ARCADIS

Inventarisation of bat mitigation measures and their suitability for offshore wind in the Netherlands

Rijkswaterstaat & Wozep

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WOZEP
DUTCH GOVERNMENTAL OFFSHORE WIND ECOLOGICAL PROGRAMME

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Contents

Summary

In assistance to the Dutch Ministry of Climate Policy and Green Growth, and Rijkswaterstaat, this report addresses critical knowledge gaps regarding the impact of offshore wind farms on bat populations in the North Sea. Specifically, concerns have arisen about the potential for bat fatalities caused by interactions with operational offshore wind turbines, as well as construction and decommissioning activities. These concerns are amplified by the lack of detailed knowledge about how bats use the North Sea environment. Given that all bat species are protected under the Natura 2000 European Habitats Directive, minimizing their potential population-level impacts is vital, especially as offshore wind energy developments (Wind op Zee) continue to expand in the Dutch North Sea.

The focus lies on identifying and evaluating mitigation measures that can reduce bat fatalities and mitigate risks associated with offshore wind farms. To achieve this, a structured methodological framework was developed, incorporating insights gathered from literature reviews, consultations with internal and external bat ecology experts, and international collaboration through the Arcadis Global Community of Practice on Offshore Wind. The study also integrates findings from workshops, AI-based information gathering, and global best practices to ensure a comprehensive overview of mitigation strategies.

A multitude of possible mitigation measures have been explored, and several along the mitigation hierarchy of ‘avoid – minimize – restore – offset’ were selected to show the highest potential in a Dutch offshore setting: spatial planning, curtailment of turbine operations during peak bat activity, adjustment of turbine characteristics, detection and deterrence technologies, and indirect (onshore) compensation measures. Spatial mitigation measures, such as avoiding areas of high bat activity, may help reduce risks but require deeper understanding of bat migration routes and behavioral patterns. Curtailment has been identified as a particularly promising measure, in which case turbines are shut down during periods of high bat activity. Combining curtailment with real-time data from detection technologies, such as radar systems, could further enhance its effectiveness while minimizing energy loss. However, challenges remain in adapting detection technologies for specific offshore environments, where conditions differ significantly from those onshore. Deterrent strategies, such as acoustic devices, have been considered but still face feasibility and efficiency concerns in offshore contexts. Similarly, adapting turbine characteristics like rotor size and ground clearance could be an effective strategy for minimizing bat collisions, but a more in-depth knowledge on bat flight altitudes (especially during migration) is required. Indirect habitat compensation could be meaningful through targeted decommissioning of turbines in high-risk areas or amelioration of known bat territories.

The findings highlight significant knowledge gaps, particularly regarding bat migration behavior and their use of offshore ecosystems. These gaps partly limit the ability to design effective mitigation strategies and necessitate further research to inform effective decision-making. Furthermore, the report emphasizes the importance of aligning mitigation strategies with ecological priorities while addressing the limitations of current technologies and knowledge. It provides recommendations for future research, including studies on bat flight behavior, migration routes, and adaptation of onshore mitigation technologies for offshore use. By bridging these knowledge gaps and refining mitigation measures, the Dutch offshore wind sector can expand responsibly, ensuring minimal impacts on bat populations while advancing renewable energy goals. Through this report, Rijkswaterstaat aims to support informed decision-making, contributing to sustainable offshore wind development and the protection of biodiversity in the North Sea.

1 Introduction

1.1 Goal

The Dutch Ministry of Economic Affairs (now Ministry of Climate Policy and Green Growth) has commissioned Rijkswaterstaat (RWS) to map out the existing knowledge gaps regarding the effects of offshore wind farms in the North Sea. One of the knowledge gaps is related to the impact of offshore wind farms on bat fatalities. Based on current knowledge, bat fatalities through interaction with operational offshore wind turbines or related construction (or decommissioning) works cannot be ruled out as an offshore presence of bats has been established. However, critical information on the use of the North Sea by bat species is still missing, e.g. data on offshore behaviour, numbers and collision risk. Based on the current assumptions and the future ambition of expanding Wind op Zee (WoZ) within the Dutch part of the North See, a further increase in potential bat fatalities offshore and population-level effects cannot be ruled out. Since all bat species are protected under the Natura 2000 European Habitats Directive, it is paramount to both get a further grip on our knowledge on bats and their ecosystem use of the North Sea and to identify which additional mitigation measures can be implemented to minimize the currently predicted future impact. This report will focus on the latter topic: the mitigation measures.

The overall goal of this inventory report is to gain insight into all (forms of) mitigation measures currently applied internationally both on-and offshore. After the inventarisation an expert validation is done to identify additional (potentially) effective mitigation measures that can be implemented to reduce the expected number of bat fatalities caused by the development of Wind op Zee (WoZ). The overall aim is to generate an (as complete as possible) overview of mitigation measures that are in use or being developed globally. After completing the overview and discussing a validating the measures with experts, we will provide advice on which measures seem most or less promising and which could be worth investigating further. This overview will enable more effective decision-making regarding the further development and research into bat mitigation measures for wind energy in the Dutch North Sea.

1.2 Team & acknowledgements

Within this project, general coordination and project management of the different subtasks was executed by a collaborative team of ARCADIS Netherlands and ARCADIS Belgium NV (referred to as *Arcadis*). Arcadis has consulted experts on different levels (see § 3.1 and § 4) and managed overall coordination and feedback by the client and instigator RWS, and in particular Wozep (Wind op Zee ecologisch programma). The project team and consulted experts are listed in Table 1:

Sincere gratitude goes out to all consulted experts, both within Arcadis and affiliated to external research institutes or consultancies, for their valuable input and constructive discussions. We would also like to express our appreciation to our client, RWS, and, in particular, Henri Zomer and Marije Wassink, for their insightful remarks and engaging meetings.

Table 1: Overview of Arcadis Project team and consulted experts

Team role	Name
Project management	Sarina Versteeg (NL), Annemie Volckaert (BE)
Project execution and reporting	Marlon de Haan (NL), Helena Voet (BE), Renzo Elias (NL), Jamil Salis (BE)
Report Quality Assurance	Sarina Versteeg (NL), Helena Voet (BE)
Arcadis international offices	Arcadis Global Community of Practice Offshore Wind, including the Arcadis teams in Australia, the United States, Canada, Chile and Brazil.
Arcadis bat ecology experts	Herman Bouman (NL) Pieterjan Dhont (BE)
External bat ecology experts	René Janssen (Bionet Natuuronderzoek) Martijn Boonman (Waardenburg Ecology) Robin Brabant (Royal Belgian Institute of Natural Sciences)
External technical advisor	Joris Diehl (RWS CIV)

1.3 Project set up

Rijkswaterstaat has engaged Arcadis to create a structured overview of mitigation measures to reduce bat fatalities in wind farms, both onshore and offshore. The Wozep team requested a structured step by step approach, which was further developed by the Arcadis team. The steps will be elaborated on further within this report, but the general process is as follows:

1. Literature review and consultation with national and international experts and organizations, such as EUROBATS[1] and BWEC[2], to gather and summarize all relevant information. Outcomes from an international workshop in 2024 will also be incorporated. Step 1 is worked out in chapters 2 and 3.
2. Evaluation of effectiveness of these measures through existing studies, expert opinions, and context-specific analyses. Discrepancies between studies will be highlighted, and expert judgment will be applied where scientific evidence is lacking. Step 2 is worked out in chapter 4.
   The overview and initial validation resulting from step 1 and 2 is presented in chapter 4.
3. Assessment of applicability of the measures to the Dutch ecological context. This involves identifying the options with potential and worth researching based on feasibility and effectiveness, tailored to national conditions. As is worked out in chapter 5.
4. Identification of the most suitable measures for offshore wind farms, considering offshore-specific factors, such as saltwater exposure and turbine size. The results form the basis of this advisory report, including recommendations for further research and practical implementation, as can be found in chapter 6.

1.4 Report structure

- Chapter 1 introduces the matter and outlines the project approach
- Chapter 2 focuses on outlining how the methodological framework was developed.
- Chapter 3 explains the approach taken to collect relevant literature and information for constructing the framework.
- Chapter 4 provides a condensed overview of the measures identified.
- Chapter 5 presents the findings and insights gained during the validation phase
- Chapter 6 offers a conclusion and recommendations based on the outcomes of the study.

[1] EUROBATS, officially known as the Agreement on the Conservation of Populations of European Bats, is an international treaty under the framework of the Convention on Migratory Species (CMS). It aims to protect bat populations across Europe by promoting research, conservation measures, and collaboration among member countries. URL: *https://www.eurobats.org/*

[2] Bats and Wind Energy Cooperative (BWEC) is an alliance of experts from government agencies, private industry academia, and non-governmental organizations that cooperate to advance and disseminate science-based solutions to cost effectively quantify and mitigate the impact of wind turbines on bats. URL: *https://www.batsandwind.org/*

2 Setting up the methodological framework

2.1 Organizing information in the framework

To allow for an efficient and structured mitigation measures overview, a methodological framework was developed. Within the framework, each mitigation measure from a separate literature source corresponded to a separate entry. Before full implementation, the framework was tested, reviewed and approved by Rijkswaterstaat.

The framework provides an overview of the information gathered from the literature review, as well as the results of the analysis (internal and external expert judgment) regarding the effectiveness, feasibility, and applicability to the Dutch and offshore context for different mitigation measures. The full final framework can be consulted in Appendix A.

The **information** included in the framework consists of, among other things: measures, sources, practical applications (onshore/offshore + location), technical conditions and limitations, cost information (per turbine), reliability, effectiveness estimates etc., all supported by literature. All parameters presented per mitigation measure are shown in Table 2 on the next page. In this way, all information was concisely summarized in this data framework. Furthermore, it is worth noting that while *mitigation measure* is a manual description, measures were organized by types. An elaboration on the types of mitigation identified can be found in paragraph 2.2. Once the technical information had been gathered, the potential of each mitigation measure is concluded in an assessment. Which is elaborated upon in paragraph 2.3.

To support a uniform population of the data framework by the consultants and experts, **technical** choices were based on facilitating this process. The framework is built in Microsoft Office Excel (version 2501), supported by multiple tabs with drop-down menus and definitions. The information for each mitigation measure was entered in a streamlined way through the use of a limited set of input options, implemented in Excel using dropdown menus and supported by a coded add-in for multiple selections. Other columns, e.g. *description* or *remarks*, could be used for free input. An overview of the parameters available within each dropdown menu are described listed in Table 2.

The full final framework in the Excel file with its assessments is included as Appendix A. The literature used for the report can be found on the second tab of Appendix A.

Table 2: Framework inventory and important details of the mitigation. All columns with more than one entry represent the different options in a dropdown menu.

Code data source	Source reference	Mitigation measure	Short description	Other sources	Mitigation type	Species bats	Dispersion type	Environment	Location*	Implementation status	Technical requirements	Cost estimate (per turbine)	Remarks and notes
Individual number of the data	Reference to the source	Type of mitigation (manual description)	Description of mitigation measure as described in source	Possible other sources which analyzes the mitigation type of the main source	collision reduction	Brown long-eared bat	Migrating	Offshore	Netherlands	Implemented - best practice	weather conditions	already part of regular planning costs	
					avoidance	Grey long-eared bat	Local Movement	Coastal	Belgium	Implemented - innovative	salt environment	+100 k EUR	
					compensation	Common Pipistrelle	Both	Onshore	Europe North	Proposed by study - but not implemented	type turbines	+50 k EUR	
					detection	Nathusius' pipistrelle	Unknown		Europe West	unknown	installation options	+10 k EUR	
					visual deterrence	Soprano pipistrelle bat			Europe South		no information found	<10k EUR	
					acoustic deterrence	Greater Mouse-Eared Bat			North Sea General		see remarks	unknown	
					deterrence (visual & acoustic)	Geoffroy's bat			Non-Europe				
						Natterer's bat							
						Daubenton's bat							
						Pond bat							
						Whiskered bat							
						Brandt's bat							
						Bechstein's bat							
						Noctule bat							
						Lesser noctule							
						Big brown bat							
						Parti-coloured bat							
						Barbastelle bat							
						other European							
						All European							
						other non-European							
						All							
						Not specified							

2.2 Determining mitigation types

As an overall structured framework, the widely recognized mitigation hierarchy was applied, commonly used to manage biodiversity impacts related to development projects. An overview of this hierarchy is presented in Figure 2-1. The bottom two mitigation steps, avoidance and minimization, are of a preventative nature and aim at managing the predicted impacts on biodiversity (and ecosystem services) until the remediative steps of restoration and offsetting (i.e. compensating) can reduce the residual biodiversity impact until 'No Net Loss' is achieved.

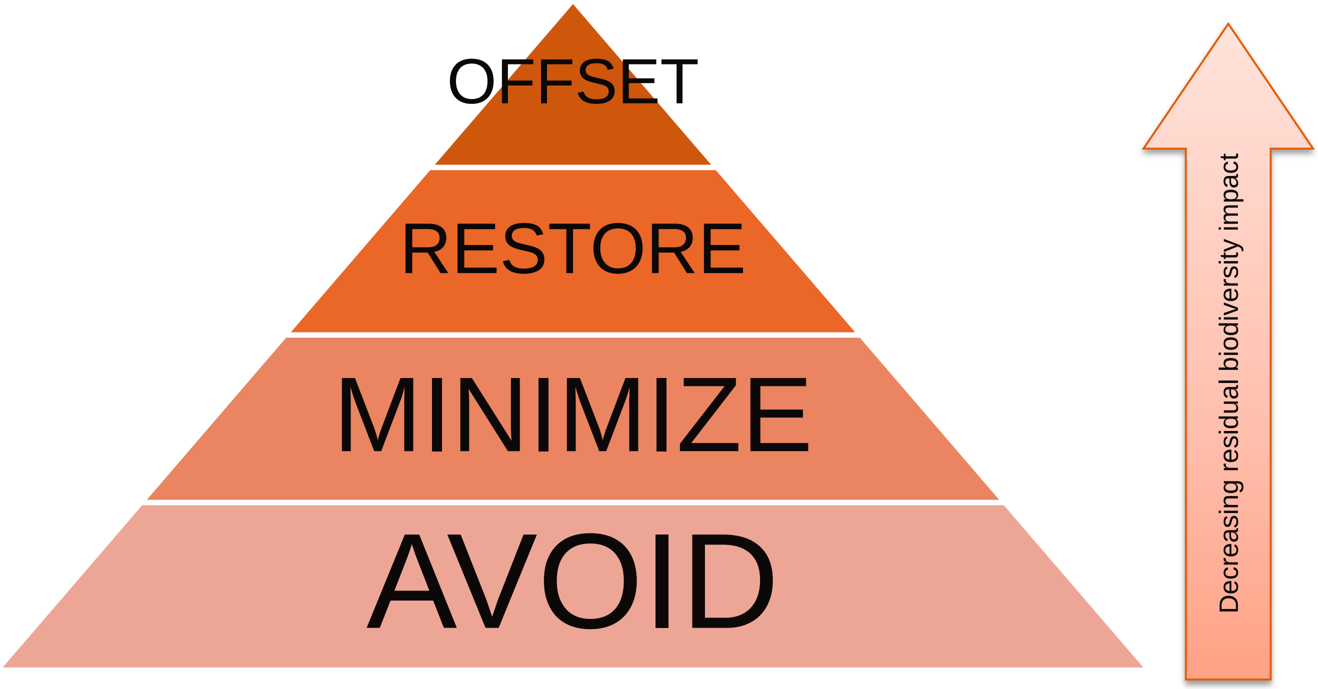

Figure 2-1: Biodiversity impact mitigation hierarchy, with decreasing residual biodiversity impact towards the top.

The mitigation measure types included in the methodological framework of this study, as discerned by the authors, are structured within the mitigation hierarchy and are listed below and elaborated upon in Table 3.

AVOIDANCE
- Habitat management
- Micro-siting
- Spatial planning

MINIMIZATION
- Construction phase measures
- Curtailment
- Detection
- Deterrence
- Turbine characteristics

RESTORATION
- Decommissioning

OFFSET/COMPENSATION
- Compensation

Table 3: Description of mitigation measure types and definitions

Mitigation type	Sub type	Definition
Compensation		The mitigation measure *compensation* refers to the application of compensatory measures often at a different location.
Construction phase measures		This mitigation measure refers to actions taken during the construction phase, before the wind turbine or wind farm becomes operational. Examples include scheduling construction outside active bat seasons to minimize disturbance.
Curtailment		The mitigation measure *curtailment* refers to the stand-still principle, achieved through feathering and/or increasing the cut-in speed. There are three types of curtailment: Blanket curtailment which refers to a fixed approach where wind turbines are shut down when e.g. windspeeds are below 5 m/s. Informed curtailment: shut down when a bat is detected. Smart curtailment*: curtailment based on bat activity measured in rotor swept area, a data-driven approach that adjusts turbine operation based on (real-time) environmental factors and bat activity. Opportunities for smart curtailment are studied using innovative technology and the implementation of improved algorithms.
Decommissioning		*Decommissioning,* assessing the operational functionality of wind turbines or wind farms and dismantling them if standards are not met, thereby reducing collision risks.
Detection		*Detection* measures aim to optimize collision risk mitigation by implementing detection systems that enhance these efforts. Examples of this include (AI-)cameras and bat detectors. Detection will therefore always operate in tandem with additional mitigation measures.
Deterrence	Visual*	This mitigation measure focuses on deterrent systems that use visual disturbances to discourage bats from specific locations. Examples include the use of ultra-bright lights.
Deterrence	Acoustic*	This mitigation measure focuses on deterrent systems that use acoustic disturbances to discourage bats from specific locations. Examples include the use of ultrasonic sound.
Deterrence	Other	This mitigation measure focuses on deterrent systems that do not rely on sight or hearing. Examples include scent-based agents and the use of electromagnetic fields.
Habitat management		This mitigation measure involves modifying the environment to make it less favorable for bats.
Micro-siting		*Micro-siting* involves the spatial planning within the wind farm itself. It includes optimizing the position (e.g., clustered or dispersed) and the number of turbines, as well as other facilities such as roads and power lines within the wind farm. This process can also involve maintaining turbine-free movement corridors between key landscape and habitat features, such as known roosting or breeding sites and foraging areas.
Spatial planning		The mitigation measure *spatial planning* aims to reduce impacts on bats by incorporating large-scale spatial considerations. This approach ensures that locations with a high risk of collisions are avoided. Examples of this measure include avoiding known migration routes, establishing buffer zones, and maintaining fixed minimum distances from known roosting sites.
Turbine characteristics		*Turbine characteristics* include measures that focus on the physical attributes of a single wind turbine. These can include turbine height, rotor diameter, ground clearance, and more.

** Some studies combine both deterrent systems into a single tool (i.e., devices that emit both bright lights and ultrasonic sound).*

2.3 Assessment methodology

Following the technical information, for each measure an analysis on the effectiveness and applicability to the Dutch and offshore context was done. These can be found in column P -S in Appendix A. During the literature review this analysis focused on four topics: effectivity, suitability to the Dutch ecosystem, suitability to the offshore environment and uncertainty level. The assessment outcomes were roughly divided into three categories: not suitable, has potential and common/applicable. The precise terms and color schemes used per criterium can be found in Table 4.

After the literature review, the expert analysis focused on effectiveness and applicability to the Dutch and offshore context. This resulted in two more added columns to the framework (U and V in Appendix A), as well as a column containing relevant additions and comments.

Once all subcategories were filled out, a final assessment was done on a semi-qualitative scale (using a four-tier color scale) for each criterion. The color scales and assessment rules are presented in Table 5, and the final assessment can be found in column Y of appendix A.

Table 4: Drop down menu options used for the assessment of each mitigation measure and its applicability in the offshore North Sea context.

Effectivity	Suitability ecological NL	Suitability offshore NL	Uncertainty level
Sufficient scientific evidence from literature - validated by experts	Common species NL	Direct implementation	Multiple studies (scientific info) - high level of detail
Insufficient scientific evidence from literature - validated as high potential by experts	Similarity species NL	Currently onshore - potential offshore (extrapolation)	Research ongoing (sporadic studies) - high level of detail
Insufficient scientific evidence from literature - not supported by experts	Not suitable	Currently onshore - Not suitable offshore	Non-scientific info
			Poor level of detail - not reliable

Table 5: Drop down menu options for the final assessment of each mitigation measure.

Final assessment category	Applied when
Already implemented - is best practice	Five or six out of all criteria are green.
Worth researching	Some green, some yellow, no red criteria.
Has some potential	Mainly yellow, some green and red criteria.
Not worth investigating further	50% or more of the criteria is red.

3 Literature study and information gathering

3.1 Consulting international colleagues

3.1.1 Method

Arcadis has an international network of experts working on offshore wind, called the Arcadis Global Community of Practice Offshore Wind. Some of these colleagues work on very technical matters such as designing cable grids and power stations, but many of them operate in environmental permitting. To ensure colleagues exchange information and collaborate internationally, a live conference on offshore wind was organised in September 2024 (see Figure 3-1).This network was consulted to provide information on the bat mitigation measures. The request was submitted via email to all the participants from the Community of Practice (CoP) Offshore Wind. The request included literature and information on best practices, as well as known and used bat mitigation measures in wind farms in their countries. Both offshore and onshore examples could be included, as well as any species of bat. The goal was to create an overview of international knowledge and then decide which measures have potential in the Dutch offshore environment.

As a result, information was received from colleagues stationed in Australia, the United States, Canada, Chile and Brazil. The information was compiled and added to the literature (listed in Appendix A, tab 2).

Figure 3-1: Offshore wind fall school Glasgow, September 2024. A selection of all Arcadis colleagues working on offshore wind from around the world.

3.1.2 Gathered information

The request for information was returned with many replies, ranging from various emails with sources to words of encouragement and requests to share the results. In Table 6, the Arcadis operational countries which provided input are listed.

Table 6: overview of Arcadis operational countries which provided input for the review.

Arcadis operational country	Input received	Short summary input	Resulted in Code Data Source nr. in Appendix A
Australia	Wind energy guidelines, papers	Guidelines for spatial planning and papers with the measures curtailment and deterrents	27, 17, 30
Brazil	Papers	List of papers about bat mitigation measures in Brazil	31, 32, 33, 34
Canada	Canadian based reports, Environmental Assessments, Assessment and Status Reports	Wide range of inputs, from EEAs to Recovery Strategies and Offshore bat observation maps and database	19, 21, 22
Chile	Papers and guidelines	List of papers mainly on curtailment and guidelines regarding monitoring	24, 12, 36,
U.S. Louisville KY	Deterrent systems, wildlife systems and REWI research Hub	Websites to relevant deterrent and monitoring systems.	28, 35
U.S. Eastern US	Link to the Bureau of Ocean Energy Management	Has the EIA and EIS documents as well as a number of biological consultations.	No new relevant measures found.
U.S. Northeast NYS	Link to New York State Energy Research and Development Authority	This had some relevant studies	18

3.2 Online literature searches

3.2.1 Method

In this study, all measures known to the authors and recent measures from scientific and grey literature are described. References to conceptual measures, for which no scientific evidence is yet found in the literature, are included in the framework with a clear indication that information is missing, or further research is necessary. Reverse searching was also applied during the literature search. This method uses the reference list of relevant papers to search for additional literature.

The main search engines used were Google and Google Scholar. To prevent outdated literature on measures, mainly sources from 2015 onwards were used. The search terms were focused on general mitigation, including terms such as "bat mitigation", "bat wind turbine mitigation", "bat migration mitigation" and "global bat mitigation measures", as well as more specific measure types, such as "bat deterrence systems" and "bat detection measures".

3.2.2 Gathered information

The online literature research resulted in 14 rows of findings summarized in Appendix A. The focus was primarily on recent scientific papers to ensure the information was up-to-date and relevant. As the information began to overlap and repeat the search was concluded. Additionally, several summary papers were identified (often addressing both birds and bats in their assessment) and relevant mitigation measures were added to the matrix.

3.3 Other literature sources

3.3.1 Method

Other literature sources were suggested references by the in- and external experts (see § 4) and the information gathered at the NSEC Workshop - Mitigation measures offshore wind as provided by Rijkswaterstaat.

3.3.2 Gathered information

The experts provided code data source 36 to 40 in the literature sources of the methodological framework (Appendix A, tab 2). The report on the NSEC Workshop provided by Rijkswaterstaat is found in code data source 29.

3.4 Consulting AI

3.4.1 Method

In the effort of gathering a complete state of the art concerning bat mitigation measures, Artificial Intelligence (AI) was applied. To this end, two different AI environments were consulted. The first consisted of the Arcadis version of ChatGPT (A-GPT). The difference with regular AI includes, among other things, that this segregated environment does not have permission to use our data for learning purposes. Additionally, Microsoft Copilot was used because of its integration with Microsoft Edge, providing an edge over A-GPT regarding linking provided information to their sources. The applications were tested for their added value in the data inventory, and the outcomes were rigorously checked for reliability.

AI used:
- GPT- 4o https://arcadisgpt.poweredby.arcadis.com/
- Microsoft Copilot https://copilot.microsoft.com

In total, four prompts were designed for reproducibility and tried as single prompts, each done in a new chat. Additionally, a comparison with Co-pilot in regard to finding sources was made. For each prompt, the AI response is included in Appendix B.

In a first prompt, the AI was asked to produce mitigation measures:

Provide a list including sources with mitigation measures for bats for offshore wind farms. Put the different mitigation measures in categories.

After analysing the results, the next prompt was redesigned to focus on acquisition of sources concerning a single category of mitigation measure and linking these results to the sources:

Provide a list with as many reliable sources as possible on operational-phase mitigation measures for bats for offshore windfarms. Add a link to google scholar and if available one other legit link as well. Check all the links for linking to the correct source you provided. The sources cannot be older than 2020.

For prompt number three the focus was on acquiring as many of the different mitigation measures available on internet as possible, followed by a manual search for the related papers:

Provide a list with all the different mitigation measures available for bats for windfarms, make it as comprehensive as possible.

In the last prompt, the A-GPT was asked to analyse an extensive 400-page Environmental Assessment for mitigation measures:

Can you analyse this report and provide me with all the mitigation measures for bats?

Additionally, the second prompt was reused in a different AI environment (Microsoft Co-pilot), in order to conduct a comparison:

Provide a list with as many reliable sources as possible on operational-phase mitigation measures for bats for offshore windfarms. Add a link to google scholar and if available one other legit link as well. Check all the links for linking to the correct source you provided. The sources cannot be older than 2020.

The gathered information from this method is presented in Appendix B. An output analysis summary is discussed in the next paragraphs.

3.4.2 AI output analysis and gathered information

What worked:
A-GPT performed well in organizing and categorizing information. In Prompts 1 and 3, it provided clear lists of mitigation measures that were detailed and easy to follow. Its ability to pinpoint where mitigation measures were mentioned in reports, as seen in Prompt 4, was especially useful for quickly finding relevant sections. Copilot also showed promise in Prompt 5 by providing working links to PDFs and summarizing documents, making it helpful for gathering content directly from sources. Overall, A-GPT's ability to structure information and locate details within reports made it a valuable tool for handling complex topics.

What didn't work:
A-GPT struggled with reliability when it came to sources. In Prompts 2 and 4, it generated references and links that did not lead to real or accurate papers, requiring users to double-check everything manually. There were also errors in categorizing mitigation measures, like placing lighting strategies under deterrents in Prompt 1. In Prompt 4, A-GPT did not always focus on measures specific to bats, and the page numbers provided referred to the PDF reader instead of the report itself, which caused confusion. While Copilot offered working links in Prompt 5, it failed to meet the requirement for sources newer than 2020, reducing the relevance of the results. These issues highlight the need for careful review when relying on AI for precise or source-heavy tasks.

Overall recommendations:
When using AI, it's important to verify the information it provides, especially when it comes to sources and links. While AI is great at organizing and categorizing data, it can sometimes make mistakes, like fabricating references or misplacing details. For tasks involving reports, its ability to pinpoint sections is helpful, but users should double-check page numbers and ensure the measures are truly relevant. Added value is found in the ability to summarize content from PDFs, though the scope is limited, and it doesn't always meet specific requirements like source age. Overall, AI is a useful tool for organizing information but works best when combined with manual checks to ensure accuracy and reliability.

Information gathered:
A-GPT didn't directly provide accurate or existing papers in every case. A few of the references provided by A-GPT did exist but had already been used in the literature review, limiting their novelty. As a result, no entries were added to Appendix A based on the AI consultation.

For the interested reader, a full report on this AI-experiment can be found in Appendix B.

4 Mitigation measures overview

4.1 Brief overview of all measures found

The literature review and expert consultations identified 10 main types of mitigation measures as was presented in § 2.2. The specific measures can be found in the methodological framework in Appendix A. This mitigation measures overview includes all found measures, both on- and offshore, and can be interpreted as a glossary. The mitigation measure types have been structured according to the previously described mitigation hierarchy (see Figure 2-1).

Habitat management
Three habitat management measures were found but were considered as not relevant for offshore. Two of these measures focused on reducing attraction by food sources through vegetation management and providing alternative habitat to lure bats away from high-collision risk areas. Additionally, one measure focused on reducing habitat degradation through the construction of fences around wind farms to limit human activity.

Micro-siting
Three mitigation measures from the framework focus on micro-siting. These measures aim to avoid high collision risk locations and are implemented in the early stages of project design. Micro-siting specifically focuses on turbine placement and spatial arrangement on a localized scale, within the wind farm area. Turbine configurations can vary, ranging from clustered layouts to linear arrangements or even the creation of turbine-free movement corridors.

Spatial planning
In total, seven spatial mitigation measures are discussed in the framework. Similarly to micro-siting, these measures focus on avoiding high collision risk locations and are implemented in the early stages of project design. They rely heavily on knowledge of local species distribution, migration patterns, activity levels, roosting sites, and other ecological factors.

Construction phase measures
Two construction phase measures are included in the framework, focusing mainly on time management. Construction should be limited during sensitive periods, and pre-construction vegetation clearing should be conducted outside sensitive periods.

Curtailment
A total of 11 mitigation measures focusses on curtailment, which is widely regarded as the most commonly applied and most effective method for reducing collision risk. A distinction must be made between the three types of curtailment. Blanket curtailment involves reducing or shutting down wind turbine operations at fixed times or under specific conditions (e.g., during high wind speeds or wildlife migration periods) without real-time adjustments. In contrast, smart curtailment utilizes real-time data (e.g., weather conditions, detected bat and bird activity, or grid demand) to dynamically adjust turbine operations. The latter approach minimizes energy loss while still achieving mitigation objectives, by reducing wildlife collisions and optimizing grid efficiency. Various experimental models are being developed to enhance smart curtailment. However, their effectiveness is still under investigation. Finally, informed curtailment shuts down turbine operations when bats are detected.

Detection
A total of 12 detection measures are examined in the framework. These measures can be categorized into acoustic detection (relying on bat vocalizations), visual detection (predominantly utilizing thermal imaging), radar detection and telemetry detection (only for tagged individuals).

Deterrence
The framework includes nine measures aiming at mitigation through deterrence of bats. Only one measure focuses on the use of visual deterrence. This study examined the effectiveness of drone-mounted visual deterrence in combination with acoustic deterrence as a potential strategy to reduce bat mortality. Six additional measures focus on the use of acoustic deterrence systems, which employ ultrasonic sounds to deter bats. Finally, two measures explore alternative deterrent systems, specifically electromagnetic radiation.

Turbine characteristics
Ten mitigation measures focus on turbine characteristics, primarily aspects such as height and rotor diameter. Other characteristics, such as lighting regime and ground clearance, are also considered. However, it is important to note that these mitigation measures primarily aim to explore the impact of specific turbine characteristics. Limited relevant information is available on modified turbine characteristics.

Decommissioning
The two decommissioning measures found in the literature describe how turbines that do not produce the projected amount of electricity could be decommissioned to prevent unnecessary collision risks. Additionally, turbines which are not expected to be put back in operation (e.g. due to technical failure) should be decommissioned for the same reason.

Compensation
Three measures focus on the implementation of compensatory strategies. These include population-enhancing compensatory measures outside the project area, as well as on-site restoration efforts following the dismantling of the turbines.

4.2 Initial scientific validation

A scientific validation of each mitigation measure was conducted to evaluate its effectiveness and preliminary suitability for onshore and offshore applicability, which is detailed in columns P to S of the methodological framework (see Appendix A). For a comprehensive, measure-by-measure evaluation of scientific validation, we refer to full framework (see Appendix A).

All ten mitigation measure types were subjected to scientific validation. Curtailment proved the most versatile, as this mitigation measure is still studied intensively, and literature contained a wide range of different curtailment strategies. The standstill with low windspeeds, for example, was proven very effective to prevent bat collision but very crude in terms of energy efficiency. Improving curtailment by looking at multiple predictors and models seems like the way forward, with a growing amount of validated research to back up its effectiveness.

Spatial planning and micro-siting are scientifically proven to be effective and the same goes for habitat management, compensation, construction phase measures and decommissioning.

For bat mitigation through the use of deterrents, scientific validation was dependent on the type of deterrent and the novelty of the technique. Novel deterrent techniques, such as the use of electromagnetic fields, had little to no scientific validation (yet), while different acoustic deterrent techniques were supported by multiple scientific studies. Visual deterrents differed greatly in the amount and conclusion of scientific validation studies, as some contradicting literature was found.

Reviewing mitigation measures linked to turbine characteristics turned up literature discussing scientifically validated correlations between rotor height and turbine size and bat mortality. Other turbine characteristics seemed to be less covered in literature.

Detection measures aiming to optimize collision risk mitigation is a research area where most of the novel systems originate from. Detection systems, either singular or combined to increase sensitivity, are being developed swiftly and the research is still cutting-edge. Therefore, most novel systems are not yet scientifically validated, but show great potential nonetheless.

5 Expert Validation

5.1 Method and consulted experts

5.1.1 Internal experts

After compiling all gathered knowledge on bat mitigation measures in the methodological framework and reviewing over 40 literature sources, an internal expert workshop was organized with two bat ecology experts working at Arcadis Netherlands and Belgium. This in-house interview served as a first evaluation of the effectiveness and applicability of the gathered mitigation measures within the Dutch offshore context. During the consultation session, the initial assessment of sources conducted by the literature reviewers was reviewed and validated. The measures were evaluated, and their effectiveness and feasibility were thoroughly discussed. The following internal experts contributed to this part of the study:

- Herman Bouman (NL)
- Pieterjan Dhont (BE)

5.1.2 External bat expert consultation

5.1.2.1 Method and chosen experts

Experts affiliated with multiple consortia were approached, including ecologists linked to EUROBAT, BWEC, BOEM, and NSEC. In Belgium, connections with knowledge institutions such as the Research Institute for Nature and Forest (INBO) and the Royal Belgian Institute of Natural Sciences (KBIN) were established as well.

The final selection of external experts was based on Arcadis' existing network and the experts' availability. This process began immediately after project approval to ensure interviews could be scheduled in alignment with all agendas. Unfortunately, not all the experts we hoped to engage—particularly individuals from key organizations such as EUROBAT—were available to participate in the interview process. An elaboration on these challenges can be found in § 5.1.2.2.

Despite these limitations, we successfully conducted interviews with two Dutch and one Belgian bat experts. The following experts contributed to this study:

- René Janssen (Bionet Natuuronderzoek)
- Martijn Boonman (Waardenburg Ecology)
- Robin Brabant (Royal Belgian institute of Natural Sciences)

Before the interviews, the experts were asked to provide additional literature deemed relevant to this study. During the interviews, all the mitigation measures gathered in the framework and reviewed through the methods described above were discussed, seeking their insights and opinions on these approaches.

5.1.2.2 Challenges

Identifying and engaging experts to contribute to the project proved to be a challenging task due to several factors. Firstly, the short runtime of the project presented significant logistical difficulties. Attempting to schedule interviews as early as January for discussions planned in March created a tight timeline, leaving insufficient time for experts to adjust their schedules and commit to participation.

Secondly, there were discrepancies between the scope of the project as envisioned by the research team and the expectations or preferences of the experts. While the project aimed to focus on specific mitigation and compensation measures for bats around offshore wind turbines, some experts expressed a desire for a broader scope that included additional topics or considerations. This mismatch in expectations limited their willingness to contribute within the defined parameters of the project.

Lastly, some experts preferred a more substantial role in the project, such as full partnerships, rather than the more limited consulting role initially envisioned. These experts sought deeper involvement in the research process and decision-making, which was not aligned with the project's structure or timeline. This divergence in preferred levels of engagement further complicated efforts to secure their input.

These challenges underscore the importance of aligning project objectives and timelines with expert expectations and availability to ensure meaningful collaboration in future initiatives.

5.1.2.3 Technical advisor

To assess the applicability of mitigation measures with potential and worth researching in the offshore context, technical input was provided by Joris Diehl from Rijkswaterstaat's Centrale Informatievoorziening (CIV) department. As an engagement manager specializing in ecological sensors, Joris shared his expertise and offered valuable insights into the feasibility and implementation of these measures. With his background as an ecologist at the Offshore Expertise Centrum (OEC), he contributed his professional opinion on how well the promising measures could be adapted to the unique challenges of the marine environment.

5.2 Outcomes expert validation

The literature provided by the in- and external experts was already listed in paragraph 3.3.2. The input contributed to the methodological framework in Appendix A, in particular to column U and V of Appendix A.

The input of both internal and external experts, as well as the technical advisor, is summarized per mitigation type below and is presented in agreement with the mitigation hierarchy (see Figure 2-1). The expert discussions were open to mitigation of bat collisions in all environments, with a focus on offshore when possible.

Habitat management
Habitat management, a measure commonly used for land-based wind farms, is considered irrelevant for offshore wind parks. Bats generally do not use offshore areas as foraging habitat, and therefore habitat management measures are not easily applicable in the North Sea environment. <u>Habitat management measures in an offshore environment are therefore not taken into further consideration</u>

Micro-siting
The placing and spacing between wind turbines within a concession zone may play a role in bat collisions, but this remains uncertain. Investigating the impact of turbine density on bats could be worthwhile. Experts note that bats offshore do not follow landscape features or landmarks, which makes micro-siting irrelevant in the context of offshore North Sea projects. Onshore, factors such as vegetation structures should be considered in turbine placement. For example, barriers could potentially be avoided by arranging turbines in a single row or orienting them differently. These considerations may help reduce the risk of bat fatalities.

Spatial planning
Spatial planning, which entails designing larger-scale wind farm layouts to minimize bat impacts, is not deemed a priority for offshore wind farms in the North Sea in this context. Site selection for offshore wind parks is typically the result of decisions made by multiple countries and is primarily based on marine spatial planning and a multitude of technical and geomorphological parameters. However, research into bat migration and flight routes over the North Sea is critical, as these patterns are not sufficiently understood. Until recently, for example, only sporadic information was available on the migration behavior of the parti-colored bat (*Vespertilio murinus*). In 2025, Belgian scientists were able to attach a tracker to a stranded individual[3]. This revealed astonishing insights into its migratory patterns, behavior that remains poorly understood to this day and requires more research. Better knowledge of these routes (for all bat species) could help inform more effective mitigation strategies in the planning of future offshore wind farms. Spatial planning in an onshore wind farm could be far more effective than in an offshore environment.

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[3] https://www.vrt.be/vrtnws/nl/2025/04/07/tweekleurige-vleermuis-vliegt-in-1-nacht-2-keer-het-kanaal-over/

Construction phase measures
Mitigation measures implemented during the construction phase of wind farms are unlikely to provide significant benefits for bat conservation. Construction activities typically occur during daylight hours, when bats are not typically active. While nighttime lighting used during construction may attract insects, and consequently bats, there are no operational turbines at this stage, meaning no collisions or fatalities for Nathusius' pipistrelles are expected. Experts therefore conclude that construction phase measures are not necessary for bat conservation. It appears that operational effects, such as those caused by functioning turbines, are more critical to consider than construction-related effects. Nighttime lighting during the construction phase may be relevant, but only to a limited extent. The presence of lighting during the operational phase is very limited, so similarly limited in relevance.

Curtailment
Curtailment is considered a promising mitigation measure, provided that further research is conducted to address knowledge gaps and rebate assumptions. Curtailment involves periodically stopping wind turbines during critical periods of bat migration, such as in May and August/September, and is considered a promising mitigation measure. However, migration routes are still poorly understood, which limits its applicability. Curtailment models need to be divided into variables to assess whether this approach is relevant for offshore situations. Experts note that this is the most practical solution currently available to address bat mortality risks. However, they emphasize that curtailment is more relevant for land-based wind farms than offshore installations. Certain wind parks, such as those located near major migration routes like the Afsluitdijk, pose a greater threat to Nathusius' pipistrelles compared to offshore wind parks.

Detection
Detection technologies, such as radar or Infra-red and thermal camera systems, show potential for identifying bats approaching wind turbines and could play a role in mitigation strategies. However, experts highlight several challenges regarding their feasibility in offshore environments. Experts question whether detection measures are cost-effective. For detection to be successful, the distance between the monitoring equipment and the bats must be properly aligned. Additionally, sound-based detection systems may be ineffective in the North Sea, as sound does not carry far enough to detect bats in the entirety of the rotor swept area and so provide timely detection for bats nearing this area, Radar-based detection may hold more potential, but it requires further research to determine its effectiveness and feasibility. Detection based on These challenges must be addressed before detection technologies can be considered viable solutions.

Deterrence
Blade modifications, such as texture or paint applications, may deter bats but are unlikely to be implemented due to concerns about reduced turbine efficiency and energy production or are not proven to be effective. Acoustic deterrence measures are believed to be more promising for offshore wind farms, as onshore installations often overlap with bat habitats, complicating their suitability and effectiveness. Sound-based deterrence devices also face significant limitations offshore, as ultrasonic frequencies required to deter bats like Nathusius' pipistrelles (37-40 kHz) do not propagate effectively over long distances. In general, and depending on temperature and relative humidity, a 20-30 m detection distance can be assumed. These technical and practical challenges reduce the applicability of deterrence measures in offshore wind farms. UV-based deterrence methods require additional research, as they could potentially attract bats (or the prey of bats) by acting as the only light source in the offshore environment. Questions persist regarding the influence of electromagnetic fields on bats and whether they are efficient as a deterrence measure. Further research is deemed essential to evaluate the effectiveness of these technologies.

Turbine characteristics
A notable trend in wind energy development is the use of increasingly larger turbines. This raises concerns about potential collision risk and linked negative effects on Nathusius' pipistrelles in offshore environments, although this remains an assumption and requires further investigation. These mitigation measures show potential, as they could be tailored specifically to the characteristics of bat migration behavior rather than focusing solely on foraging behavior. The distance between the turbine blades and the water surface (i.e. ground clearance) is highlighted as a critical factor in determining collision risks. Further research into bat flight behavior and altitude could prove an interesting and relatively straightforward advance to assess to what extent offshore turbine blades pose a collision risk for migrating bats.

Decommissioning
Decommissioning wind parks that fail to generate sufficient energy is not considered a practical mitigation measure. In practice, such ‘underachieving’ wind farms are often expanded to improve profitability rather than dismantled. Alternatively, these wind parks may be sold and relocated to other regions, such as Eastern Europe, which further diminishes their feasibility as a mitigation strategy if they are placed somewhere where bat fatalities are not mitigated. <u>Bat mortality mitigation through decommissioning measures is therefore not taken into further consideration.</u>

Compensation
Compensation measures, such as (re)creating or offsetting habitats, have proven effective for land-based wind farms but are not relevant in offshore environments. Since offshore wind parks do not lead to the loss of bat habitats, such measures are unnecessary in this context. However, experts have suggested that effective compensation could involve decommissioning and/or curtailing turbines located in high-risk areas where scientific evidence identifies significant bat mortality. This targeted approach offers a practical solution to reduce bat fatalities in regions with elevated risks, balancing renewable energy development with wildlife conservation. Additionally, experts also agree that approaching compensation measures more holistically could be beneficial for mitigating bat mortality. Compensation of potential offshore bat mortalities as a result of operational wind farms could be achieved through improvements or enhancements at verified onshore bat territories (e.g. roosting colonies), and as such, apply compensation on a population level.

5.3 Expert judgement on measures with potential in the Netherlands

Next to scientific validation of the mitigation measures’ effectiveness, the suitability of these measures within the Netherlands was assessed. As some of the mitigation measures encountered during the literature study are designed for specific foreign bat species and some of these species do not have the same characteristics as the commonly encountered Dutch bat species. Based on the internal and external expert sessions, mitigation measures were re-evaluated with an eye on suitability in the Netherlands (both onshore and offshore) and details on this selection can be found in columns U to Y of the methodological framework in Appendix A.

Spatial planning and micro-siting
One of the key points discussed during the expert workshops was the importance of spatial planning in reducing bat fatalities. It was emphasized that proper upfront site selection is a more critical issue than on-site mitigation measures, as avoidance should always precede minimizing potential impacts according to the mitigation hierarchy (see also Figure 2-1). Spatial planning is therefore crucial when selecting new wind farm locations. However, it was noted that various important factors are at play during spatial planning, including technical and geomorphological considerations, ecological implications are not always prioritised and known. Significant knowledge gaps remain regarding migration patterns which could make mitigation through spatial planning and micro-siting potentially more effective.

Construction phase measures
Some of these mitigation measures were recognized as having potential but were not extensively discussed due to their limited applicability in offshore environments. Construction phase measures, such as minimizing nighttime construction activities, were included in the framework to provide a complete overview nonetheless.

Curtailment
Experts highlight that targeting curtailment efforts at these high-risk land-based locations would likely yield more significant conservation benefits than further improving curtailment offshore. Currently, offshore bat curtailment only takes place during autumn the autumn migration period, it was discussed that the cutoff period is only relevant during specific high-risk months not only the autumn migration period. Further research into peak months and bat behaviour is required to optimize the effectiveness of curtailment. Additionally, the use of curtailment in terms of appropriate cut-in wind speed for turbines to power on was deemed a very relevant mitigation measure, but additional research into flight speeds and preferred wind speeds could similarly optimize its effectiveness. Moreover, it was suggested that there are correlations between wind direction, the migration period (spring or autumn migration), the region (northern versus

southern Netherlands), as well as other weather conditions (e.g., rain), which differ significantly from migratory patterns over land. While various variables are already used in offshore curtailment, better understanding these factors could provide valuable insights for tailoring curtailment measures to specific situations and locations.

Detection

Proximity detection and acoustic detection were considered, and concerns were raised about their feasibility. Acoustic detection, where bats are detected using sound recorders, was deemed impractical due to its short range and the time required to shut down turbines. Proximity detection, e.g. using camera or radar systems, may offer a more cost-effective alternative, but technical aspects, such as detection range and the speed of turbine shutdown, require further investigation. As only a tiny portion of rotor swept area is sampled with the acoustic detection, many bats remain undetected. Additionally, concerns remain about how quickly a wind turbine can be stopped after detection. In an emergency, turbines can be stopped in a few seconds, but a potentially large number of false detections make for a problematic scenario in this case. It takes ca. 5-10 minutes to stop a turbine in a ‘regular’ way, meaning this method would not be effective if detection only has a limited range. Experts highlight several more challenges regarding the feasibility of detection systems in offshore environments. Devices like speakers, recorders and cameras are prone to corrosion due to saltwater exposure and require frequent maintenance, which is complicated by workforce limitations and logistical demands.

Deterrence

Experts are generally skeptical about deterrence measures aimed at reducing bat collisions with wind turbines. Acoustic and UV deterrents were identified as potentially more interesting offshore than onshore, as they have less impact on marine habitats. However, UV deterrents require further research, as they may inadvertently attract bats if they are the only light source in the area. The short range and scale of ultrasonic deterrents pose challenges compared to the size of offshore turbines. However, the possibility to use deterrents as a supplemental measure should be considered, according to experts. Electromagnetic fields were discussed as a potential deterrent, but more research is needed to assess its viability and effectiveness.

Turbine characteristics

Mitigation through turbine characteristics do have potential to be effective. Onshore, this is particularly relevant when wind turbines are placed near structures such as rows of trees, with blades intersecting bat flight routes. Offshore, increasing ground clearance could hold potential as a bat collision mitigation measure, but experts emphasize that the flight altitude of bats over the sea is still not well understood. Adapting turbine characteristics shows potential as a mitigation measure because this approach focuses solely on research of bats' migration behaviour rather than foraging behaviour, which does not occur at offshore wind farms. This makes the implementation of this measure possibly more applicable for offshore situations.

Compensation measures

Compensation measures, such as creating or enhancing habitat in close proximity to wind farms, were identified as having potential in areas with diverse and ecologically distinct habitats. However, offshore environments were considered to have limited potential for such measures due to their lack of ecological diversity relevant to bats. It was suggested that effective compensation could involve decommissioning or curtailing certain high-risk onshore wind turbines in areas where scientific evidence demonstrates significant bat mortality. This approach may offer a viable solution to reduce bat fatalities in areas of heightened risk. Additionally, indirect compensation measures could be located within known onshore bat territories.

5.4 Applicability in the Dutch offshore scene

After internal and external expert workshops, several mitigation measures were found to be less suitable mitigation of bat casualties in an offshore environment due to ecological traits related to (migrating) bats as well as technical challenges. Many mitigation measures considered as best or common practice when considering an onshore wind farm, cannot readily be applied in an offshore marine environment. Critical differences in biotic and abiotic parameters arise, meaning an onshore to offshore extrapolation is not always feasible. Technical advisor Joris Diehl was consulted in order to gain further insights, and valuable input was provided on the feasibility of the measures with potential and worth researching.

Habitat management

Habitat management was considered irrelevant offshore, as bats mostly lack roosting or foraging habitats in these areas. Mainly migration behavior is observed offshore, and therefore the marine environment acts as a transient habitat for temporary use.

Micro-siting and spatial planning

Micro-siting and spatial planning cannot be extrapolated one-on-one from an onshore to an offshore context. On land, these measures can work by considering things like vegetation and proximity to bat habitats, but offshore environments lack these ecological features. Micro-siting is not particularly effective offshore because there is little to adjust in terms of site-specific risks for bats. Spatial planning also poses specific problems in terms of applicability offshore, as bats don't forage in the marine environment and their migration routes offshore are still not fully understood. However, as a rule of thumb, experts agree that avoiding the nearshore areas is a must. Bats can make use of these first few kilometers offshore when migrating parallel to the coast or when foraging in coastal habitats.

Construction phase

Construction phase measures, such as limiting nighttime activities, do not readily apply to offshore environments since bats are not attracted to marine construction sites in a similar way to e.g. foraging or nesting seabirds. To that end, limiting construction to preferred seasons or an adopting a tailored light management could be beneficial.

Curtailment

Curtailment, which involves temporarily shutting down wind turbines during high-risk periods, is shown to be an effective way to reduce bat fatalities offshore. By focusing on specific times of the year when bats are most active or when wind speeds are no longer favorable for migrating bats, this approach has great potential to minimize collisions. However, its success relies on better understanding bat migration patterns and pinpointing peak activity periods in offshore environments, where data is still limited. With more research, curtailment could become a practical and targeted solution that balances bat protection with energy production needs.

Detection

Acoustic detection systems are largely considered impractical for offshore use due to several technical and logistical challenges. These systems rely on high-frequency microphones to detect bat activity, but their detection range is very narrow, making them inefficient in the expansive marine environment. Additionally, the time required to shut down a turbine after detection (ca. 10 minutes) further limits their ability to effectively prevent bat fatalities. A quicker shut down time can be achieved by a forced stop, but this is only allowed in emergency situations. Adding to these issues is the limited durability of high-frequency microphones, which typically last only about a year. Replacing these microphones annually across large offshore wind farms would be logistically complex, prohibitively expensive, and unsustainable, making acoustic detection an unviable solution for offshore bat mitigation.

Radar detection can be used to detect small bats and birds from approximately a 2-kilometer distance. However, by itself, most radar detection cannot distinguish between birds and bats. Technological advances in radar systems include the ability to differentiate between birds and bats based on wing beat frequency, which could be a way forward in using radar as part of an effective mitigation strategy. For more detailed information on the type of organism or on the species detected by the radar system, this technology must be paired with visual detection. Visual detection systems for monitoring bat activity face several challenges in offshore settings. Methods like cameras and AI-powered systems require high-resolution imaging, and their effectiveness is limited by factors like low light conditions, the large scale of the marine environment and the small size of bats, all making visual detection of bats harder. Infrared and thermal cameras can help with nighttime detection but maintaining them in harsh offshore conditions is expensive and complex.

Deterrence

Light and UV deterrents could potentially attract insects and by that bats rather than deter them. In offshore environments, these deterrents may inadvertently draw bats closer to the wind farm if these are the only light sources in the vicinity. The absence of surrounding structures or habitats further limits their effectiveness in the marine setting. Similarly, acoustic deterrents face challenges in offshore implementation, as the ultrasound frequencies used do not carry far (approx. a few meters) relatively to the vast size of wind turbines and the distances between them. High frequency deterrence is also species dependent, with some methods currently untested for European bat species. This significantly reduces their ability to independently and effectively deter bats in large offshore wind farms.

Turbine characteristic

Adapting turbine characteristics shows potential as a mitigation measure within the Dutch offshore context, as it focuses specifically on bats' migration behavior rather than foraging behavior, which is generally absent in offshore environments. By tailoring turbine designs to migration patterns, this approach addresses the unique challenges of offshore wind farms. However, further research is needed to determine how specific turbine adaptations can effectively reduce collision risks and align with the ecological realities of the Dutch offshore scene. To incentivize further research into the applicability of turbine characteristics as an effective bat mitigation measure in offshore wind farms, it is crucial that ecological tender criteria are included in the early phases of tendering for offshore concessions.

Compensation and specific decommissioning

Compensation measures within the offshore environment are largely inapplicable due to the absence of ecological features relevant to bats. Offshore areas lack diverse habitats that could be enhanced or restored as a form of compensation, making such measures ineffective in this setting. Alternatively, a more viable approach to compensation (or rather restoration) involves decommissioning high-risk onshore wind turbines in areas with proven high bat mortality. This strategy could help offset the impact of offshore wind farms by reducing bat fatalities in regions where the risk is significantly higher. Additionally, ecological compensation could be achieved by improving certain onshore habitats (e.g. coastal habitats or established bat territories) and thus offsetting the potential offshore biodiversity impact.

6 Conclusion, discussion and recommendations

In this chapter, a concluding advice is provided on the measures with potential and worth researching (§ 6.1), the opportunities and limitations of the current research are discussed (§ 6.2) and recommendations for further research are given (§ 6.3).

6.1 Advice on measures with potential and worth researching

Based on the information above, we recommend the following measures as the mitigation strategies with potential related to bat casualties due to offshore wind farms: spatial planning, curtailment, detection, deterrence, turbine characteristics and (onshore) compensation. These measures show potential for reducing bat fatalities, particularly in the offshore Dutch context, and are further discussed below. The measures are prioritized (top to bottom) based on the mitigation hierarchy. It is important to note that the consulted bat ecology experts, looking primarily at mitigation measures potential effectiveness for the overall bat population, encourage 'compensation' as the first priority, as mortality rates onshore are significantly higher. In line with the mitigation hierarchy and within the offshore context, however, the proposed prioritization for the offshore context is as follows:

Priority	Motivation
1. Spatial planning	Avoidance comes before mitigating (mitigation hierarchy)
2. Curtailment	Considered to have the most potential (offshore) and to be most readily executable
3. Turbine characteristics	Considered to have potential, but more research is needed
4. Detection	Highest potential in tandem with curtailment, but (a lot of) research is needed
5. Deterrence	Few measures seem promising, but there are many technical challenges
6. Compensation	Most innovative and out-of-the-box, but further down on the mitigation hierarchy

Spatial planning
Several experts, i.a. Robin Brabant, have included marine spatial planning as a straightforward mitigation measure to reduce bat casualties. Since avoidance should always precede minimization (see the mitigation hierarchy in Figure 2-1), safeguarding the first few kilometers offshore could prove to be the first crucial step in an effective mitigation strategy. In practice this has already been done in the Netherlands as future wind farms are planned further offshore, where spatial planning is considered a less effective measure. Further research on preferred offshore routes and behaviors of migrating bat species could aid in defining potentially effective mitigation measures in terms of spatial planning offshore.

Curtailment
Curtailment, the temporary shutdown of wind turbines, is proven to be one of the most effective bat mitigation measures and shows great potential for further improvement. This can be achieved through advancing knowledge on preferred weather, by targeting specific migration periods or by adjusting the cut-in wind speed for turbines to favorable wind speeds for migrating bats. Currently, the migration period in spring is not well researched and does not have curtailment measures. The option of curtailment in spring should be re-evaluated. Additionally, this measure can be combined with advancements in tools and detection technology, meaning curtailment could be implemented based on more precise data, like radar-detected bat activity. Both curtailment (singular) and the combination with detection tools (combined) could prove effective and applicable to offshore wind farms.

Turbine characteristics
Adapting turbine characteristics, such as rotor size and ground clearance, could be an effective strategy for minimizing bat collisions. However, this measure relies on a deeper understanding of bat flight altitudes, particularly during spring and autumn migration periods. Comprehensive research into bat flight behavior is crucial to inform and optimize potential turbine modifications. Additionally, the potential costs, such as reduced efficiency and its impact on wind farm revenue projections, must be carefully weighed to ensure a balanced approach between conservation and economic viability.

Detection

Detection technologies, such as radar or wildlife tracking systems, show promise for identifying bats near wind turbines. Systems like MUSE, which combine multiple detection methods, are potentially adaptable for offshore use. Integrating advanced technologies such as AI-based systems may further enhance their effectiveness and suitability for the Dutch offshore environment. Further research into these possibilities could enhance mitigation strategies in the future.

Deterrence

Few deterrence measures appear promising. Further research is needed to determine if the correct ultrasonic frequencies can effectively deter specific bat species. However, the inability of sound to travel long distances combined with the large size of offshore wind turbines, must be considered to ensure the effectiveness of these systems in marine environments.

Compensation

An innovative mitigation approach involves curtailment strategies in onshore wind farms. Experts such as René Janssen, Martijn Boonman and Herman Bouman have emphasized that mitigating potential biodiversity impacts from offshore wind energy development can be more effectively accomplished by applying measures to onshore wind farms or improving established bat habitats. Onshore mitigation efforts may offer greater effectiveness due to the closer interaction between land-based wind turbines and bat habitats as well as higher density of bats and bat species. But for instance, decommissioning wind farms is not viewed as a practical or pragmatic mitigation measure, as these installations are often expanded for profitability or relocated to other regions, such as Eastern Europe, where bat fatalities may not be adequately mitigated. Given these limitations, decommissioning is not considered a worthwhile area for further research. Compensation efforts can address specific structural and ecological factors unique to onshore environments, such as vegetation, migration routes, and species behavior.

6.2 Opportunities and limitations of the current research set-up

This research set-up provides useful insights into ways to mitigate bat mortality caused by wind turbines, both onshore and offshore. While it offers opportunities for advancing bat conservation, certain limitations must be acknowledged to improve future research efforts.

Opportunities

1. **Focus on mitigation measures**
   By focusing specifically on mitigation measures, the research can dive into practical solutions, like curtailment, detection, deterrence, and turbine design. This approach ensures the study is actionable and directly relevant to reducing bat fatalities.

2. **International collaboration**
   Using an international network of experts and organizations has helped enrich the study, bringing in a variety of perspectives and knowledge. These connections have been especially helpful for exploring emerging technologies and understanding how they might work in both onshore and offshore settings.

3. **The potential of AI**
   Exploring AI-based systems for detection and wildlife tracking opens exciting possibilities. AI could improve the accuracy of bat detection, streamline data analysis, and make curtailment strategies more efficient. These innovations could be a game-changer, particularly for offshore applications.

4. **Identifying knowledge gaps**
   The methodological framework resulted in a clear and comprehensive overview of current knowledge gaps, like bat migration routes, flight altitudes, and how long technologies can last in an offshore environment. Highlighting these gaps gives future studies a clear direction to focus on.

5. **Adapting measures to offshore contexts**
   The study explores how existing measures, like radar detection or deterrence systems, can be adapted to offshore environments. This opens opportunities to develop solutions tailored to the unique challenges of wind farms at sea.

Limitations

1. **Narrow scope**
   The research focuses exclusively on mitigation measures, which means broader issues like habitat restoration or population recovery aren't (primarily) addressed. While this focus is practical, it leaves some important aspects of bat conservation out of the picture. Additionally, although we made every effort to identify all relevant mitigation measures by consulting numerous experts and sources, it is possible that some literature or insights may have been missed. This limitation highlights the need for continued exploration of emerging studies and perspectives to ensure a more comprehensive understanding of bat conservation strategies.

2. **Short timeframe**
   The limited duration of the project prevented an even deeper dive into certain relevant research areas and consulting a wider range of experts. Relying on existing literature and available input was necessary, but limited how much new data could be gathered.

3. **Limited expert input**
   While expert consultation was central to the study, scheduling and scope conflicts meant not all desired stakeholders could participate. This reduced the diversity of perspectives, particularly from experts who might have had insights into cutting-edge measures or regional differences.

4. **Technological challenges**
   Technologies like radar and AI systems show promise, but their use offshore is still uncertain. Issues like saltwater corrosion, frequent maintenance needs, and short battery life make it hard to implement these solutions effectively. These practical challenges need to be addressed before they can live up to their full potential offshore.

5. **Knowledge gaps in offshore contexts**
   Despite a multitude of relevant studies and technologies on bat mitigation in offshore wind farms is already available, this study highlighted a lack of data on key topics like bat migration routes, flight altitudes, and behavior offshore. This information would assist in verifying onshore-to-offshore extrapolations and help draw firm conclusions about the effectiveness of certain measures.

This research set-up is a starting point for understanding how to mitigate bat mortality in relation to offshore wind turbines. Its focus on mitigation measures, use of international networks, and exploration of emerging technologies like AI, all offer exciting opportunities to build on. However, the study's narrow scope, short timeframe, limited expert input, and lack of data on offshore contexts highlight areas that need more attention in the future. Addressing these challenges will help ensure that future studies are more thorough and impactful.

6.3 Recommendations for future research

To advance bat conservation efforts and improve the effectiveness of mitigation measures, future research should focus on addressing key knowledge gaps and exploring innovative approaches tailored to both onshore and offshore wind farm contexts. Proposed recommendations should be considered an addition to the current best practice and are structured within two categories: fundamental research and mitigation research.

6.3.1 Fundamental research

As a prerequisite to studying how specific mitigation techniques can be applied to maximize effectiveness, fundamental research is necessary to get a better understanding of offshore bat ecology and behavior. Moreover, this insight is especially applicable to the prioritized mitigation measures as listed in § 6.1. A compilation of recommendations regarding fundamental research, lined up with the prioritized mitigation measures presented in this report, is addressed below. Plans for some of these topics already exist within the Wozep research program 2024-2030.

Investigating bat mortality rates
Future research should focus on quantifying the number of Nathusius' pipistrelles and other bat species impacted by wind turbines, both onshore and offshore. Current evidence suggests that land-based wind turbines pose significantly greater risks to this migratory species compared to offshore installations. To better understand these effects, it is essential to investigate the population dynamics of Nathusius' pipistrelles in detail. Gaining a more accurate understanding of their population size, distribution, and migratory behavior would allow for improved calculations of mortality rates and a clearer assessment of the overall impact of wind energy development on this species. One practical approach to studying these impacts involves using telemetry and GPS tracking to monitor migrating bats, enabling researchers to identify collision risk hotspots and key migratory corridors.

Mapping migration routes over the sea
Another critical knowledge gap is the preferred migration routes of bats over the sea, if such routes exist at all. Understanding these routes would enable better decision-making in the placement of wind turbines and inform mitigation strategies such as micro-siting and spatial planning. If bats follow specific pathways during migration, wind farms could be relocated or arranged in ways that minimize collision risks. Research into migration routes is vital to ensure that offshore wind energy development does not unnecessarily impact bat populations. This subject is already being researched by Wageningen University & Research and could be improved by improving the MOTUS-system (or other high-potential radar systems) and telemetry-tagging more bats and analyzing their migration patterns. René Janssen additionally suggested reevaluating the tagging system and expanding offshore receiver networks to ensure a more comprehensive monitoring approach. Mapping migration routes in general is a critical step toward reducing the knowledge gap of the spatial usage of bats in offshore wind energy areas and knowledge on migration routes can help with spatial planning.

Investigating bat flight altitudes over the North Sea
The flight altitude of Nathusius' pipistrelles during both migration and foraging activities over the sea remains largely unknown. This knowledge gap is particularly significant, as it directly relates to the collision risk posed by turbine blades. If migrating or foraging bats fly at heights that intersect with the rotor sweep zone, adjustments to turbine blade designs or operation may be necessary. Research into bat flight behavior and altitude over the North Sea would provide critical insights into how offshore wind farms can be adapted to reduce risks to bats. This research could be done by GPS-tagging bats and improving radar systems.

Leveraging existing Wozep data
Knowledge gaps for the three topics above (mortality rates, migration routes and bat flight altitudes) can be closed with new research. Additionally, an attempt could be made to find new insights by reanalyzing telemetry data from Wozep-funded studies. This could present an opportunity to uncover additional insights. Similarly, yet to be analyzed MOTUS tracking data may still hold untapped potential to improve our understanding of bat migratory behavior. Revisiting these existing datasets could provide valuable information to guide future research.

Investigating bat populations
Monitoring bat populations, particularly migratory species like Nathusius' pipistrelle is complex. Genetic studies have revealed a slight decline in genetic diversity, highlighting the importance of establishing a consistent monitoring program. Annual genetic sampling could provide valuable insights into population health and trends. Strategic locations where bat activity is high could serve as key sampling sites. By integrating this effort with ongoing WOZEP research, which already involves tagging bats, and directly collaborating with specialized DNA laboratories, a more efficient and focused approach to monitoring bat populations can be developed.

6.3.2 Mitigation research

Additional recommendations for future research focus on analyzing how the applicability of specific mitigation measures can be optimized to achieve a significant decrease in bat fatalities. To this end, both desk study and practical approaches can be used to fill current knowledge and experience gaps. The use of and adherence to ecological tender criteria (for the offshore wind farms) could be the right incentive that is needed to prioritize this kind of mitigation research.

A general issue with recommending to test mitigation measures offshore is that to date no reliable way of measuring bat mortality has been discovered (as mentioned in 6.3.1). While ideally, we would suggest field comparisons for specific technologies in different set ups, the effectiveness of measures cannot easily be measured. This means that for now our advice is mainly focused on testing the potential and technical durability of options, rather than a full-blown experiment. We hope in the coming years this offshore monitoring issue will be solved.

Recommended research topics concerning specific mitigation techniques are listed below in order of feasibility and priority.

Understanding the durability of offshore technology
Further research is needed to assess the durability and feasibility of deploying detection and deterrence systems in offshore environments. Experts have raised concerns about the sustainability of these technologies, particularly in saltwater conditions. Devices such as ultrasonic deterrents, radar systems, cameras and acoustic detection tools are prone to corrosion and require frequent maintenance and replacement. Investigating how and how long these technologies can function effectively in marine environments is essential to determine whether they can be reliably implemented for bat conservation offshore. We recommend setting up practical field tests in offshore wind farms to assess the durability and feasibility of monitoring equipment in collaboration with the wind park owners. Splitting this factor from 'effectiveness for bat mortality' might allow for a clearer image of what is and is not technically feasible offshore.

Technically improving curtailment effectiveness with the outcomes of fundamental research
We recommend improving current curtailment methods and strategies based on the outcomes of fundamental research mentioned in 6.3.1. With improved knowledge, curtailment during spring migration is recommended, Once effective methods for bat mortality rates measurement offshore are used, curtailment strategies can be compared in a practical set up. As outcomes are uncertain, giving solid and concrete advice on how to do this is currently not attainable.

Exploring costs of curtailment
Expert Pieterjan Dhont suggested to continue the current practice of mapping of the costs of curtailment in order to assess whether it is a viable and sustainable mitigation measure for offshore environments. This analysis could include estimating the expenses associated with deploying acoustic detectors around a wind farm and developing technology to directly link these detectors to turbine shutdown systems. Understanding these costs would help determine the feasibility of implementing curtailment as an effective solution for reducing bat mortality in offshore wind farms.

Analyzing the effectiveness of mitigation measures
Applied research into the effectiveness of mitigation measures will allow for better estimates of changing collision risks and potentially avoided bat mortalities. Relatively simple study designs such as BACI (before-after-control-impact) with the use of a specific mitigation technology could add much needed insights into the potential of new and upcoming technologies, or add to the reliability of current best practice. A non-exhaustive list of possible mitigation techniques that would benefit greatly from testing include the use of electromagnetic fields, radar-based detection, offshore detection ranges, vibration (collision) based detection and the use of telemetry tagging for small specimens like bat species. Once again, this advice is practically limited by lack of monitoring measures offshore. High potential measures that are still in early development stages such as vibration (collision)- or electromagnetic field detection could maybe be applied and compared onshore to ensure their effectiveness before going offshore. This can be done in parallel to testing the offshore technical durability. Techniques that have been tested further such as telemetry detection can already be applied offshore in parallel to new (mortality) measuring techniques.

Follow-up of relevant international research and literature

As a first step, this report gathered information on the current state of affairs in regards to (offshore) mitigation of bat casualties in operational wind parks. The resulting literature list forms a quintessential starting point for a recurring check-up (e.g. semi-annually) of the ongoing international research on topical technologies. Another non-exhaustive suggestion list of literature, software and technologies to keep on the radar include:

- Deterrent technologies (acoustic, visual and others), including their integration into other applications, such as the use of drones. Relevant literature sources (see Appendix A) include 2, 5, 13, 15, 16, 17, 26, 39 and 43.
- Detection techniques, including automated and AI-supported techniques, as these are rapidly developing on the international market. Relevant literature sources (see Appendix A) include 2, 7, 25 and 28.
- Detection software/hardware and possible advances in updates, functionalities and technological designs. Relevant literature sources (see Appendix A) include 28, 29, 35, 38, 41, 42, 44 and 45.

Assessing the importance of ground clearance

Experts Martijn Boonman and Robin Brabant highlighted the importance of ground clearance—the distance between turbine blades and the ground—in relation to bat mortality. On land, this factor is particularly critical, as bats often navigate near wind turbines by following structures such as rows of trees. These flight patterns increase the likelihood of collisions when turbine blades are positioned closer to the ground. Offshore, the role of ground clearance may be less significant, but current knowledge is insufficient to draw firm conclusions. Further research into flight behavior and altitude over the sea would complement studies on ground clearance, helping to design offshore turbines in ways that minimize bat collisions. Practically the current recommendation is to continue research efforts into the flight altitude and mortality rates knowledge gaps. Once a reliable way of determining offshore bat mortality has been established, the mortality rate differences between offshore wind farms with different ground clearances can be studied.

Appendices

Appendix A Excel with Mitigation measures overview

Appendix A can be found in a separate Excel file called “Appendix A Methodological framework”

Appendix B AI report

Appendix B can be found in a separate PDF file called “Appendix B Artificial Intelligence Report”

Colophon

INVENTARISATION OF BAT MITIGATION MEASURES AND THEIR SUITABILITY FOR OFFSHORE WIND IN THE NETHERLANDS

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