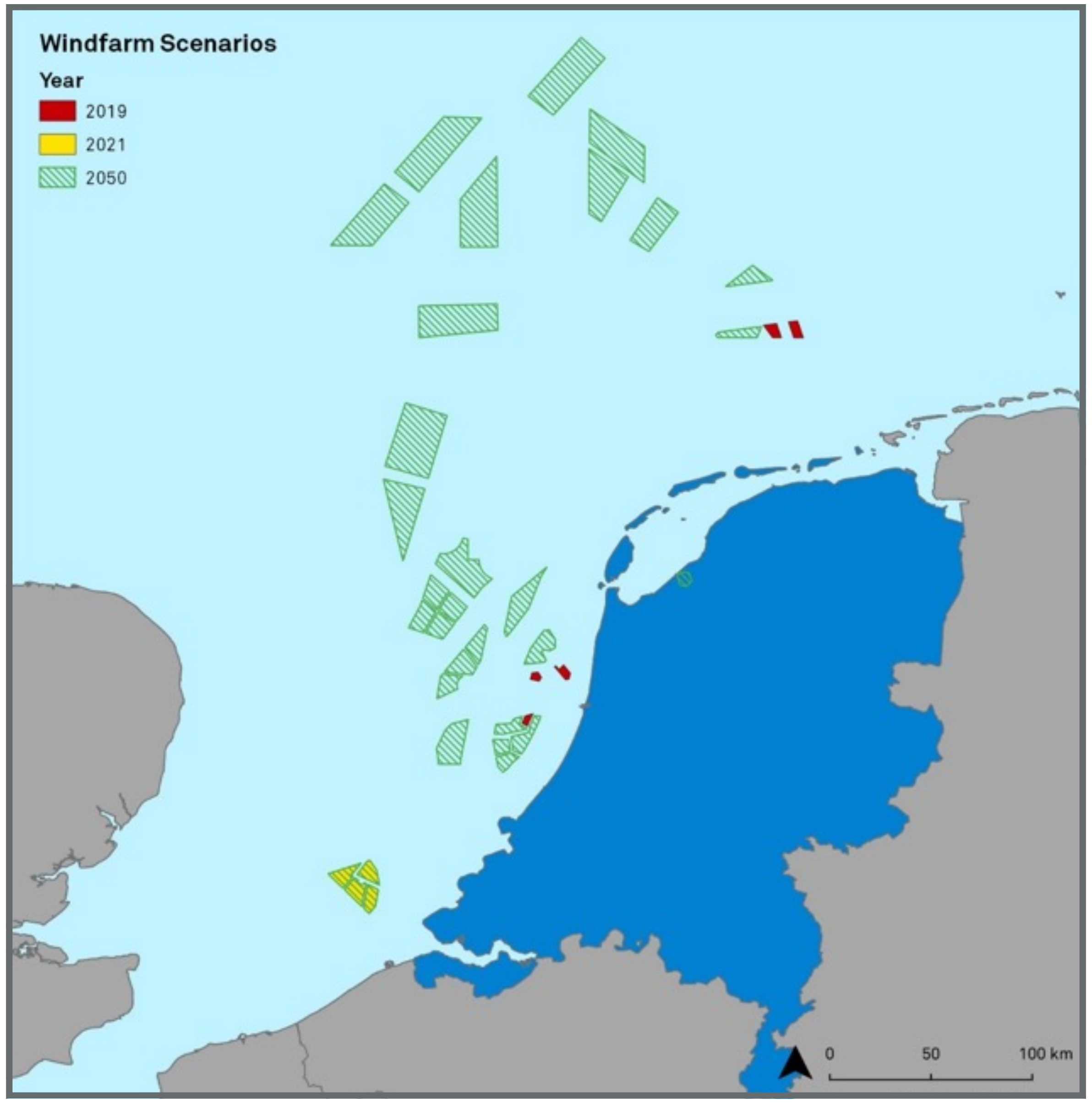

Figure 8 – Current (red and yellow) and planned (green) offshore wind farms in the Dutch part of the North Sea in 2050 (Baas 2022) - https://wins50.nl/.

The utilization of both horizontal and vertical radar measurements to train the model is also proposed as a means to enhance its accuracy. Given that each radar setup has its own limitations and strengths, employing both ensures redundancy in the system and provides more reliable radar parameters for input into the model, thereby improving MTR predictions. It's important to note that the Start/Stop procedure is presently mandatory for new offshore wind farm license holders in the Dutch part of the North Sea. By contributing site-specific radar measurements, these license holders can facilitate the long-term development of the model, enabling its extension to offshore areas further from the coast. This contributes to the accumulation of more accurate and site-specific information for these regions, aligning with objectives outlined in Wozep's Multi-year Program 2024-2023 (van Nieuwpoort *et al.*, 2023). Figure 9 illustrates the current (red and yellow) and planned (green) offshore wind farms in the Dutch part of the North Sea.

Image: Seagulls at the Dutch North Sea coast

SECTION SIX
BIRD CURTAILMENT AT THE SEA BASIN LEVEL

The Netherlands emerges as a frontrunner in the development and implementation of bird curtailment strategies in offshore wind farms, with a specific focus on mitigating collision casualties during peak migration periods of songbirds. Other countries, such as Germany and France, are either actively implementing bird curtailment measures or are poised to do so with discussions underway regarding the integration of bird curtailment protocols into future offshore wind projects.

Conversely, in the other countries examined within this study, bird curtailment remains unimplemented in currently operational offshore wind farms. However, discussions are ongoing regarding its potential adoption and integration into future projects. This trend underscores the growing recognition and importance placed on bird curtailment strategies across various regions, signalling a broader shift towards proactive measures aimed at avian conservation within the offshore wind energy sector (Degraer et al., 2023).

With the increasing interest in implementing bird curtailment measures on a larger scale and fostering cooperation between nations, the idea of coordinating curtailment at a basin sea level has emerged as a promising option to reduce bird collisions at offshore windfarms across larger areas, including important migratory flyways. However, implementing curtailment on such a scale requires careful consideration of various aspects, as outlined on the following pages..

6.1 Monitoring Technology and Site-specific Information


Image © Vidar Nordli Mathisen

The deployment of appropriate monitoring technology is crucial, not only for evaluating the efficacy of bird curtailment measures, but also for driving ongoing developments tailored to specific sites. Despite significant strides, understanding the true impact of bird collisions with offshore wind turbines remains a critical knowledge gap. Several European countries, including the Netherlands, United Kingdom and Germany, are actively addressing this issue.

Deploying monitoring technology to assess migration patterns and offshore bird activity, particularly in relation to distance from the coast, is essential for gaining insights into bird behaviour and temporal-spatial variations at offshore locations. This understanding is vital for refining and advancing curtailment procedures. Therefore, comprehensive and coordinated monitoring of bird behaviour at a larger scale, such as the Greater North Sea, would facilitate the characterization of bird migration patterns over the sea under diverse conditions (e.g. distance from shore, topography, meteorological). Consequently, the development of multiple models tailored to different locations within the same sea basin would be feasible, involving the collaboration of national environment authorities from the sea basin countries.

A key function provided by technology is the ability to monitor actual collision events at offshore wind farms. This component of monitoring efforts is key to gaining a comprehensive understanding of the interaction between bird species and offshore wind turbines, which can lead to collisions and result in the death or injury of birds. Furthermore, this aspect of monitoring is closely tied to a key element of curtailment monitoring: evaluating the effectiveness of the curtailment measures. This evaluation is directly linked to the number of collisions prevented compared to the predicted collisions based on baseline studies.

6.2 Expansion of Predictive Model Development

The predictive model plays a pivotal role in shaping the development and execution of a species-generalist (migratory bird) predictive curtailment strategy, as it identifies peak migration periods necessitating curtailment.

Following the inaugural bird curtailment implementation in the Netherlands, under the Start/Stop Project, an evaluation of the bird migration prediction model highlighted avenues for further refinement. Specifically, Kraal *et al.* (2023) proposed an improvement of the model by incorporating a broader array of temporal data, notably weather data and bird radar measurements, to enhance the accuracy of its outputs. This suggests that the integration of bird radar measurements from other areas of a given region and also radar data from neighbouring countries might contribute to this objective, namely to better predict the timing and intensity of migration across the migratory route.


Image © Aron Yigin

An interesting result from Kraal *et al.* (2023) shows that adjusting the timing of weather forecasts used within the bird migration prediction model could potentially enhance the model's predictive accuracy when compared against actual radar measurements. Utilizing more recent weather forecasts notably improves the model's accuracy, as evidenced by preliminary results from a single migration period. However, further investigation into this area is warranted to validate findings across different migration periods.

Moreover, the timing of weather forecasts holds significance in curtailment procedure development, as it directly impacts the ability of Transmission System Operators (TSOs) to make grid arrangements prior to curtailment periods. Presently, in the Netherlands the TSO, TenneT, requires a 48-hour notice to ensure the stability of the energy supply during curtailment periods.

Image: Female Goosander

6.3 Refinement of Curtailment Procedures

Refining curtailment procedures involves various considerations, including the determination of MTR thresholds for bird curtailment. In 2022, van Bemmelen *et al.*, proposed a nuanced approach to determining MTR thresholds by optimizing the relationship between migration intensity and power yield.

This optimization involves factoring in wind speed, resulting in distinct thresholds for different wind speed categories (low, intermediate and strong). In the German curtailment procedure, for instance, bird curtailment is excluded during high wind speeds (>7 Beaufort) when bird migratory activity is anticipated to be low and during low wind speeds (<3 Beaufort) when turbines are not generating energy.

Implementing multiple MTR thresholds for curtailment based on wind speed categories could potentially mitigate energy yield losses. By considering wind speed variations, curtailment procedures can be tailored to maximize the conservation impact on bird populations while minimizing the impact on energy production.

6.4 Research on Large-scale Grid Stability and Integration

Image © Mitchell Orr

When contemplating a large-scale curtailment strategy, whether at a sea-basin level or nationally, it is imperative to assess grid stability in response to curtailment periods. With the projected expansion of offshore wind energy capacity by 2030 and 2050, simultaneous implementation of curtailment measures across such a vast expanse could be unfeasible and potentially ineffective.

Further research should be conducted to comprehensively address and evaluate the impact of large-scale curtailment and the capacity to implement curtailment simultaneously across multiple offshore wind farms. Key questions, such as the impact on market function, setting limits on annual curtailment hours and developing curtailment strategies responsive to national grid energy supply, must be thoroughly investigated. One potential approach to enable bird curtailment implementation at a sea-basin level involves the development of site-specific and time-related spread of bird migration prediction models. Such models could facilitate staggered implementation of curtailment in different areas of the sea basin, aligning with site-specific periods of peak migration.

In the context of reducing collisions of local seabirds, the latest tender for offshore area attribution in the Netherlands - IJmuiden Ver sites Alpha and Beta - mandates the development and implementation of local curtailment strategies. These strategies involve partially shutting down turbines when target species are present, allowing for selective curtailment of turbines posing collision risks to specific species. This species and site-specific curtailment strategy enables the setting of limits on annual curtailment hours and the partial shutdown of turbines within offshore wind farms.

National regulations on grid operation may permit the implementation of local curtailment on a smaller scale without prior notice to the Transmission System Operator (TSO), provided maximum system impact requirements are not exceeded.

6.5 International Cooperation and Supervision

The development and implementation of bird curtailment at a sea-basin level should prioritize reducing impacts on bird species and address the following key considerations:

- Monitoring and data gathering – comprehensive monitoring and data collection of bird activity are essential across all countries involved in curtailment initiatives; this data serves as the foundation for understanding bird behaviour and migration patterns within the sea basin.
- Development of bird migration prediction models – each country or region involved should develop bird migration prediction models tailored to their specific conditions; these models enable curtailment measures to be implemented effectively and site-specifically, optimizing their impact on bird populations.
- Data sharing amongst relevant parties – collaboration and data sharing among relevant stakeholders in all countries are crucial for fostering a holistic understanding of bird migration dynamics and facilitating coordinated curtailment efforts.
- Coordination and supervision – establishing a committee comprising representatives from every country involved in curtailment is essential for coordinating and supervising sea-basin level curtailment initiatives; this committee should oversee implementation, address challenges and ensure adherence to established guidelines and protocols.

The Netherlands' Start/Stop procedure serves as a model for organized curtailment structures, involving key stakeholders impacted by curtailment measures. Prior to implementing sea-basin level curtailment initiatives, it is advisable to follow similar steps:

- Development of site-specific bird migration models – tailoring bird migration models to specific sites within the sea basin enhances the accuracy and effectiveness of curtailment strategies.
- Establishment of curtailment rules – curating curtailment rules aligned with local conditions, informed by recommendations from existing studies such as those by Kraal *et al.* (2023) and van Bemmelen *et al.* (2022); this ensures the relevance and efficacy of curtailment measures.
- Creation of a stakeholders' group – forming stakeholder groups comprising offshore wind farm owners, national environmental authorities, Transmission System Operators (TSOs), academia and Non-Governmental Organizations (NGOs) fosters collaboration, consensus-building and shared responsibility in curtailment initiatives.
- Monitoring and assessment – communicate any adjustments or improvements to the curtailment procedures in order to standardize the process across all stakeholders.

SECTION SEVEN KEY FINDINGS

This report identifies two primary curtailment strategies for mitigating the impact of bird collisions with offshore wind turbines: 1) species-generalist and 2) species-specific. Drawing from standards established by the Netherlands and other leading initiatives, a) species-generalist bird curtailment predictive strategies can be implemented to mitigate collisions involving migratory songbirds and b) real-time local curtailment measures target local seabirds and/or migratory species when these species are deemed at risk of collision. These strategies represent proactive approaches aimed at minimizing avian fatalities and promoting biodiversity conservation within offshore wind energy ecosystems (Degraer *et al.*, 2023).

Drawing upon the insights gathered in this report, the implementation of bird curtailment at a sea basin level, informed by bird migration prediction models, necessitates meticulous attention to the following key factors:

- **Monitoring technology and site-specific information** – utilization of advanced monitoring technology tailored to the characteristics of each offshore wind farm site is crucial for effective bird collision mitigation.
- **Expansion of predictive model development** – continuous refinement and expansion of predictive models are necessary to enhance the accuracy of bird migration forecasts and optimize curtailment strategies.
- **Refinement of curtailment procedures** – ongoing refinement of curtailment procedures are essential to ensure their efficacy in minimizing bird collisions while maximizing energy production efficiency.
- **Research on large-scale grid stability and integration** – research efforts should focus on assessing the impact of bird curtailment measures on the stability and integration of large-scale offshore wind energy grids spanning multiple countries.
- **Consideration of regional implementation lag** – recognizing the variation in bird migration patterns and timings across different regions, there should be a consideration of the lag in implementing bird curtailment measures to align with site-specific migration dynamics.
- **International cooperation and supervision** – facilitating international cooperation and supervision mechanisms is critical to harmonize bird curtailment procedures, share best practices and ensure consistent standards across borders.

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SECTION EIGHT

ANNEXES

ANNEX I QUESTIONNAIRE SENT TO OFFSHORE WIND ENERGY DEVELOPERS AND OPERATORS

1. Name of Company
2. Project Contact
3. Date of interview/response
4. In what regions do you operate offshore windfarms? Please specify sea basin/country.
5. How many offshore wind farms are you currently operating in the North Sea and Baltic Sea regions?
6. Are you developing/operating any offshore windfarm in which bird collision has been identified as a risk? If yes, please specify.
7. Have you made adjustments to the project design (e.g. layout, number of turbines, location) due to expected avian collision impact? If yes, please specify.
8. Are curtailment measures implemented in the offshore windfarms operated by your company? If yes, please indicate the number of offshore wind farms, their location and capacity, if possible.
9. Is the curtailment measure determined by national authorities or determined based on environmental studies results? Are the curtailment periods also determined by the authorities?
10. If appliable, do your projects' lenders have environmental standards that determine bird curtailment? If yes, could you identify those lenders?
11. For each windfarm, please indicate the % of the offshore windfarm covered by curtailment measure (% of turbines).
12. What type of curtailment is being implemented (e.g. seasonal/all-year, nocturnal/diurnal, species-specific/generalist)? Please indicate number of offshore windfarms with each type of curtailment.
13. Could you please elaborate on the criteria defined for curtailment (e.g. mean traffic rate, presence of target species)?
14. Is the curtailment implementation being monitored in the above-mentioned offshore wind farms? Could you please provide results if available (e.g. reduced % of avian collision)?
15. What is the expected impact on energy production due to curtailment implementation (in % annual equivalent time)?
16. What is the impact of curtailment for the expected turbine maintenance? Is it expected to reduce lifetime of the equipment?
17. Is the grid operator involved in the curtailment implementation? Is there a requirement to inform the energy grid operator of curtailment periods?
18. Are the curtailment measure specifications, such as periods of curtailment and duration specific for the individual windfarms you operate or are they common to other offshore windfarms in the same region, even if operated by other energy developers?
19. Are curtailment reports publicly available? Could you please provide them for the purpose of this study?

ANNEX II QUESTIONNAIRE SENT TO TSOs.

1. Name of Company
2. Project Contact
3. Date of interview/response
4. Country
5. What is the offshore wind farm energy capacity in your area of operation?
6. What is the planned capacity for the years (2030 and 2050) in your country?
7. Have any specific conditions been placed on windfarm operators (either for all windfarms, or for individual windfarms) in your area of operation to implement specific measures to mitigate collision of birds?
8. What are the (potential) operational limitations to implement curtailment or shutdown on offshore wind farms regarding the stability of the grid in terms of energy production? E.g. as part of Project Start-Stop in the Netherlands, authorities decide shutdown periods based on modelling and windfarm operators with a a 48-hours' notice.
9. What considerations should be taken into account if curtailment was to be implemented at a sea basin level (e.g. involving multiple offshore windfarms at national level or even international level)?

ANNEX III QUESTIONNAIRE SENT TO NATIONAL ENVIRONMENTAL AUTHORITIES

1. Name of Institution
2. Project Contact
3. Date of interview/response
4. Country
5. Does national legislation require mandatory evaluation of environmental impacts of offshore wind developments on bird species?
6. Is there any specific requirement (mandatory or guidelines) to monitor the impact of collision (empirical or estimates) in offshore windfarms during post-construction phase? Is this currently being implemented in any windfarms?
7. Is curtailment a mitigation measure considered for implementation in your country to mitigate the impact of collision on bird species? If yes, is it currently mandatory or just recommended?
8. Is there any operational offshore wind farm with curtailment measures in your country? If yes, are there monitoring schemes to evaluate its results?
9. Considering the current and planned development of offshore wind projects, is curtailment seen as a measure that could become mandatory in the future?
10. What criteria would you consider relevant for the determination of curtailment in an offshore windfarm?
11. If you consider any other information to be relevant for the implementation of bird curtailment in offshore windfarms, could you please indicate them?

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