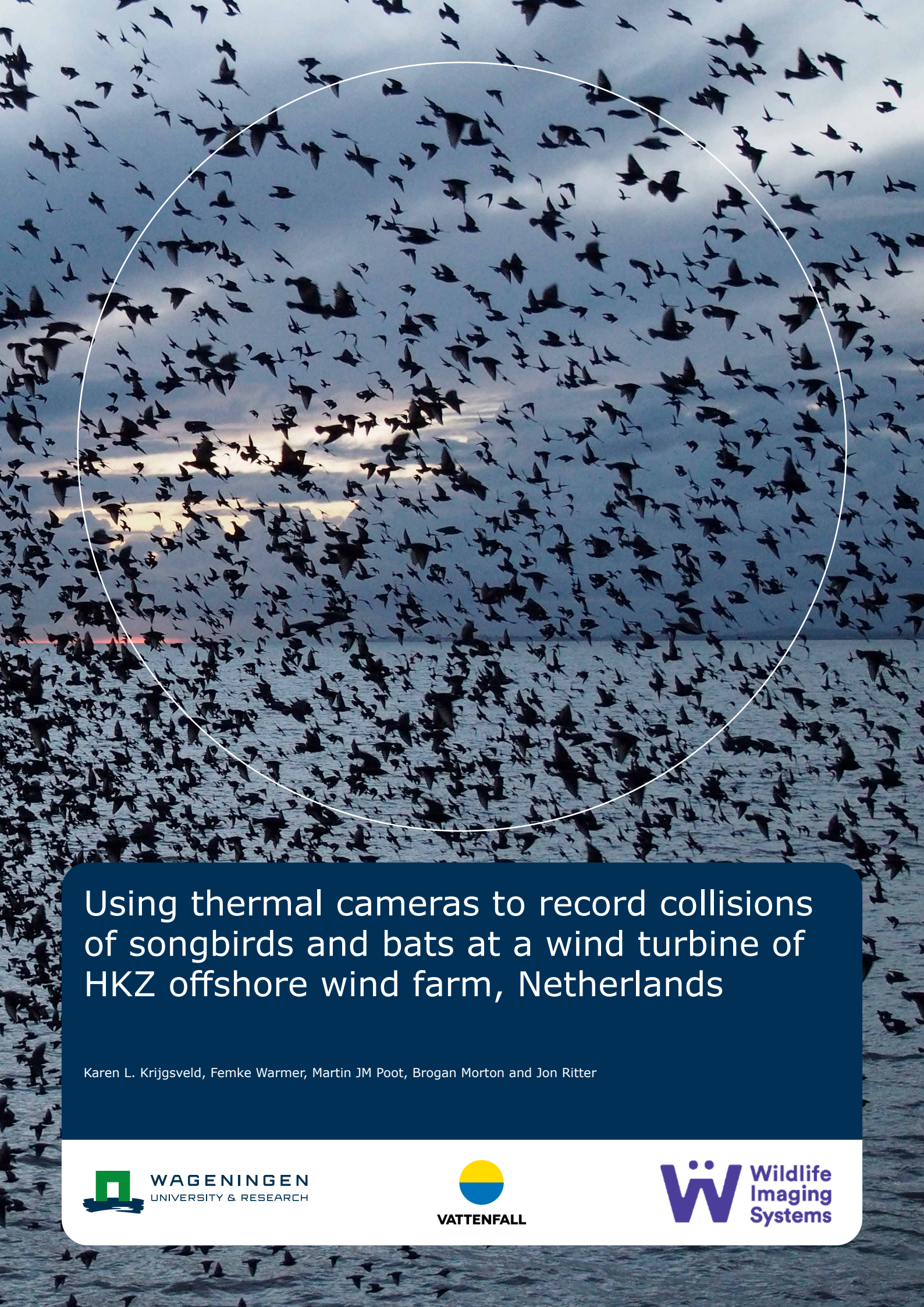




# Using thermal cameras to record collisions of songbirds and bats at a wind turbine of HKZ offshore wind farm, Netherlands

Karen L. Krijgsveld, Femke Warmer, Martin JM Poot, Brogan Morton and Jon Ritter



**WAGENINGEN**  
UNIVERSITY & RESEARCH



**VATTENFALL**





# Using thermal cameras to record collisions of songbirds and bats at a wind turbine of HKZ offshore wind farm, Netherlands

Karen L. Krijgsveld, Femke Warmer, Martin JM Poot, Brogan Morton and Jon Ritter

1 Wageningen University & Research

2 Wildlife Imaging Systems

This pilot study was commissioned by Vattenfall and was carried out by Wageningen Environmental Research and Wildlife Imaging Systems (project number 5200048345)

Wageningen Environmental Research  
Wageningen, August 2026

Reviewed by:

Sander Moonen, Researcher animal ecology (WENR)

Approved for publication:

Marion Kluivers-Poodt, Teamleader of Animal Ecology, (WENR)

Report 3541

ISSN 1566-7197



**WAGENINGEN**  
UNIVERSITY & RESEARCH

---

Krijgsveld KL, Warmer F, Poot MJM, Morton B, Ritter J, 2026. *Using thermal cameras to record collisions of songbirds and bats at a wind turbine of HKZ offshore wind farm, Netherlands*. Wageningen, Wageningen Environmental Research, Report 3541. 46 pp.; 17 fig.; 6 tab.; 39 ref.

In deze pilotstudie is een meetsysteem getest om aanvaringen te kunnen meten van 's nachts trekkende zangvogels en vleermuizen met offshore windturbines. Het systeem is ontwikkeld door Wildlife Imaging Systems en gebaseerd op thermische camera's. Gedurende negen maanden is continu gemeten op een offshore windturbine in windpark Hollandse Kust Zuid van Vattenfall. Er werden 22 aanvaringen geregistreerd, waarvan drie bevestigd of vrijwel zeker. Het systeem bleek technisch toepasbaar op zee en leverde betrouwbare empirische gegevens. Deze ontwikkeling is een grote stap in het invullen van de kennislacune aangaande het aantal vogels en vleermuizen dat met offshore windturbines in aanvaring komt. Uitgebreidere monitoring is nodig voor inzichten in het aantal en de omstandigheden waaronder deze aanvaringen optreden.

In this pilot study, a monitoring system developed by Wildlife Imaging Systems that is based on thermal imaging cameras, was tested for its ability to detect collisions of nocturnally flying songbirds and bats with offshore wind turbines. Continuous monitoring was conducted over a nine-month period at a single offshore turbine off the Dutch coast. A total of 22 collision events were detected, of which three were confirmed or with high confidence. The system proved technically feasible for deployment offshore and demonstrated its potential to generate reliable empirical data on collision events. This development is an important step towards addressing a key knowledge gap concerning the number of birds and bats colliding with offshore wind turbines. Monitoring across multiple wind farms and seasons is required to quantify collision rates offshore and to identify the environmental and operational conditions under which collisions occur.

Keywords: Bird collisions, offshore wind turbines, nocturnal songbird migration, thermal cameras

The pdf file is free of charge and can be downloaded from <https://doi.org/10.18174/721562> or via the website [wur.eu/environmental-research](http://wur.eu/environmental-research) (scroll down to Publications – Wageningen Environmental Research reports). Wageningen Environmental Research does not deliver printed versions of the Wageningen Environmental Research reports.

© 2026 Stichting Wageningen Research, Wageningen Environmental Research  
P.O. Box 47, 6700 AA Wageningen, The Netherlands, T +31 (0)317 48 07 00, [wur.eu/environmental-research](http://wur.eu/environmental-research)



This work is licensed under the Creative Commons CC BY-NC-ND 4.0 license. This license enables reusers to reproduce and distribute the material in any medium or format in unadapted form only, for non-commercial purposes only, and only so long as attribution is given to the creator and reference is made to the original source. Reproduction and distribution are not allowed for those parts of this work of which it is clear that copyrights are explicitly reserved or owned by third parties.

Wageningen Environmental Research assumes no liability for any losses resulting from the use of the research results or recommendations in this report.



Wageningen Environmental Research operates a certified quality management system in accordance with ISO 9001 and an environmental management system that complies with the ISO 14001 standard.

In addition, Wageningen Environmental Research applies the principles of ISO 26000 to fulfil its social responsibility.

Wageningen Environmental Research Report 3541 | ISSN 1566-7197

Photo cover: © Julian Hoffman. Starlings flying over sea at Brighton. For details see <https://julian-hoffman.com/2020/04/27/a-murmuration-of-starlings/>.

---

---

# Contents

|                                                                               |           |
|-------------------------------------------------------------------------------|-----------|
| <b>Verification</b>                                                           | <b>7</b>  |
| <b>Summary</b>                                                                | <b>9</b>  |
| <b>1 Introduction</b>                                                         | <b>11</b> |
| <b>2 Methods</b>                                                              | <b>13</b> |
| 2.1 Study location, study period, and turbine specifics                       | 13        |
| 2.2 WIS camera system operation                                               | 13        |
| 2.3 WIS collision data processing                                             | 14        |
| 2.4 Collision labelling                                                       | 15        |
| 2.5 Collision data analysis                                                   | 16        |
| 2.6 Acoustic monitoring                                                       | 16        |
| 2.7 Flight intensities from bird radar                                        | 17        |
| <b>3 Results</b>                                                              | <b>18</b> |
| 3.1 Objects observed                                                          | 18        |
| 3.2 Confirmed collisions                                                      | 19        |
| 3.3 Circumstances of collisions                                               | 21        |
| 3.4 Comparing flight intensities measured with thermal cameras and bird radar | 25        |
| 3.5 Bat activity                                                              | 27        |
| <b>4 Discussion</b>                                                           | <b>28</b> |
| 4.1 Detecting collisions                                                      | 28        |
| 4.2 Detection performance                                                     | 28        |
| 4.3 Number of collisions                                                      | 30        |
| 4.4 Species identification                                                    | 30        |
| 4.5 Circumstances of collisions                                               | 31        |
| 4.6 Classification uncertainty and system improvements                        | 32        |
| 4.7 Implications                                                              | 33        |
| 4.8 In conclusion                                                             | 34        |
| <b>Acknowledgements</b>                                                       | <b>35</b> |
| <b>References</b>                                                             | <b>36</b> |
| <b>Appendices</b>                                                             | <b>38</b> |

---

---

# Verification

Report: Using thermal cameras to record collisions of songbirds and bats at a wind turbine of HKZ offshore wind farm, Netherlands  
Project number: 5200048345

Wageningen Environmental Research (WENR) values the quality of our end products greatly. A review of the reports on scientific quality by a reviewer is a standard part of our quality policy.

Approved reviewer who stated the appraisal,

position: Researcher animal ecology (WENR)

name: Sander Moonen

date: 5-8-2026

Approved team leader responsible for the contents,

name: Marion Kluivers-Poodt

date: 5-8-2026



---

# Summary

Collision mortality of birds and bats at offshore wind turbines represents a prominent biodiversity concern, yet empirical collision data from the offshore environment are virtually absent. Nocturnal migratory passerines and bats have received particularly little attention in this context, despite crossing the North Sea in numbers of several hundred million individuals per season.

We conducted a proof-of-concept study at a single offshore wind turbine, applying a monitoring system based on thermal cameras developed by Wildlife Imaging Systems. Outward-facing cameras continuously monitored the 360° area below the rotor-swept zone for falling objects, while upward-facing cameras provided visual verification of collision events and recorded flight intensity. Acoustic monitoring was conducted simultaneously to record bat activity. The system operated across one spring and one autumn migration season and one summer (from January 31 2025 until November 30 2025).

A total of 22 collision detections were identified over a period of nine months, including two confirmed collisions and one high-confidence collision. Only four of these collision detections occurred during periods with high migration rates. Instead, the three confirmed / high-confidence collisions were recorded at higher wind speeds of 10-15 m/s, as well as the majority of mid-confidence spring and autumn collision detections, suggesting that high wind speeds may elevate collision risk independently of migration intensity. Bird flight intensities measured by the WIS cameras were significantly correlated with migration traffic rates derived from nearby bird radars, indicating not only that the cameras could quantify nearby migration traffic rates, but also that detection performance was adequate and the probability of false negatives was limited. No collision events could be specifically attributed to bats, due to the fact that collision detections could mostly not be attributed to specific species groups. However, bat activity recorded acoustically at the turbine was low and temporally restricted.

The WIS system proved operationally feasible in the offshore environment and capable of detecting collision events at night and for small-bodied species of birds and bats, and therewith constitutes a means to empirically measure collisions at offshore wind turbines. Results provide first indications that collision risk may be more closely associated with adverse meteorological conditions than with high migration intensity during favourable tailwind situations, with implications for the design of curtailment strategies.

Direct empirical measurement of bird and bat collision rates at offshore wind turbines is technically achievable using continuous automated monitoring with thermal cameras. This opens up the possibility to generate the empirical collision rate data needed to parametrise and validate the collision risk models on which offshore wind impact assessments and consenting procedures currently depend. To achieve this, systematic deployment across multiple turbines and seasons is required.



---

# 1 Introduction

Offshore wind energy is a key factor worldwide in the transition towards renewable energy. In Europe, the North Sea basin currently hosts an estimated 30–35 GW of installed capacity in over 100 offshore wind farms, and the outlook is to triple this to approximately 100 GW by 2040 (Frémaux 2026). Collisions of birds and bats with wind turbines are among the most prominent biodiversity concerns associated with wind energy development. On land, collision rates at individual turbines typically range between 0 and 40 birds per year, depending largely on turbine location (Sovacool 2009, Marques *et al.* 2014).

Offshore, collision rates are to date virtually unknown, due to fundamental difficulties with quantifying fatalities at sea. Post-construction fatality monitoring through systematic carcass searches, a well-established standard approach at terrestrial wind farms, cannot be applied in the offshore environment: carcasses are rapidly removed from the vicinity of turbines through sinking, scavenging, and wind- and wave-driven dispersal, while access to turbine structures — where a proportion of carcasses might otherwise be retained — is severely restricted due to the need for boat access and weather conditions in combination with extensive safety regulations. Collision mortality of nocturnal migrants at offshore structures has been documented at illuminated platforms where carcasses could be physically recovered (Hüppop *et al.* 2016), but no equivalent method has been available for wind turbines, where carcasses are lost to the sea. Collision risk estimates of birds employed in environmental impact assessments have therefore relied thus far on theoretical models, of which the Band model (Band 2012) is the predominant framework. A critical review of four decades of avian collision risk modelling confirms that these models are particularly sensitive to avoidance rates and flight heights as key input parameters (Cook *et al.* 2025). Although the empirical basis for these parameters has grown progressively with the accumulation of monitoring studies (Ozsanlav-Harris *et al.* 2023), the absence of empirical collision rate data severely limits our understanding of the actual mortality imposed by offshore wind turbines (Kleyheeg-Hartman *et al.* 2018).

To date, there are only two known instances where actual bird collisions at operational offshore wind turbines were recorded directly. The ORJIP Bird Collision Avoidance Study, conducted at Vattenfall's Thanet Offshore Wind Farm in the English Channel over a two-year period (2014–2016) using a multi-sensor system of radar, human observers and automated video, documented six collisions from the analysis of over 12,000 videos that contained evidence of bird activity (Skov *et al.* 2018). A subsequent two-year monitoring programme at the Aberdeen Offshore Wind Farm in the North Sea, employing radar-triggered high-resolution digital cameras, recorded no collisions or near-misses across nearly 10,000 seabird videos obtained under daylight conditions and adequate visibility (Skov *et al.* 2025). Both studies focused exclusively on diurnal seabird species under daytime conditions, leaving collision rates for nocturnally migrating birds entirely unquantified.

Critically, both studies employed radar-triggered camera systems in which individual birds were tracked following prior detection by radar. While such a design is well-suited for quantifying avoidance behaviour, it may be less suitable for obtaining unbiased estimates of collision events, as birds entering the rotor-swept area without prior radar detection would remain undetected. This limitation could be particularly important for small nocturnal migrants, that are generally less detectable by radar but may occur in large numbers during migration and could consequently contribute substantially to overall collision numbers. A monitoring approach in which the turbine itself — rather than relying on prior detection and tracking of individual birds — is kept under continuous observation, may therefore provide a more unbiased estimate of actual collision rates.

To date, no studies have quantified the intensity of migratory bat movements across the North Sea. Tracking studies using the MOTUS system have demonstrated that *Nathusius' pipistrelle* (*Nathusius' pipistrelle*) is capable of non-stop crossings of the North Sea (Lagerveld *et al.* 2024); however, the extent to which these movements occur within the rotor-swept zone of offshore wind turbines remains unknown (Lagerveld *et al.* 2026). Given that the mitigation toolkit for offshore environments is strongly constrained by ecological, technical, and logistical uncertainties, the Dutch government, following the precautionary principle, applies a

---

fixed autumn curtailment procedure based on a combination of temporal, wind speed, and temperature thresholds. These current mitigation measures rely largely on acoustic detections (Boonman & Japink 2022). Nevertheless, it remains highly uncertain whether bats recorded by offshore detectors represent actively migrating individuals or animals temporarily stopping offshore after becoming stranded under unfavourable weather conditions. Consequently, the fate and behavioural ecology of these individuals at sea also remain unresolved. At present, neither acoustic monitoring nor knowledge derived from tagged individuals can reliably predict actual collision rates of bats offshore (Lagerveld *et al.* 2026).

Research on the effects of offshore wind farms on birds has indeed focused predominantly on seabirds, given their high protection status and the sensitivity of their long-lived, K-selected populations to additional mortality (Furness *et al.* 2013). However, migratory songbirds and bats represent additional species groups of considerable concern with regard to offshore wind turbines, that have received comparatively little attention in the offshore context. Passerines cross the North Sea in numbers estimated at several hundred million individuals per season, comprising approximately 250 species of which the majority migrates nocturnally (Lack 1959, Hüppop *et al.* 2006, Fijn *et al.* 2015). The resulting flight intensities at rotor height may generate substantial absolute numbers of collision fatalities, even at low per-individual collision probabilities. Bats, although crossing in far smaller numbers, are of particular conservation concern given the disproportionately large population-level consequences of even modest additional mortality in these slow-reproducing species (Frick *et al.* 2017, Voigt *et al.* 2022). No empirical collision data exists for either group at offshore wind turbines.

A robust approach to monitor offshore collisions was developed by TNO, whose WTBird® system uses optical fibre vibration sensors embedded in turbine blades to detect the acoustic signature of a collision event, triggering camera recordings for subsequent verification (Wiggelinkhuizen *et al.* 2006). The system has more recently developed into a multi-sensor platform combining vibration sensors, thermal cameras and radar, recently demonstrated to detect collisions of birds and bats, with detection performance comparable to parallel carcass surveys at an onshore turbine (Western EcoSystems Technology 2025). The acoustic system has to be built into the rotor blades, which has thus far limited the deployment offshore. Recent advances in camera technology — in particular the development of thermal imaging systems capable of continuous nocturnal operation at sufficient resolution — combined with progress in automated image analysis through artificial intelligence and computer vision, have enabled a new generation of monitoring approaches. Early work on turbine-mounted automated detection systems using near-infrared and thermal cameras was reported by Happ *et al.* (2021). Subsequent studies have applied AI-based deep learning algorithms to distinguish flying birds from other objects in radar-triggered video footage (Skov *et al.* 2025), and buoy-mounted camera platforms incorporating AI-based species identification at floating offshore wind installations (Spoor & BTO 2025). These developments indicate that direct empirical quantification of bird collision rates at offshore wind turbines is becoming technically practicable.

Here, we present the results of a pilot study applying a camera-based monitoring system developed by Wildlife Imaging Systems (WIS), which was previously tested and validated for bat fatality detection at wind turbines on land (Weaver *et al.* 2025). The system operates through continuous 360° monitoring of the area surrounding a turbine using outward-facing cameras that detect falling objects, with recordings subsequently processed through a classification model to identify potential collision victims. Four additional upward-facing cameras provide simultaneous data on flight intensity and serve as visual validation of detected collision events. The central question addressed in this study is whether the WIS system provides a viable means of quantifying actual collision rates at offshore wind turbines, including at night and for small-bodied species. Critically, if the system proves capable of detecting collisions of small passerines and bats — the most demanding case given their small body size and predominantly nocturnal passage — it can be considered capable of detecting collisions of larger species such as seabirds under daytime conditions. The study was conducted as a proof-of-concept pilot at a single turbine over one spring and one autumn migration season, supplemented by acoustic monitoring to support species-level interpretation of collision events. We assess under which meteorological and migratory conditions collisions occurred, and we present what are, to our knowledge, the first empirical measurements of passerine collision rates at an offshore wind turbine.

---

## 2 Methods

### 2.1 Study location, study period, and turbine specifics

Measurements were carried out in the Dutch North Sea at offshore wind farm Hollandse Kust Zuid (HKZ) of Vattenfall, located 18 – 39 km off the Dutch coast, roughly at a latitude between the cities of Amsterdam and The Hague. The system was installed in turbine W6, situated in the northeastern corner of the wind farm. This location was chosen to maximize passage of songbirds at rotor height in the vicinity of the turbine. In autumn, songbird migration in the area is oriented predominantly towards SW, with generally higher numbers at turbine altitudes than in spring (Krijgsveld et al 2012, Fijn et al 2015, Bradarić *et al.* 2020). This turbine stood at the northern edge and one position west of the corner turbine. Although passage rate of migrating passerines was expected to be maximal at the corner turbine, this turbine was avoided because it was fitted with a fog horn and marine navigational lights that may affect bird behaviour. The selected turbine only had a constant red aviation light. The wind farm is operational since September 2023 and consists of 139 turbines. Turbines are of the type Siemens Gamesa 11 MW, and turbine dimensions are: hub height 128 m above MSL, length rotor blades 97 m, maximum tip height 225 m MSL, minimum tip height 31 m MSL. The system was installed in November 2024 and data for analysis were collected from January 31 2025 until November 30 2025.

### 2.2 WIS camera system operation

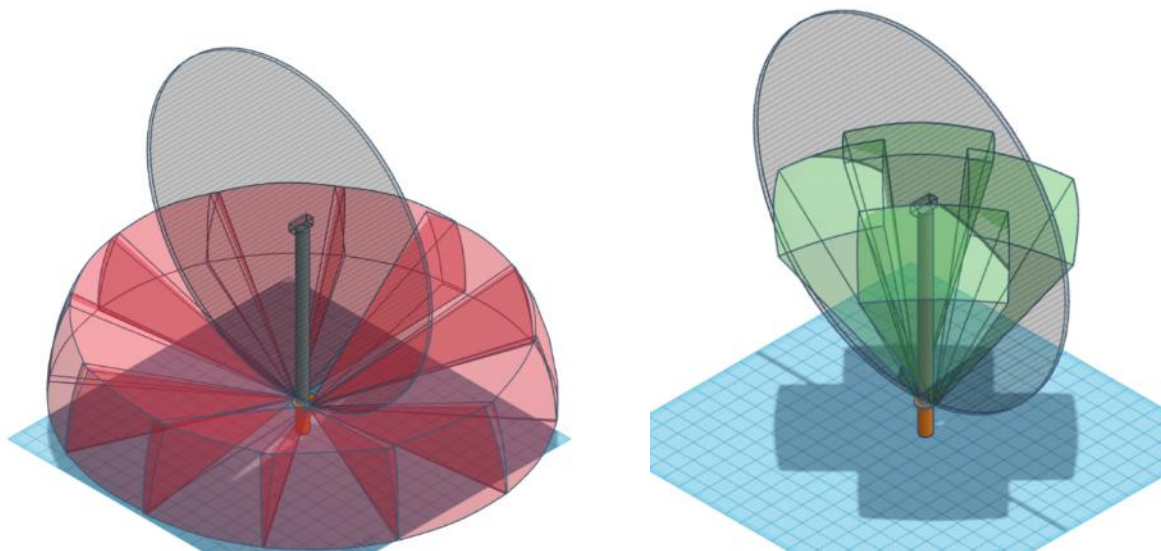
We deployed 16 Axis Q1952-E thermal cameras with 19 mm lenses, all operational for 24 hours a day. Uptime of the cameras was virtually 100% after initial setup and installation, related mainly to solving small bugs in scripts. One camera turned out to be dysfunctional on installation and had to be replaced, which could not be realized until May 2025 due to limited access to the turbine. Including this camera, uptime was still 97% over the entire period; excluding this camera, uptime was > 99%. On average, 283 videos were recorded per day per camera, for 302 days (192 for the 16<sup>th</sup> camera), resulting in approximately  $1.34 \times 10^6$  videos of 5 minutes each.

Of the 16 cameras deployed, 12 were used to measure direct mortality caused by the wind turbine. Their field of view was directed radially outward away from the turbine tower (Figure 1). Focal length of the cameras was chosen to see a 10 cm object up to 115 m away, covering the whole area below the rotor-swept zone for all wildlife of interest. Each camera had a horizontal field of view of 31°, meaning 12 cameras covered the full 360° around the base of the tower. The goal of these cameras was to detect a falling object after a direct fatality. All cameras operated 24 hours a day.

The additional 4 cameras were looking up and pitched slightly away from the nacelle, thus monitoring the rotor-swept zone (Figure 1). These 4 cameras were positioned such that they were each monitoring a side of the turbine, in the four cardinal directions. These cameras did not cover the entire volume of air at lower altitudes: coverage of the rotor-swept zone was complete from 190 m above MSL and up (the upper sweep of the rotors) and coverage was 360 degrees at 62 m above MSL (between minimum tip height and nacelle). The goal of these cameras was to monitor the flux of bird detections through the rotor-swept zone as well as monitor for direct collisions, when a falling carcass was detected on the outward-looking cameras. Specifications and settings of all 16 cameras were the same, meaning that outward- and upward-looking cameras had the same field of view.

All cameras were mounted on the railing of the transition platform, at 17.5 m above mean sea level. Cameras were mounted at four different mounting stations on the north, south, west and southeast side of the platform respectively (appendix figure A1). The northern station consisted of two brackets, housing six outward-looking cameras facing from west to east, as well as one upward-looking camera pointed

approximately due north. The southern bracket also consisted of two brackets, housing the remaining six outward-looking cameras facing east to west, as well as one upward-looking camera pointed approximately due south. The western station housed one upward-looking camera facing approximately due west, and the southeastern station housed one upward-looking camera facing approximately due southeast. The southeastern bracket was restricted from the eastern side of the transition platform and was placed as close to the cardinal direction as possible.



**Figure 1** Visualization of the camera setup of the WIS-system. Left panel: 12 thermal cameras looking outward from the turbine monitored the airspace below the rotor-swept zone with full 360-degree coverage. Right panel: 4 upward-looking thermal cameras monitored flight activity in the rotor-swept zone with limited coverage of the rotor-swept zone.

## 2.3 WIS collision data processing

All camera data were processed using state-of-the-art machine vision and machine learning to automatically detect, track, and classify each detection, similar to methods in Weaver et al (2025). For this study, two site-specific models were created, one for the outward-looking cameras and one for the upward-looking cameras. The models slightly differ because of the different aspects from which the cameras see the volant life. Both models classified tracks into classes like bird, insect, plane and noise.

For the upward-looking cameras, the classified tracks were then used to analyse the flux of animal activity near the turbine (bird activity). To produce the bird activity measurement, the tracks labelled as a bird were summed into bins with each detection representing  $1/30^{\text{th}}$  of a second of bird activity (for a 30 fps camera). Each detection point was thus counted as  $1/30$  of a second. This is especially important when multiple bird tracks occurred on the same frame; these were all treated as individual detections and summed together. Thus, for each bird detection, we added  $1/30$  of a bird-second to the metric, meaning that each bird was counted individually. This “bird-second” metric (number of seconds with bird activity) was then averaged per hour and compared with the flight intensities as measured with a nearby bird radar.

For the outward-looking cameras, once the tracks were classified, the summary images representing all activity seen during a 5-minute period were reviewed for a large proportion of the study (until July 2025). During this review, a human reviewer was looking for objects in the images that appeared to be falling objects (moving from the top of the frame to the bottom of the frame). The video was reviewed to verify the track direction. These tracks were then aggregated to produce a test set of tracks in which a rules-based classifier was created to filter similar tracks to be reviewed. The rules-based classifier was built to allow all tracks of apparent falling objects into a subset of potential falling objects, while rejecting all other tracks. The purpose of this initial classifier was to allow for a larger portion of false positives than anticipated, to thus

---

reduce the chance of missing true fatality events. During this step, 0.00065% of all the tracks from the outward-looking cameras was selected as downward tracks to be evaluated and labelled manually (n=782).

## 2.4 Collision labelling

The selection of 782 downward tracks was subsequently manually evaluated and labelled into one of the following categories: confirmed collision, high-confidence collision, mid-confidence collision (together called 'collision detections' here), animal flying (bird/bat), insect, unsure (track could not be confidently assigned to one of the categories), and other (non-animal tracks, such as water or turbine maintenance activity) (appendix figure A2). Both the summary images and videos of the tracks were used during labelling, as well as additional footage from the upward-looking cameras. The tracks were processed in two batches: the first covering the period February – June and the second covering July – November.

The tracks were manually evaluated by two groups of observers (WUR and WIS). All tracks were assessed independently by both groups and by two individuals within these groups, after which conflicting labels were discussed to get a best estimate and come to a final set of labels. Tracks were evaluated independently per observer and then discussed per group; except for the first labelling round at WENR (spring and summer data), where both observers evaluated tracks together for training purposes. A labelling protocol and a set of labelling rules was developed to standardize this process and ensure maximum objectivity during labelling (appendix table A1). Each label had its own set of rules and rules were weighted to imply importance.

We identified four main collision indicators:

1. **Vertical corroboration:** activity or direct hit on footage of the upward looking cameras within same time window;
2. **Secondary tracks:** several tracks visible with similar trajectories within the same time window (indicating several pieces of a carcass). This only applied when rotor was spinning, since sufficient velocity will be needed to break apart the carcass. These objects were counted as one collision event;
3. **Rotation:** object rotating in fall at a constant rhythm, showing as a track that was fading in and out (flickering) and/or with a wave shape to it; and
4. **No active flight:** no speed changes, no direction changes, object was not moving faster than expected for the shape and size (than terminal velocity).

Living animals were best characterized by active flight and by the track showing that the object was moving away from the camera (detections becoming smaller along the track and separation distance decreasing) or towards it. The main indicators of active flight were sharp or active changes in direction along a track, as well as speed changes and visible wing beats. A less tangible part of active flight was related to terminal velocity and the "expected speed" of a falling object.

Furthermore, an important part of evaluating the tracks and distinguishing between labels was understanding the relationship between size, shape, speed, and brightness (*i.e.* heat signature) of the detections. This relationship provided insight in distance from the camera and could inform whether the object was warm- or cold-blooded. Warm-blooded animals could be detected at larger distances from the camera than cold-blooded animals (insects). Therefore, small and bright detections close together indicated an object further away from the camera that was warm enough to still be detected at that distance and thus representing a warm-blooded animal. When a warm-blooded animal was detected close to the camera, it appeared very bright and relatively defined, and the detections were more spaced out. Conversely, tracks that moved very fast and were shapeless and blurry represented insects (*i.e.* cold-blooded animals close to the camera), rather than birds or bats.

---

## 2.5 Collision data analysis

After the final labelling was completed, two additional filtering steps were applied to the identified collision detections: 1) tracks were merged for several occurrences where more than one track was related to the same distinct falling object(s) ( $n = 9$ ) and 2) tracks at times of service activity were excluded as these in all likelihood reflect false positives from human activity on and around the turbine, while the turbine was curtailed.

Civil sunrise and sunset times (local time) were used to group the tracks into daytime and nighttime. To analyse seasonal effects, data were attributed to spring (Mar-May), summer (Jun-Aug), autumn (Sep-Nov) and winter season (Dec-Feb). Data on wind speed and direction were obtained from the substation at HKZ wind farm and were provided by Vattenfall. Data visualization was done in R (version 4.5.1; R Core Team 2025).

## 2.6 Acoustic monitoring

Bat activity around the turbine was monitored on the transition platform and at the nacelle. On the transition platform, activity was monitored with the Wildlife Acoustics – SMART System with three microphones (SMART MIC-1) directed north, north-west and south-south-west. Data and status updates were accessed and retrieved via the SMART control panel throughout the study period. The system was triggered and set to record all day. The minimum trigger frequency was 16 kHz, the gain was set to 12 dB, pre- and post-trigger were set to 3 sec, and all other settings were set to default.

Data was collected from February 17 to December 8 2025, for a total of 294 recording nights. One of the microphones malfunctioned from February 24 onward and was replaced on May 6 – during this period data were collected by the two remaining functioning microphones.

On the nacelle, bat activity was monitored with two Wildlife Acoustics – Song meter mini Bat 2 Li-ion recorders. The recorders were triggered (minimum trigger frequency of 16 kHz) and set to record from 30min before sunset until 30min after sunrise. All other settings were set to default. The Song meter mini Bat 2 recorders are battery powered stand-alone recorders, and the deployed devices were exchanged at regular intervals of roughly six weeks starting March 15 2025 (subject to permits for visits to the nacelle).

All recordings were processed and manually annotated using the software BatExplorer (version 2.3.2.0; Elekon AG, Switzerland). The nacelle data was partially preprocessed using Kaleidoscope (version 5.9.0; Wildlife Acoustics Inc., U.S.A.) to remove noise recordings and reduce the number of recordings to be analysed in BatExplorer. Recordings were annotated to the lowest taxonomic level possible. Sequences belonging to the Nyctaloid group (including the genera *Eptesicus*, *Nyctalus*, and *Vespertilio*) were not identified to species level. Bat activity was expressed as the number of minutes with at least one bat recording (bat-minutes) instead of the number of recordings, to prevent over-estimation of bat presence due to overlap of recordings between and within microphones. Note that the bat-minutes do not reflect the total amount of time that bats were present at the turbine.

In addition to the acoustic monitoring of bat activity, we also attempted to monitor bird vocalisations with two Wildlife Acoustics – Song meter Mini 2 li-ion recorders at the nacelle. The recorders were set to record 24/7 with 15-minute recordings. During data exploration it became apparent that there was too much ambient noise within the bandwidth of bird sounds to reliably and efficiently extract any bird calls other than an occasional gull and finch, despite attempts to filter out turbine noise. These data were omitted from further analyses.

---

## 2.7 Flight intensities from bird radar

Flight intensities as measured with a bird radar were used to compare flight activity measured with the cameras. For this purpose, data were used from two offshore bird radars, one at wind farm Luchterduinen (ca. 5 km W of the study turbine) and one at the substation of wind farm Hollandse Kust Zuid (ca. 15 km SW of the study turbine). Radars were 3D-flex radars of Robin Radar Systems, of which low-altitude data (up to ca. 250 m altitude) of the horizontal radar was available. Data from these radars were processed to exclude rain and sea clutter. Radar-obtained fluxes were calculated as migration traffic rate (MTR), being the number of bird tracks passing a 1-km line in one hour.

## 3 Results

### 3.1 Objects observed

A total of 782 downward tracks were evaluated and labelled. Tracks presented differently depending on the type of object, the size, distance from the camera, heat signature and contrast with the environment (appendix figure A2). Generally, detections looked like small dots, which for most tracks did not allow for identification of species or species groups. Occasionally wing outlines or wingbeats could be seen indicating birds and bats (appendix figure A2).

During the first independent labelling round, 69 unique tracks were labelled as collision detections. WIS and WUR identified respectively 55 and 62 collision detections, of which 48 (70%) overlapped between the two groups (Table 1). Subsequently, these detections were inspected and discussed in more detail, to eliminate false positives. This step was used to train the observers and develop a set of labelling rules (Table A2), and formed an important step to come to objective classification. Especially insect tracks were removed in this step, as these in particular required training to differentiate from actual collision detections. Also, tracks at times of service activity at the turbine were removed in this step. After final labelling and filtering of the collision detections, 22 tracks were identified as Collision detections (of which we are mid to highly confident that they constituted genuine collision events), 82 tracks as Animal flying (bird/bat), 615 as Insect, 6 as Unsure, and 26 as Other (Table 2). The 22 collision detections include 2 confirmed collisions and 1 high-confidence collision (see also appendix table A2). The latter three provide a hard lower bound, while the full set of 22 collision detections represents our best estimate of the upper bound of collision events, which includes a level of precaution to prevent collisions being underestimated.

**Table 1** Labelling comparison between WENR and WIS. Green cells indicate overlap in labelling between both groups.

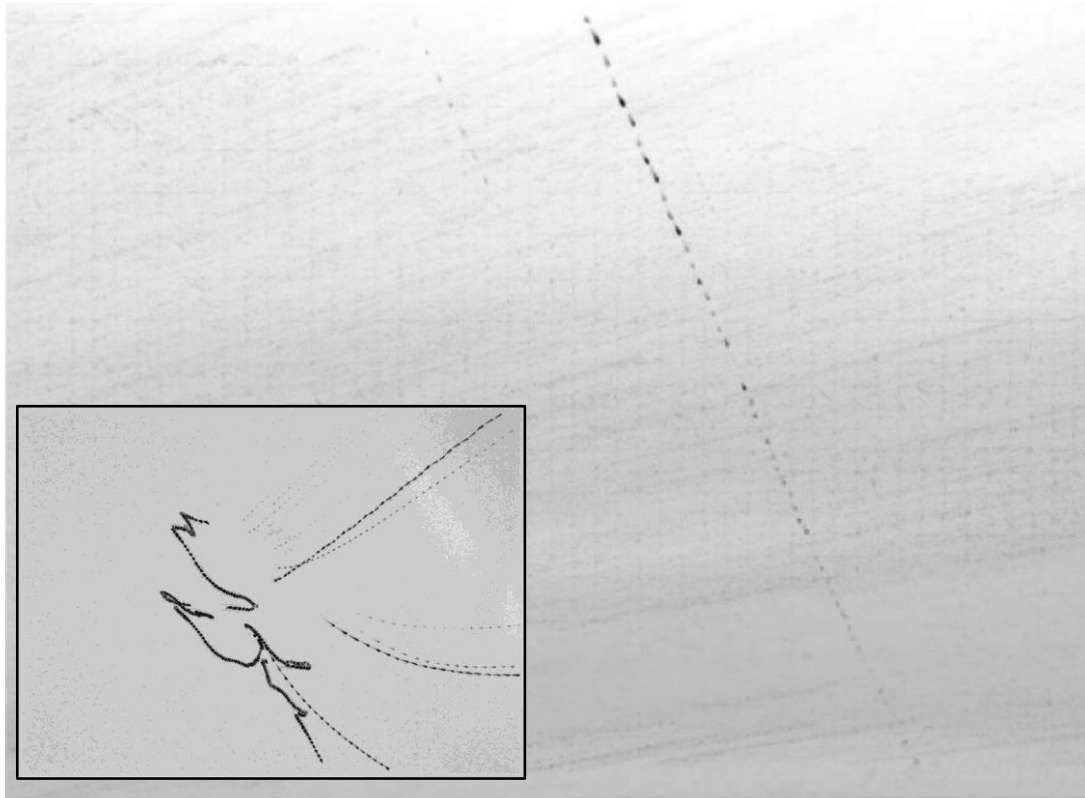
| WUR \ WIS           | WIS                 |               |            |          |           | Total      |
|---------------------|---------------------|---------------|------------|----------|-----------|------------|
|                     | Collision detection | Animal flying | Insect     | Unsure   | Other     |            |
| Collision detection | 48                  | 7             | 6          | 1        | 0         | <b>62</b>  |
| Animal flying       | 3                   | 74            | 115        | 1        | 0         | <b>193</b> |
| Insect              | 0                   | 1             | 468        | 1        | 0         | <b>470</b> |
| Unsure              | 4                   | 4             | 25         | 0        | 0         | <b>33</b>  |
| Other               | 0                   | 0             | 0          | 2        | 22        | <b>24</b>  |
| <b>Total</b>        | <b>55</b>           | <b>86</b>     | <b>614</b> | <b>5</b> | <b>22</b> | <b>782</b> |

**Table 2** Number of tracks per label category after final labelling and filtering of collision detections.

| Label                | Number of tracks |
|----------------------|------------------|
| Collision detections | 22               |
| Animal flying        | 82               |
| Insect               | 615              |
| Unsure               | 6                |
| Other                | 26               |
| <b>Total</b>         | <b>751</b>       |

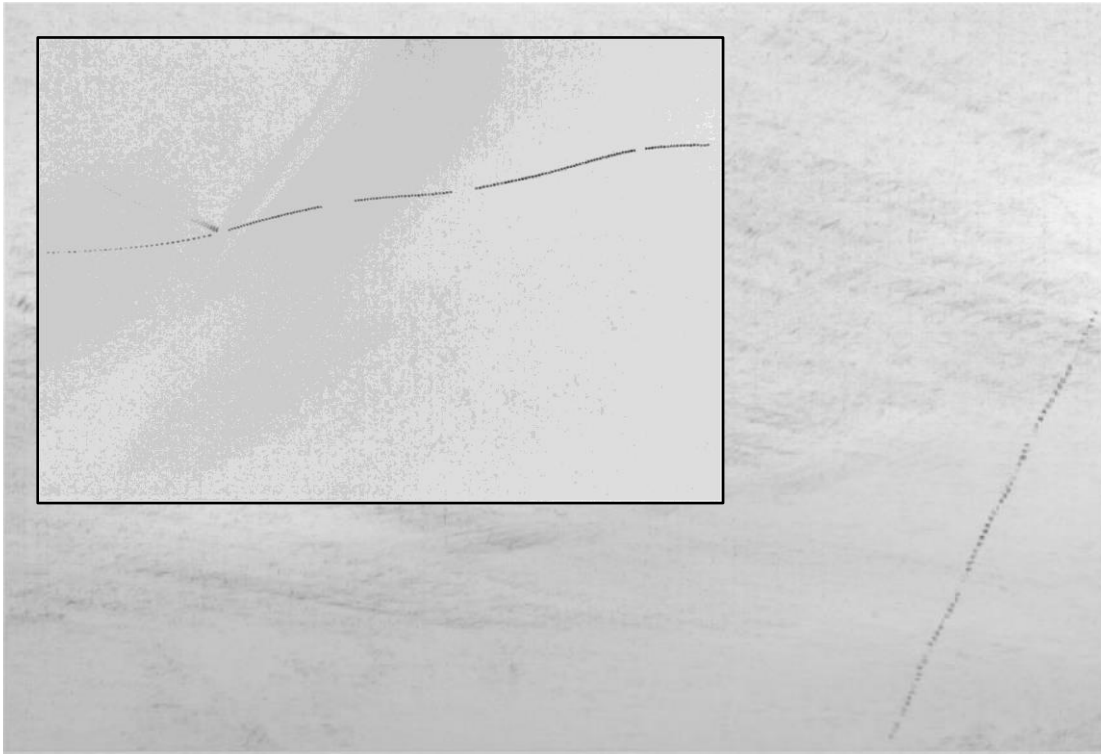
## 3.2 Confirmed collisions

The two confirmed and one high-confidence collision all occurred either in the evening or at night. The first confirmed collision occurred on April 15 2025, at 00:03 at night (local time) in the W/WSW direction of the turbine. The summary image of the outward looking cameras shows two parallel tracks (figure 2) that occur within seconds from each other with no active flight, identifying this as a collision detection. Furthermore, footage from the upward-looking cameras provided vertical corroboration of a collision, with a direct hit caught on camera (figure 2). The summary image and video show an animal (most likely a songbird) struggling in the drafts of the blade and being hit by the blade, rendering it a confirmed collision.



**Figure 2** Summary image of the confirmed collision on April 15, showing the 2 parallel tracks of the falling bird remains in the large frame (2<sup>nd</sup> short and vague track on the left of the long track), and the corroborating footage of the actual collision in the inset, showing the arbitrary movement of the bird struggling in the rotor wake and the remains cast to the right upon collision. Colours are inverted from the original image for visual clarity.

The second confirmed collision occurred on November 22 2025, at 20:53 in the evening, NE of the turbine. From the summary image of the outward-looking cameras this track was identified as a collision detection due to the rotating aspect of the track, no indications of active flight, and no notable speed-related traits (figure 3). Vertical corroboration from the upward-looking cameras confirmed this track as a confirmed collision – the footage shows another direct hit (note the additional deviating track on the left side of the inset; figure 3).



**Figure 3** Summary image of a confirmed collision on November 22 at 20:53, with the outward-looking camera detecting a track with rotating aspect (track on the right in the large frame), corroborated by the upward-looking cameras recording the collision (inset); gaps in the flight path indicate passage of the rotor blade; the hit occurred on the left end of the track. Colours are inverted from the original image for visual clarity.

Finally, we identified one high-confidence collision: a track from the outward looking cameras of which we are confident it is a collision, but the collision could not be confirmed on the upward looking cameras (note that the upward looking cameras did not have full coverage of the rotor-swept zone). This high-confidence collision occurred on March 18, 2025, at 23:05 at night in the W/WNW direction (figure 4). The presence of a cluster of downward tracks, all occurring within several seconds, gives us a strong indication of this being a fatality. Moreover, several of the tracks have a flickering appearance, indicating some rotation in the track, and no active flight or noticeable speed traits could be found.



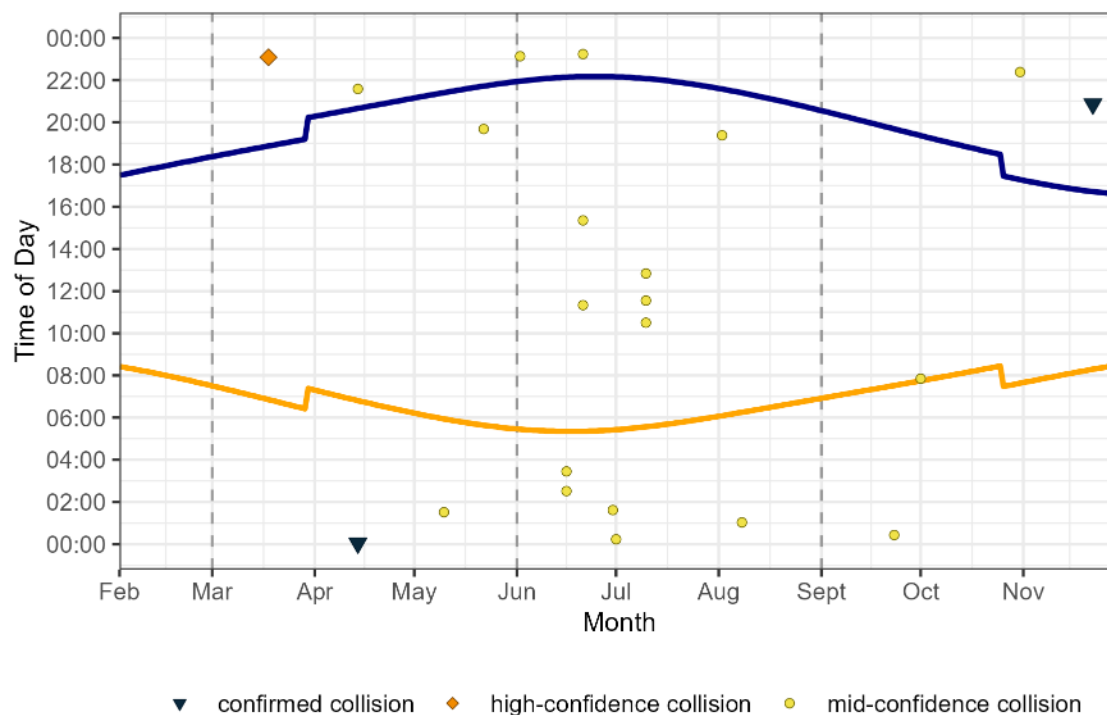
**Figure 4** Summary image of a high-confidence collision on March 18 2025, consisting of tracks of multiple objects falling down simultaneously. Because there was no visual corroboration from the upward looking cameras, this was not classified as a confirmed collision. Colours are inverted from the original image for visual clarity.

### 3.3 Circumstances of collisions

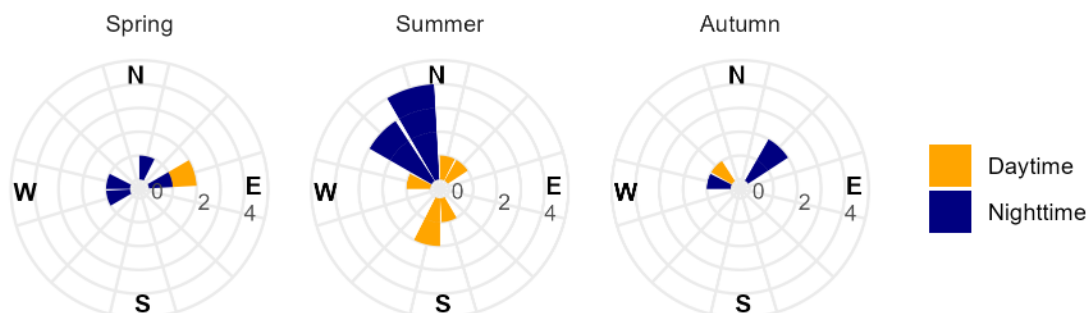
About two thirds of the collision detections occurred during the night (64% of total) and the majority occurred in summer (59% of total; Table 3). There were no collision detections recorded in winter. In early spring and autumn the seven collision detections occurred predominantly at night, with one at sunrise in October and only one during daytime in May (figure 5). Across all seasons, the majority of collision detections were recorded around the northern half of the turbine, at the outer edge of the wind farm, except for three daytime collisions south of the turbine in summer (figure 6).

**Table 3** Distribution of collision detections over seasons and time of day. Note that the winter was underrepresented in the measurements.

| Season       | Daytime  | Nighttime | Total     |
|--------------|----------|-----------|-----------|
| Spring       | 1        | 4         | 5         |
| Summer       | 6        | 7         | 13        |
| Autumn       | 1        | 3         | 4         |
| Winter       | 0        | 0         | 0         |
| <b>Total</b> | <b>8</b> | <b>14</b> | <b>22</b> |

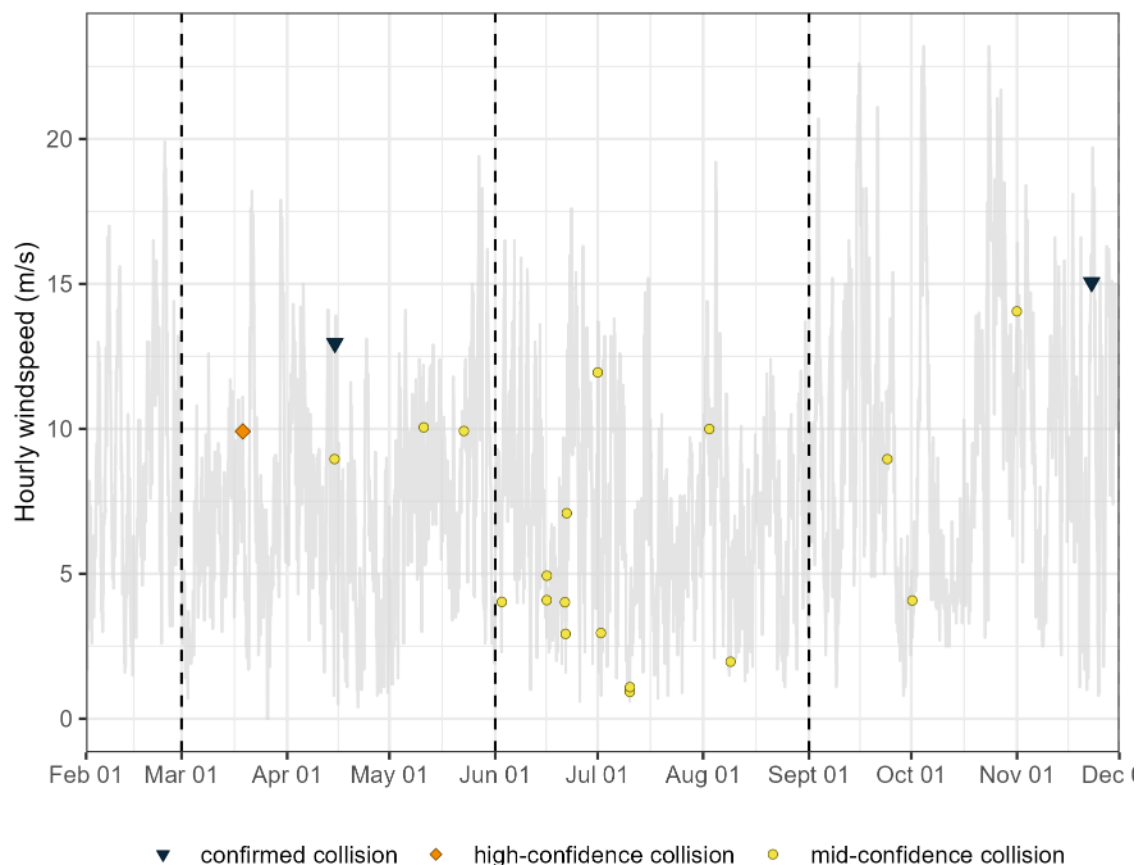


**Figure 5** Collision detections plotted over the months and time of day, with local sunrise (yellow line) and sunset (blue line) indicated. Vertical dotted lines indicate spring (Mar-May), summer (Jun-Aug) and autumn seasons (Sep-Nov).

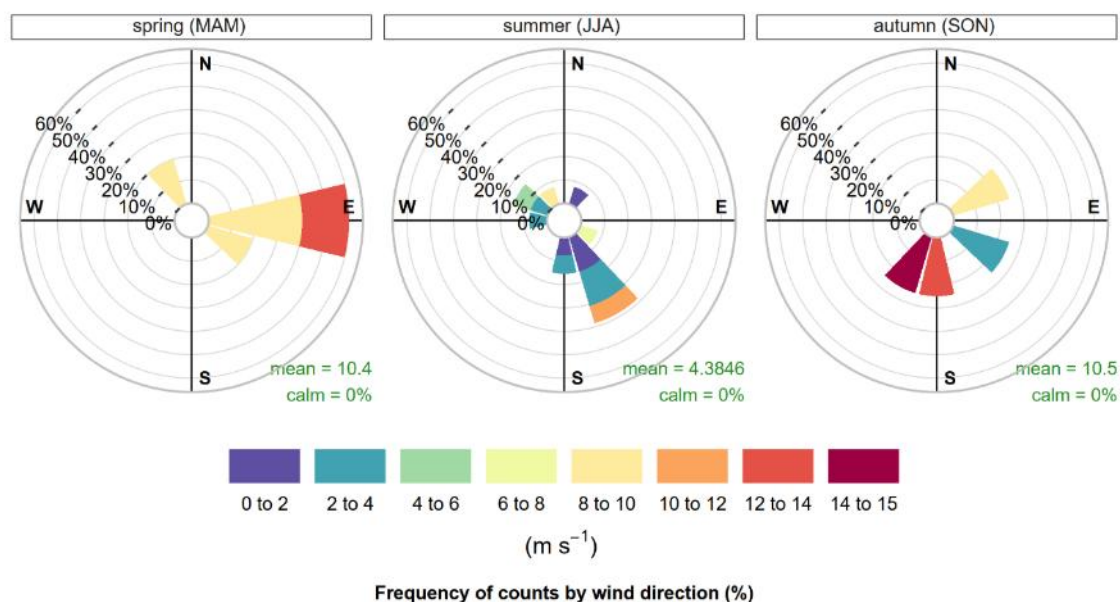


**Figure 6** Position around the turbine where the collision detections were located, visualised as the number of collision detections in each of the twelve segments around the turbine, and shown per season and for day- versus nighttime. There were no collisions detected during winter.

Hourly wind speeds at times of collision detections varied largely, between 0.6-15 m/s or 1-7 bft across the study period (figure 7), with average wind speeds of 10 m/s in spring, 4 in summer, 11 in autumn (see also appendix figure A3). Both of the confirmed collisions as well as the high-confidence collision occurred at wind speeds above 10 m/s or 5 bft (10 m/s on March 18, 13 m/s on April 15 and 15 m/s on November 22). The highest wind speed was recorded during the confirmed collision on November 22, with a south-southwesterly headwind at 15 m/s (7 bft). 11 out of 22 collision detections occurred at wind speeds below 7 m/s or 4 bft and 91% of these occurred in summer. The prevailing wind direction during collision detections differed per season (figure 8), with 80% of the collision detections in spring at easterly winds and wind direction in autumn ranging from north-east to south-west.

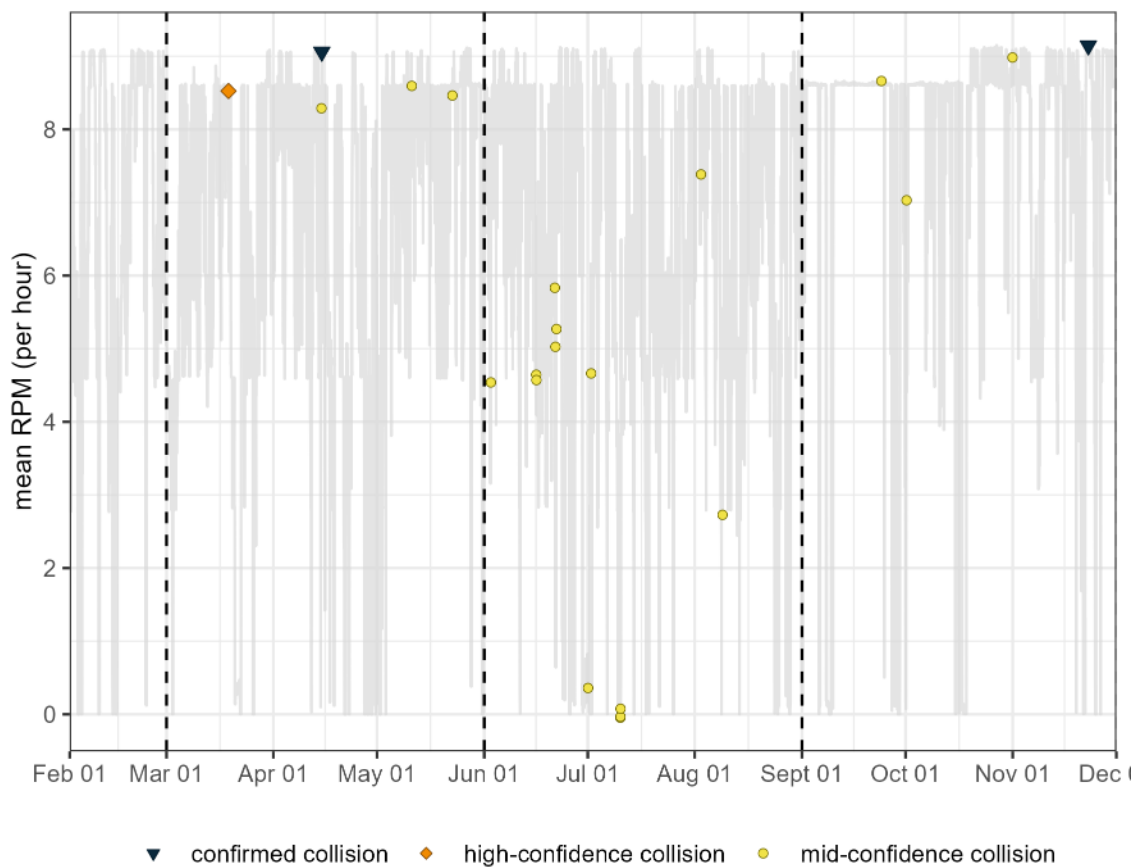


**Figure 7** Wind speed in m/s during the hour a collision detection occurred (points) and hourly wind speed (grey line). A small amount of random vertical jitter was added to each collision detection point to display overlapping values. Seasons are indicated with dashed, vertical lines.



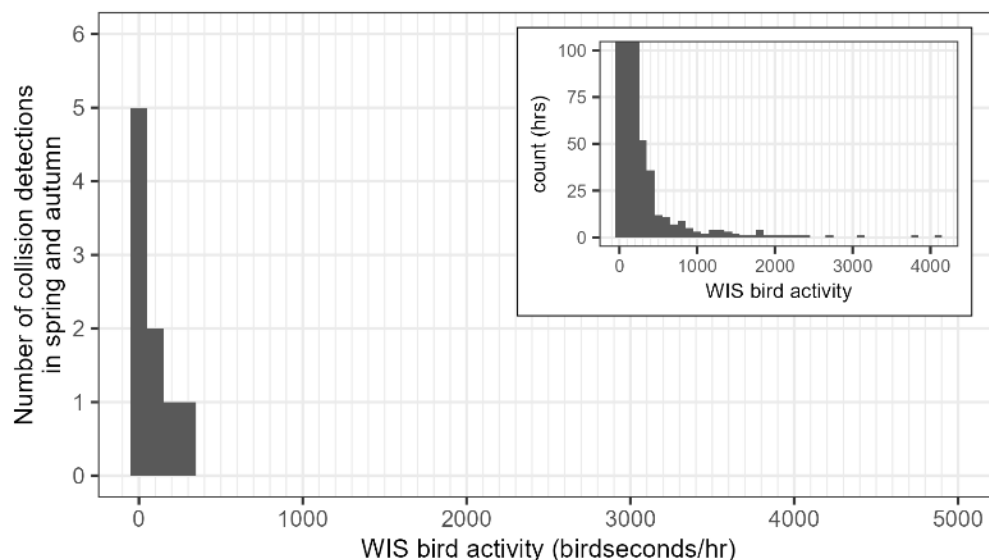
**Figure 8** Wind speed and direction at times of collision detections, shown as the frequency of counts per season ( $n=5$ ,  $n=13$ ,  $n=4$  respectively, note no collision detections in winter).

Rotor speed at times of collision detections (mean RPM across 10 min) ranged between 0 and 9 RPM (figure 9). All collision detections in spring and autumn occurred during rotor speeds of >7 RPM. During the confirmed collisions on April 14 and November 22 2025, the rotor was spinning at 9 RPM, while the high-confidence collision occurred at 8.6 RPM. In summer four collision detections occurred during (near) rotor standstill (3 during daylight hours, 1 at night).



**Figure 9** Mean rotor RPM in the 10 min bin that a collision detection occurred (points) and hourly mean RPM across the study period (grey line). A small amount of random vertical jitter was added to each collision detection point to display overlapping values. Seasons are indicated with dashed, vertical lines.

Bird activity as measured with the upward looking cameras in the hours that collisions were detected (figure 10) was 101 bird-seconds per hour on average in spring and 98 in autumn and 52 in summer, with an overall average of 72. Bird activity ranged between 0 and 4066 on average across the entire study period. No activity was measured at one of the collision detections in spring and at two of the collision detections in summer (0 bird activity in the hour of collision detection on the upward-looking cameras). Bird activity at the time of a collision detection was highest during the collision in the night of March 18 (bird activity that hour = 326 birdseconds; in the hours between sunset and midnight, maximum bird activity = 1259). Similar to the bird activities measured with the WIS system, flight intensities measured with bird radar were also mostly low at the times collision detections occurred. Maximum MTR measured during a collision detection was 310 bird tracks / km / h, measured in the early morning of October 1 at Luchterduinen (notably at HKZ, MTR was only 26; bird activity measured at the turbine was also low at 8 bird-seconds in total for that hour). On this night, wind was a gentle south-easterly sidewind (4 m/s). On the night of March 18, when bird activity during a collision measured with the cameras was highest, MTR at Luchterduinen was only 17 birds/km/h at the hour the collision took place, and 48 bird tracks/km/h max in the hours between sunset and midnight (no data from the HKZ-radar). Wind at this time was a fresh east-southeasterly sidewind (10 m/s). Radar MTRs were available for 15 of the 22 collision detections, and averaged 24 bird tracks / km / hour (maximum = 48), which is low relative to the seasonal MTRs measured in autumn (max = 516; mean = 40 birds/km/h) and spring (max=1254; mean = 81 birds/km/h at HKZ). These MTRs were available from the HKZ radar mostly, the Luchterduinen radar yielded values on only 2 of the moments of collision detections.



**Figure 10** Number of collision detections during the migratory seasons in spring and autumn, plotted against migration activity as recorded by the WIS cameras. Highest MTR measured was 4066 birdseconds/hr. The histogram in the inset shows the underlying distribution of migration activity; where counts represent the number of occurrences of MTR-values falling within each bin (note the y-axis limit is set to 100; cut-off values are 7884, 598, and 112 respectively for the first 3 bins). Bin width for both histograms is 100 birdseconds. MTR-data on hourly basis.

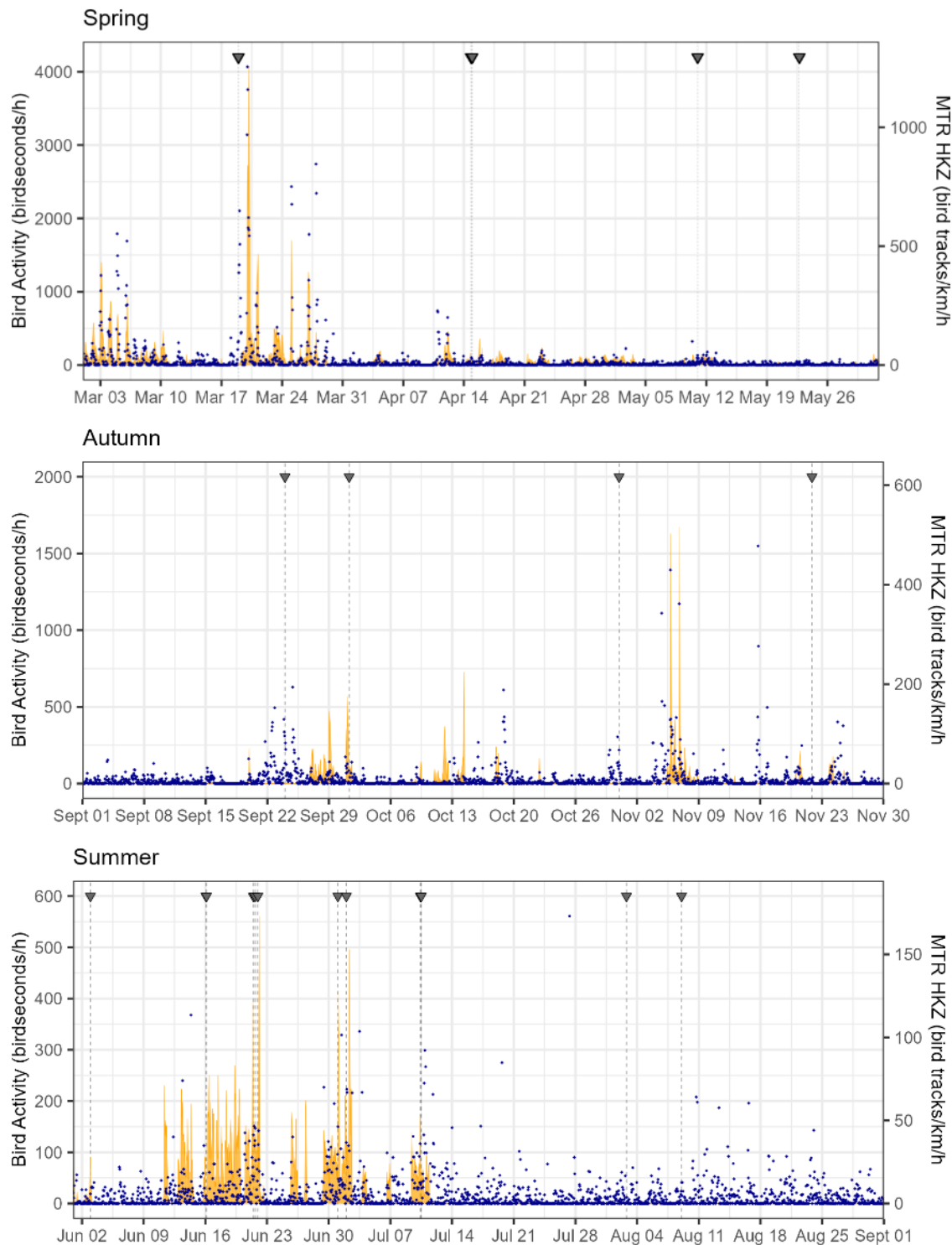
### 3.4 Comparing flight intensities measured with thermal cameras and bird radar

To relate collisions to migratory activity at those events, bird activity as measured with the upward-looking WIS system cameras was compared with MTRs measured locally with bird radar. This comparison also provides an indication of the functionality of the WIS system to detect passerines flying by under varying weather conditions. In general, migration peaks measured with the WIS cameras matched well with peaks measured with the bird radars (figure 9). On visual inspection, the three main migration peaks measured in spring were very similar. The WIS system measured substantially higher flight intensities on the nights of 4/5 and 5/6 March and again on the nights of 26-28 March, while they were more in line with the intensities measured by radar on the surrounding nights. Peaks were however measured in the same periods, which was not the case in autumn, when there were at least 4 peaks in flight activity measured by the WIS system that were not measured by the radars (notably around the nights of September 22, October 19, October 31 and November 16) and 2 peaks that were measured by the HKZ radar that were not measured by the WIS system (around the nights of Sep 29 and October 13).

Measured flight intensities correlated when compared on an hourly basis and more so when comparing maximum activity per time frame (daytime, nighttime hours before midnight, nighttime hours after midnight) (Pearson correlation on log-transformed data; on hourly basis: *Pearson's r* (2146)=0.333,  $P<0.001$ ); by time frame:  $r(350)= 0.474$ ,  $P <0.01$ ).

When comparing the major migration peaks that were observed, bird activity measured with WIS system exceeded 1500 birdseconds/hr during 9 time periods (4 before, 5 after midnight; 8 in March, 1 in November). For 8 of these time periods, radar data were available. HKZ similarly showed high flight intensities ( $MTR \geq 200$  bird tracks/km/h) on 6 of these nights, and lower values on 2 nights. The Luchterduinen radar, closer by, showed high flight intensities on 3 of these nights and lower values on 5 nights. Vice versa, the HKZ-radar measured flight intensities of 200 birds/km/h and more on 15 time periods, all at night (5 nights before midnight, 10 after). Of these nights, bird activity measured with the WIS system was high on all but 2 early morning time periods: February 26 and October 14. (6 time frames with 1500 bird seconds or more; 7 time frames with bird activity between 600 and 1500). In the early

morning hours of February 26, WIS bird activity was low (145 bird-seconds), while the radars at both HKZ and Luchterduinen measured fair migration (350-400 bird tracks/km/h). Similarly, on October 14, WIS bird activity was 47 while the radars measured between 225 and 500 bird tracks/km/h.



**Figure 11** Bird flight intensities as measured with the WIS thermal cameras (blue) and with offshore bird radar 15 km away (orange), shown for the two migration seasons (upper panel spring and middle panel autumn) and for the summer season. MTRs from bird radar (secondary axis) were scaled to match the primary y-axis for visualization purposes. Collision detections are indicated with downward triangles and vertical dashed lines. Note the differences in scale between seasons; activity was much reduced in summer.

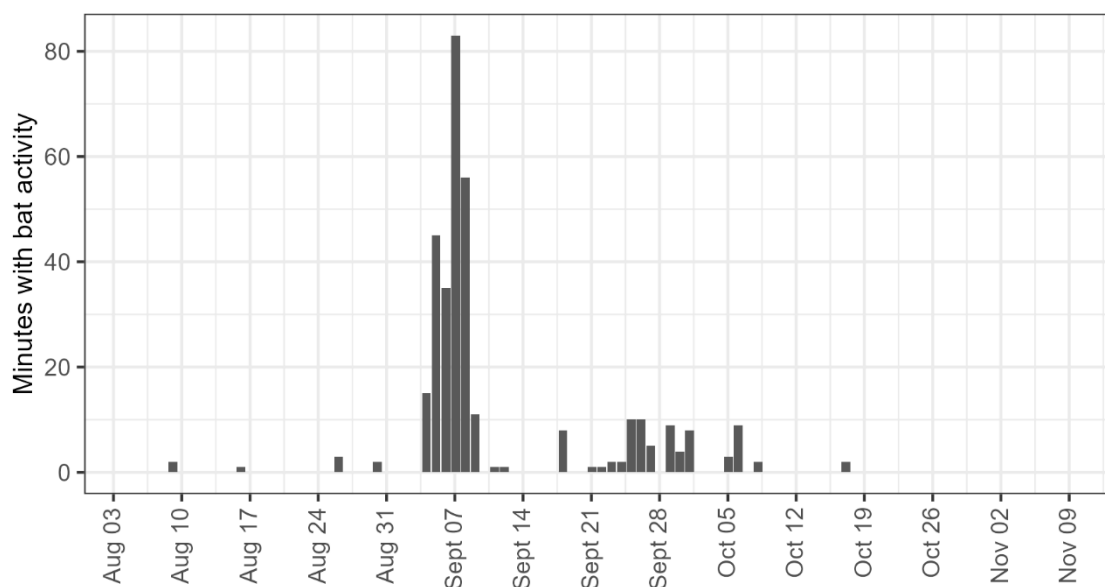
### 3.5 Bat activity

At the Nacelle, two bat species were detected on three different nights: *Nathusius' pipistrelle* (*Pipistrellus nathusii*) on September 9 and a *Nyctaloid* species on April 29 and May 24. On the transition platform, two distinct species and two species groups were identified across 343 minutes with bat activity (table 2). Bat activity was detected on 12% of the total recording nights (34 out of 294 nights). The common pipistrelle was recorded on May 11, and the *Nyctaloid* group/*Nyctalus* spec. were detected on May 12, August 10 and August 12. *Nathusius' pipistrelle* was the most commonly detected species, being recorded on 31 nights across March, April, May, August, September, and October. The species was most active during early September (figure 10). The majority of the activity was recorded at night, across windspeeds ranging between 1-17 m/s or 1-8 bft (see figures A4 and A5 in appendix). The average wind speed at times of bat activity was 6 m/s.

No relation was found between bat activity and collision detections. No collisions were recorded during times of high bat activity, and there was no bat activity detected at the times when collisions were recorded.

**Table 4** Bat activity recorded at the transition platform.

| Species                          | Number of nights | Minutes with activity |
|----------------------------------|------------------|-----------------------|
| <i>Pipistrellus nathusii</i>     | 31               | 339                   |
| <i>Pipistrellus pipistrellus</i> | 1                | 1                     |
| <i>Nyctaloid</i> group           | 2                | 2                     |
| <i>Nyctalus</i> spec.            | 1                | 1                     |
| <b>Total unique nights</b>       | <b>34</b>        | <b>343</b>            |



**Figure 12** Activity of *Nathusius' pipistrelle* (*Pipistrellus nathusii*) at the transition platform for August-November, displayed as the number of minutes with bat activity per recording night.

---

## 4 Discussion

### 4.1 Detecting collisions

The results of this pilot study demonstrate that continuous camera-based monitoring of the 360-degree area below the rotor-swept zone provides a viable means of directly quantifying bird collision rates at an offshore wind turbine, including under nocturnal conditions and for small-bodied species such as passerines. To our knowledge, this constitutes the first empirical measurement of passerine collisions at an offshore wind turbine, with the application of a turbine-mounted outward-facing camera system in an offshore context. The detection of two confirmed collisions and one high-confidence collision, alongside 19 mid-confidence collisions, across two migration seasons and one summer at a single turbine, demonstrates that the WIS system is capable of recording collision events offshore — including at night — and that the approach is operationally feasible under the challenging environmental conditions of the southern North Sea.

### 4.2 Detection performance

A key requirement for any collision monitoring system is that the objects of interest — birds and bats passing through the rotor-swept zone — are reliably detected by the system, to minimise the probability of missing an actual collision event. Two independent lines of evidence suggest that detection performance of the WIS system was adequate for this purpose. First, **visual inspection of the footage** indicated that the cameras captured many individual birds, bats and insects passing through the field of view with sufficient clarity to allow tracking and labelling, and in several cases with sufficient detail to observe wingbeats, wing outlines, and — in the case of the confirmed collisions — the moment of impact and subsequent movement of the struck animal. In all these instances, the automated detection system identified the relevant tracks, indicating that the cameras and processing software performed well at detecting tracks and identifying potential collisions. To allow evaluation and tuning of the detection and processing of the tracks, filtering to take out insect tracks from the data was set to be mild, thus allowing examination of the various types of tracks to develop labelling rules to recognize and quantify actual collisions. This also provided insight in the detection capabilities of the cameras. The manual evaluation of the summary images and tracks was subject to some uncertainty regarding collision detection. For instance, a reduction in distance between detections can indicate active flight, but minute differences in distance were difficult to determine visually. This uncertainty is reflected in the results after first independent labelling, highlighting the importance of multiple evaluators. The positive identification by all the reviewers of the confirmed collisions as mid-confidence collisions before reviewing the footage of the upward-looking camera, does confirm that the manual review of images is robust in identifying collisions.

Second, and more broadly, the **correspondence between bird flight intensities** measured by the upward-facing WIS cameras and the migration traffic rates measured by bird radar, provides an independent indication that passerines passing through the field of view of the cameras were being detected well by the system. The two measures were significantly correlated on both an hourly basis and when compared across defined time frames within the night, and the principal migration peaks identified by radar were mirrored largely in the camera data across both migration seasons. This correspondence implies that the WIS system was responsive to variation in the abundance of birds in the rotor zone, and that the probability of systematic false negatives — collision events occurring without any associated detection — was limited.

---

There were however discrepancies between the WIS camera data and the bird radar data on specific nights, that can shed light on detection performance. On 4 nights in autumn and 1 in spring, WIS measured substantial flight activity while the bird radars did not. Most notably, on the nights from the evening of Sep 22 through the morning of Sep 25, the WIS system measured high bird activity, but radar data were not available. Weather was very favourable for migration in these nights, with northeasterly tailwinds between 6 and 10 m/s, and dry. Coastal weather radars and bird counts corroborated nocturnal migratory activity (<https://www.meteo.be/services/birdDetection/#/>; [trektellen.nl/count/daytotals/](https://trektellen.nl/count/daytotals/)). These circumstances indicate that the wave of migration has been accurately recorded by the WIS system. This shows that the WIS system can shed additional light on the offshore migratory situation when information from bird radars is limited. Notably, during this migration wave a collision detection was recorded in the early morning hours of September 24. Similarly, radars were off on the late evening of Oct 31, and another collision detection was recorded as well, but at this time the high activity measured with the WIS system could not be corroborated from observations on land very well; although a sharp peak was detected on the weather radar at Den Helder just after sunset that evening and high numbers of starlings were counted at the coast the following morning. Strong migration was not expected that night as the weather conditions were unfavourable with strong southerly headwinds at 13 m/s and overcast but without precipitation. The third mismatch in autumn occurred mid October on the night of 18/19 October, when high flight activities measured with the WIS system were not matched by the low flight activities from the Luchterduinen radar (no data from HKZ radar). Weather that night was again favourable for migration with southeasterly wind at 8-9 m/s and dry. Again, coastal weather radars and local bird counts corroborated nocturnal migratory activity. Lastly, on November 16 a major peak was measured by the WIS system around sunset, but the Luchterduinen radar measured very low flight activity (no data from HKZ radar). Weather was favourable for migration with northeasterly wind at 8 m/s and dry. Strong migration was observed on the Dutch coast that night, with birds departing in westerly direction around sunset (corroborated by coastal weather radars though not so much by local bird counts, as well as by observations by KLK and MJMP from a coastal bird radar at Bloemendaal), suggesting migration did indeed occur that evening. In spring, a substantial peak was measured with the WIS system on the night of 18/19 March, that was not picked up by either of the radars. Migration conditions were unfavourable with an easterly headwind (4 bft), but temperature increased substantially the previous day which may have triggered birds to fly. Possibly, migration activity occurred low over sea and therefore not picked up by the radars. The high-confidence collision occurred this night. On all of these nights, no false positives were visible on the cameras, of for instance rain or clouds being labelled as birds. Instead, images were clean and showed clear bird tracks.

Vice versa, strong migration was measured on bird radar that was not measured with the WIS system on a number of nights. First, on 26 February in the early hours after midnight a fair amount of bird activity was measured by the bird radar, that was measured to a much smaller extent by the WIS cameras. Substantial migration activity was reported from observation posts on the Dutch coast ([trektellen.nl](https://trektellen.nl)) that night, but mostly of larger species (Northern Lapwing *Vanellus vanellus*, White-fronted Goose *Anser albifrons*), that are not likely to have led to high MTRs in the early hours after midnight. Weather was favourable however with a south-westerly tailwind of 5 m/s dry and clear sky, which resulted in higher-altitude migration, recorded at the coastal weather radars. Second, weather conditions on October 14 in the early hours after midnight were also favourable for migration, with north-easterly tailwind at a mild 4 m/s, overcast but dry. Migratory activity was reported from the Dutch coast, although predominantly further north than our study site. Third, on the night of 17/18 October, weather was favourable for migration with calm north-easterly tailwinds and dry although overcast. Migration was detected on the nearby Luchterduinen radar and not the HKZ radar further away, suggesting that migration did occur in the area. Lastly, late September (nights from 28 September through 1 October when another collision detection was recorded), calm northerly winds ranging between northwest and northeast to east and dry circumstances with some cloudy patches, provided fairly good sidewinds to tailwinds for higher-altitude migration, and coastal observations corroborated this. Elevated flight activity was measured by the thermal cameras, but not to the same extent as by the bird radar. The reason for the mismatch may lie in flight altitudes of the birds. Overall, the tailwinds on many of these nights suggest that birds may have migrated above the detection range of the upward-looking cameras. Although detection range can be reduced in dense fog and heavy rain (info camera supplier: Axis 2021), cloud cover at higher altitudes has not drastically impaired detection range in prior measurements or tests with the WIS system, and the cameras have shown stable detection ranges in most conditions. We

---

therefore do not expect detection rate was reduced on overcast nights, which was the case on two of these nights.

In summary, the circumstances suggest that the WIS system accurately detected migration peaks when the bird radars did not; but also did not detect migration peaks on nights when the bird radar did. Weather may have affected results from both systems, in that rain may erroneously elevate flight activity estimates of radar, while overcast skies may reduce estimates from thermal cameras. However, a substantial part of the migration activity that was missed on the nocturnal cameras may well have occurred at altitudes above the range of the cameras, thus reflecting a difference in detection range between the two systems rather than flaws in detection capability. Importantly, the WIS system captured reported migration activity that was not detected by the radars.

## 4.3 Number of collisions

The actual number of collisions as detected by the outward-looking cameras lies somewhere between 3 and 22. The total number of collision detections recorded — 22 across approximately one year of monitoring at a single turbine — is average relative to collision rates typically reported for birds at onshore wind turbines, which range from 0 to 40 birds per turbine per year depending on location (Sovacool 2009, Marques *et al.* 2014). Relative to the high nocturnal fluxes as well as the focus on migrating passerines that are often not considered in collision studies, the collision rate can be considered low. This is consistent with findings from onshore studies specifically targeting migratory passerines, where collision rates were similarly low despite high migration rates and did not differ systematically between nocturnally and diurnally active species (Krijgsveld *et al.* 2009, Welcker *et al.* 2016, Liedtke *et al.* 2025).

## 4.4 Species identification

Establishing what species or even species groups collided was not possible based on the footage, due to low resolution and lack of a daylight camera. The majority of tracks seemed to be of smaller objects, such as passerines, as they lacked a particular shape and were small relative to the perceived distance. Also daytime collision detections could not be identified as belonging to a small passerine or a larger seabird. Both confirmed collisions were likely to be with passerines, as could be established from the flight characteristics from the related video footage. At least a few of the 22 tracks, however, indicated a larger object falling at a greater distance based on the relationship between size and speed. In combination with some irregularities in the shape, suggesting larger objects with protruding wings or tails, we suggest these tracks may have been of larger birds such as seabirds or larger landbirds.

If the smaller-sized birds were dominating collisions, this may cautiously suggest that the collision rate of seabirds lay well below the 22 collision detections at this turbine in 10 months. This would be broadly consistent with findings from the Aberdeen offshore wind farm, where no collisions were recorded during nearly 10,000 seabird videos obtained under daytime conditions (Tjørnløv *et al.* 2023, Skov *et al.* 2025), and with the six collisions — predominantly of gulls and a gannet — recorded during two years of monitoring at the Thanet Offshore Wind Farm (Skov *et al.* 2018). It is however difficult to match with the result that many collision detections occurred in the summer, and many during daytime, a season when migration is reduced and the offshore bird population predominantly consists of seabirds. Taken together, these findings suggest that per-turbine collision rates at offshore wind turbines may be lower than or at most similar to comparable wind farms on land.

---

## 4.5 Circumstances of collisions

A striking finding of this study is that most of the **collision detections did not coincide with periods of high migratory activity**, even though high migration intensities at low flight altitudes did occur during the study period. Only on four occasions did a collision detection occur during nights that there were indications that migratory activity was high (March 18, September 24, October 1 and 31). On the other 18 nights, migration traffic rates measured with either bird radar or thermal cameras were generally low relative to seasonal maxima. Radar data averaged 26 bird tracks per km per hour in the hours that collision detections occurred (radar data available for 15 of these events), compared to seasonal means of 81 and 40 bird tracks per km per hour in spring and autumn respectively. Bird activity measured with the upward-facing WIS cameras was similarly low at most collision incidences, with only a few collision detections coinciding with elevated bird activity — notably the high-confidence collision of March 18, during which camera-measured bird activity reached 326 bird-seconds per hour, with high migration intensities in the subsequent hours (up to 2100 birdseconds). This pattern would not be expected if collisions were simply a function of bird flux: higher migration traffic rates would be expected to produce more collisions, with a substantial number of collisions on the nights with highest migration traffic. The absence of collision detections on nights with high migration intensity instead suggests that the conditions under which birds migrate may be a more important determinant of collision risk than the absolute number of birds in flight. This would affect curtailment procedures aimed at reducing mortality of migrating songbirds, which is currently aimed at nights with high migration intensity.

A plausible explanation would be that collisions are disproportionately associated with **adverse meteorological conditions**. Birds that are migrating under unfavourable conditions — such as headwinds, low cloud cover, precipitation, or reduced visibility — may be more susceptible to colliding with the turbines, either because they fly at lower altitudes, or are less able to avoid obstacles, or are less able to see or sense them, or combinations of these factors. In the southern North Sea, easterly and north-easterly winds in spring and westerly and south-westerly winds in autumn represent headwind conditions for northward- and southward-bound migrants respectively. The predominance of easterly winds during spring collision detections are broadly consistent with this hypothesis. Weather conditions during autumn collision detections were more variable, with winds ranging from north-easterly to south-westerly and varying cloud and rain occurrences, precluding a clear directional pattern consistent with headwind conditions for south- and west-bound migrants. Moreover, the three confirmed/high-confidence collisions all occurred at wind speeds above 10 m/s, as well as the majority of mid-confidence spring and autumn collision detections, suggesting that high wind speeds may elevate collision risk independently of migration intensity, possibly by reducing flight manoeuvrability or forcing migrating birds to fly at rotor heights. A systematic analysis of meteorological conditions at collision times relative to the broader distribution of conditions during the monitoring period would be required to test this hypothesis rigorously, and is recommended as a priority for future studies.

---

## 4.6 Classification uncertainty and system improvements

The range of 3 to 22 collision detections recorded in this study reflects a deliberate methodological choice rather than a fundamental limitation of the system. The initial independent labelling exercise, in which WIS and WUR identified 55 and 62 collision detections respectively with 70% overlap, should not be interpreted primarily as evidence of classification uncertainty, but rather as an illustration of the **importance of training** and explicit labelling rules when interpreting tracks that cannot be evaluated naively. Several tracks that were classified as collision detections, occurred during service activities at the turbine, while the rotors were curtailed, and were subsequently omitted from the dataset. Although it is possible for birds to collide with the rotor blades while they are not moving, or with the turbine tower, the chance of this happening is small, thus rendering it an effective mitigation method (e.g. Marques *et al.* 2014). In contrast, the chance of things falling in the process of curtailing or restarting the blades, or of the activities themselves, is much higher. In this light, it has been crucial to have a good log of **service visits** to the turbine, including the times of curtailing and repowering. We compared the visit log of Vattenfall with AIS data of ship movements to the turbine, which showed that both yielded exactly the same visits. Hence we can be certain that our collision detections do not reflect objects falling in relation to turbine visits. The final consensus labelling, conducted after training and after defining and aligning labelling criteria, yielded 22 collision detections of which we are mid to highly confident that they constituted genuine collision events. The confirmed and high-confidence collisions provide a hard lower bound, while the full set of 22 collision detections represents our best estimate of the upper bound of collision events, which includes a level of precaution to prevent collisions being underestimated. In addition to the 22 collision detections, five tracks were classified as unsure — events that could not be excluded as collision victims but equally could not be distinguished with sufficient confidence from insects or other small objects. These tracks were not included in the collision detections dataset, but represent a residual source of uncertainty in the total collision count: the true number of collision events may therefore marginally exceed the upper bound of 22, though these tracks are considered unlikely to represent actual collisions on the basis of their shape and movement characteristics.

Two categories of **false positives** warrant explicit discussion. First, birds passing through the field of view and flying away from the camera generated tracks that appeared as downward-moving objects in the 2D summary images, due to the perspective effect of increasing distance. These were identifiable during visual review and could be filtered accordingly. Second, insects represented a potential source of false positives, particularly in summer, but their characteristically small size and short detection range made them distinguishable from birds and bats in the majority of cases, and they were removed accordingly during visual review. Additionally, the low flight activity recorded with the thermal cameras during the summer months indicates that insects did not form a substantial or confounding part of the tracks. Both categories of false positives are amenable to automated filtering with further development of the WIS processing software: birds flying away from the camera (but seemingly moving down in a 2D-image) can be identified through the systematic decrease in size and distance between the subsequent detections as the track progresses, while insects can be flagged on the basis of speed, shape and erratic movement pattern. In this study, automated labelling of insects was excluded from the routine procedure to avoid missing any collisions. A comparison between automated filtering and visual inspection showed that this was not the case. Further development of the processing model, incorporating machine learning algorithms trained on the dataset generated by this pilot study, provides a straightforward means to further reducing classification uncertainty and increasing the objectivity of collision detection.

The probability of **false negatives** — actual collision events that were not detected by the system — appeared limited, based on the correspondence between camera-measured bird activity and radar-derived migration traffic rates. Nevertheless, two sources of residual uncertainty remain. The upward-facing cameras did not provide full coverage of the rotor-swept zone, meaning that visual verification of collision detections was not always possible, as illustrated by the high-confidence collision of March 18 for which upward camera corroboration was unavailable. Additionally, accurate records of human activity around the turbine are essential for excluding anthropogenic or activity-related sources of falling objects (false positives), and more systematic logging of such activity is recommended in future deployments.

---

In general, for camera-based systems to measure collisions offshore, we emphasize the importance of including daylight cameras in the system, as these enable species-level or at minimum species-group-level identification of collision victims during daytime, and allowing seabirds and large migrating landbirds to be distinguished more from passerines, thus also substantially reducing ambiguity in summer detections. Similarly, stereoscopic camera configurations can additionally enable three-dimensional reconstruction of object trajectories and accurate distance estimation, improving the discrimination between falling objects and birds flying away from the camera. An alternative detection principle is offered by the WTBird system (TNO), which detects collision events through vibration sensors in the turbine blades rather than through monitoring of falling objects below the rotor zone. The recent demonstration that the updated WTBird® system achieves detection performance comparable to carcass surveys at an onshore turbine (Western EcoSystems Technology 2025) suggests that multiple technological approaches to direct collision measurement are now converging towards operational readiness, strengthening the case for systematic offshore deployment.

## 4.7 Implications

This pilot study represents a first step towards the direct empirical quantification of bird collision rates at offshore wind turbines — a measurement that has long been practically unachievable. The results demonstrate that the **WIS system is capable of detecting collision events at sea**, including under nocturnal conditions and for small-bodied species, and thereby addresses a fundamental limitation of existing monitoring approaches. Unlike systems where individual birds are tracked upon prior detection and collision events involving undetected individuals are necessarily missed, the continuous turbine-centred monitoring approach employed here is not contingent on prior detection of the bird concerned. The present approach thus extends earlier monitoring efforts at offshore wind turbines, which employed radar-triggered camera systems optimised for quantifying avoidance behaviour (Skov *et al.* 2018, Tjørnløv *et al.* 2023, Skov *et al.* 2025).

The collision rates recorded in this study are, however, based on a **single turbine over a single year**, and must be interpreted with corresponding caution. This study is just a first step towards an empirical basis for collision risks offshore and therewith the required insights to parametrise collision risk models or to draw population-level conclusions. What it does establish is that such measurements are obtainable, and that the WIS system provides a viable platform for generating the empirical collision data that are currently absent from the offshore wind literature and that existing models — including the widely applied Band model — cannot substitute for. Systematic deployment across multiple turbines and multiple years will be required before collision risks can be estimated with sufficient precision to inform consenting procedures or cumulative effect assessments.

A finding of potential relevance to mitigation is the **apparent decoupling between collision occurrence and migration intensity**. Current curtailment strategies at offshore wind turbines are typically triggered by indicators of high migration activity. The observation in this study that collisions predominantly occurred during periods of low migration traffic, and that both confirmed collisions were associated with wind speeds exceeding 9 m/s, provides first indications that adverse meteorological conditions — rather than migration intensity per se — may be a more relevant predictor of collision risk. In measurements of collision rates near shore, Welcker (2019) and Liedtke *et al.* (2025) found similar results. If birds that migrate under unfavourable conditions, such as headwinds, high wind speeds or reduced visibility, are disproportionately at risk of colliding with turbine structures, this would have direct implications for the design of curtailment protocols. Targeted curtailment during adverse weather events, rather than or in addition to periods of peak migration, warrants investigation as a potentially more effective mitigation strategy, depending on future insights on collision rates under these conditions. These findings are preliminary and require replication across multiple turbines and seasons before operational recommendations can be made.

---

A potentially comparable mechanism may also apply to **bats**, although the evidence-base offshore remains extremely limited. Current Dutch offshore curtailment protocols for bats are largely derived from acoustic observations indicating that migratory activity is highest during relatively low wind speeds of approximately 2–3 m/s. However, tracking studies have demonstrated that migrating bats preferentially exploit tailwinds and are capable of migrating under substantially stronger wind conditions than previously assumed (Lagerveld *et al.* 2024), including moderate tailwinds of around 8–9 m/s (Lagerveld *et al.* 2026). This raises the possibility that bats migrating under favourable tailwind conditions may fly at altitudes above the rotor-swept zone, thereby reducing collision risk despite potentially high migration intensity. Conversely, acoustically detected bats at low wind speeds may represent stranded individuals migrating under suboptimal conditions, including weak tailwinds, crosswinds, or headwinds. Whether these animals are potentially at higher risk due to lower flight altitudes remains unresolved. Additional camera-based studies, such as the present study, may help provide the empirical evidence required to clarify these unresolved relationships between weather conditions, flight altitude, and collision risk.

## 4.8 In conclusion

This pilot study demonstrates that continuous camera-based monitoring of the area below the rotor-swept zone of an offshore wind turbine provides a viable means of directly detecting bird collision events, including at night and for small-bodied species such as migrating passerines and bats. The WIS system detected two confirmed collisions and one high-confidence collision, alongside 19 collision detections, across two migration seasons and one summer at a single turbine — constituting, to our knowledge, the first empirical measurements of passerine collisions at an offshore wind turbine. A high level of correlation between flight activity quantified with the WIS system and fluxes obtained locally with bird radar show that detection rate was high, and therewith show that the chance of collisions going undetected (false negatives) was limited. Although the system is in principle equally capable of detecting bat collisions, no collision events could be attributed to bats in this study, consistent with the low and temporally restricted bat activity recorded acoustically at the turbine. Manual interpretation of footage remains necessary at this stage of system development and requires training and explicit labelling criteria to maximise classification certainty. Further development of the WIS processing model, informed by the dataset generated in this pilot, offers a route towards more objective and automated collision detection. The results provide first empirical indications that collision risk at offshore wind turbines may be more closely associated with adverse meteorological conditions than with migration intensity, a finding with potential implications for the design of curtailment strategies that warrants investigation in future, larger-scale deployments. Ultimately, the approach described here opens the prospect of generating the empirical collision data that offshore wind impact assessments have long lacked, and that are needed to parametrise and validate the theoretical models on which these assessments currently depend.

---

# Acknowledgements

We thank Jesper Kyed Larsen of Vattenfall for seeing the potential of the WIS system and facilitating this study, and Bjarke Laubek of Vattenfall for providing critical knowledge and support. Iris Menger and the Vattenfall offshore team at IJmuiden supported installation and management throughout the study. Anton Vigen Smolarz and Bo Præstegaard of Circle Consult prepared installation and installed all equipment on the turbine. Bart Noort of WUR supported with selection and maintenance of acoustic detection systems. We thank RWS for providing bird activity data from their offshore bird radars.

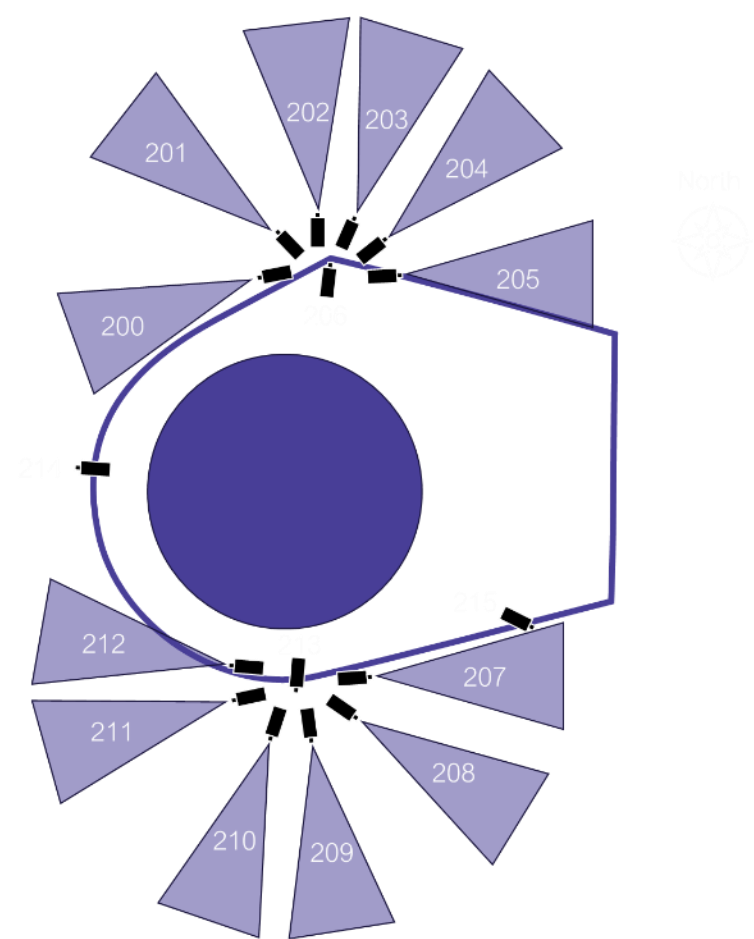
---

# References

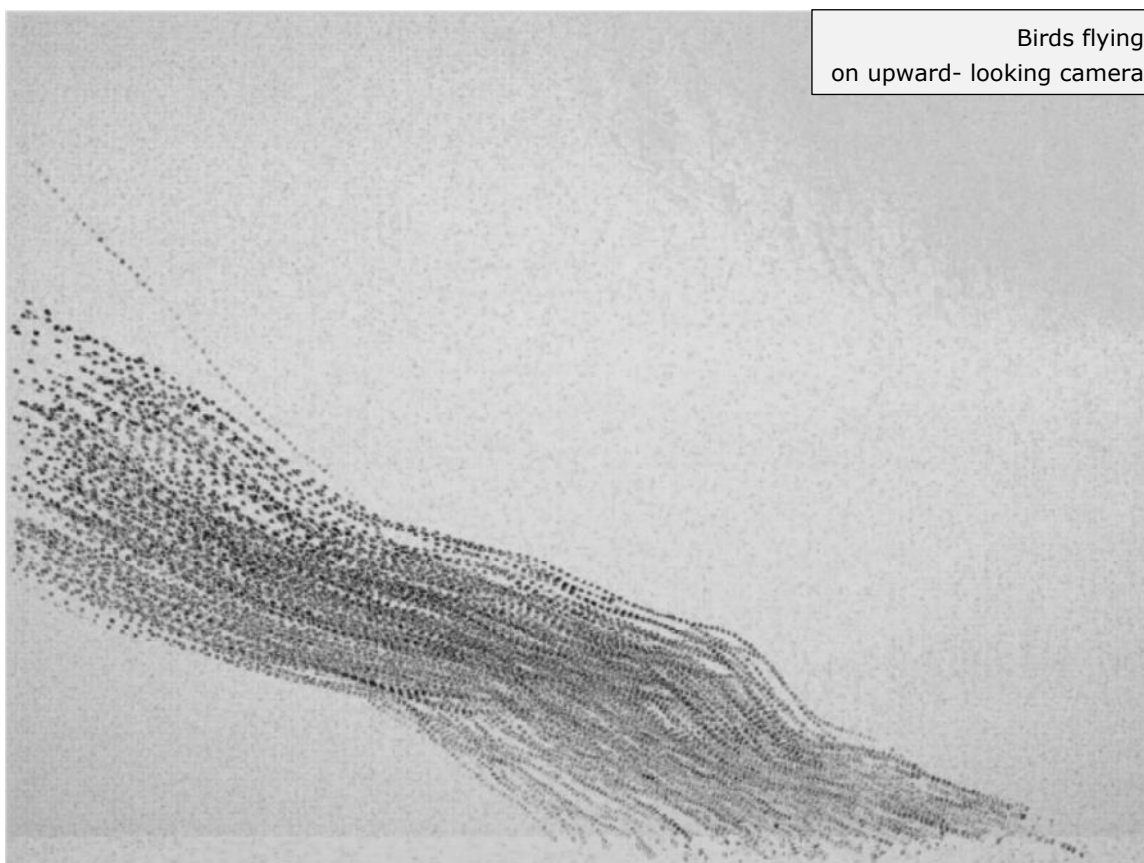
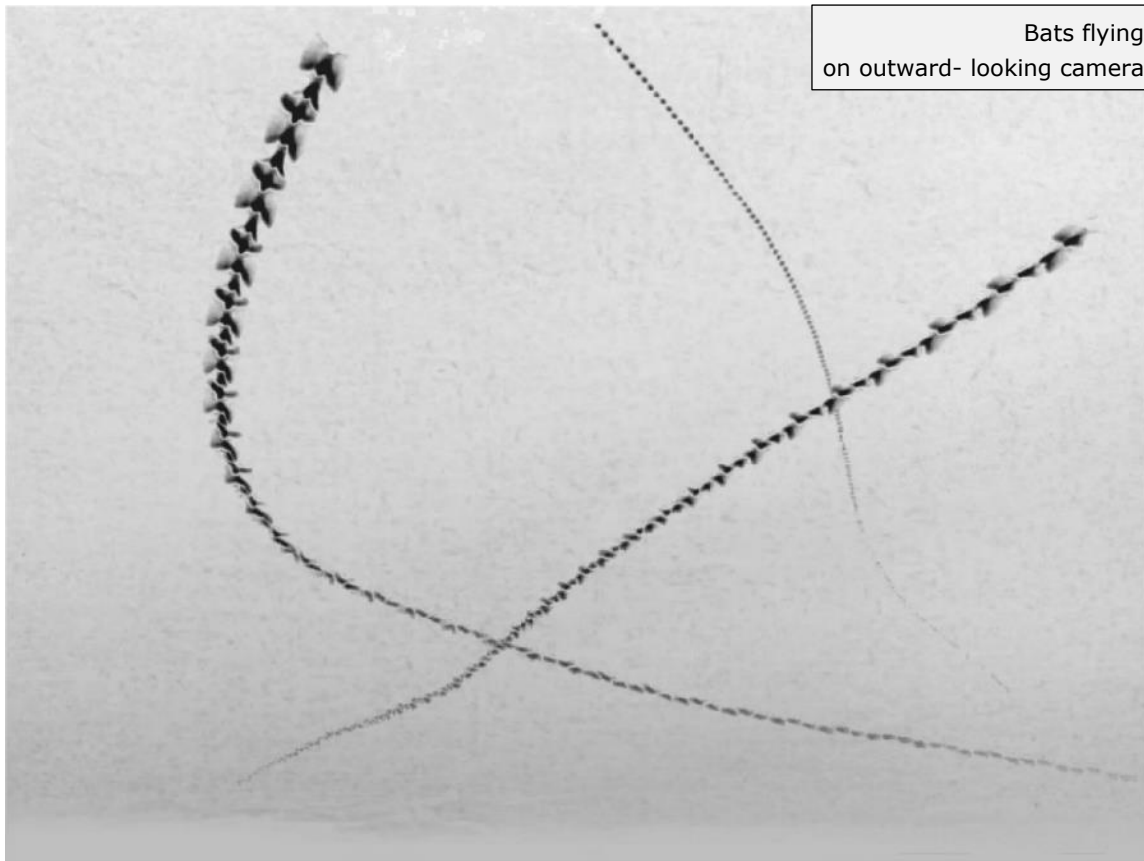
- Axis Communications (2021). White papers. <https://whitepapers.axis.com/en-us/thermal-cameras#environmental-considerations>.
- Band W. (2012). Using a collision risk model to assess bird collision risks for offshore windfarms. The Crown Estate Strategic Ornithological Support Services (SOSS) report SOSS-02. SOSS Website. Original published Sept 2011, extended to deal with flight height distribution data March 2012. [https://www.bto.org/sites/default/files/u28/downloads/Projects/Final\\_Report\\_SOSS02\\_Band1ModelGuidance.pdf](https://www.bto.org/sites/default/files/u28/downloads/Projects/Final_Report_SOSS02_Band1ModelGuidance.pdf).
- Boonman M. & Japink M. 2022. Bat curtailment IJmuiden Ver. Reducing bat mortality in offshore wind farms. Bureau Waardenburg Rapportnr. 22-227 Bureau Waardenburg, Culemborg.
- Bradarić M., Bouten W., Fijn R.C., Krijgsveld K.L. & Shamoun-Baranes J. (2020). Winds at departure shape seasonal patterns of nocturnal bird migration over the North Sea. *Journal of Avian Biology*, 51, <https://doi.org/10.1111/jav.02562>.
- Cook A.S.C.P., Salkanovic E., Masden E., Lee H.E. & Kiilerich A.H. (2025). A critical appraisal of 40 years of avian collision risk modelling: How have we got here and where do we go next? *Environmental Impact Assessment Review*, 110, 107717. <https://doi.org/10.1016/j.eiar.2024.107717>.
- Costanzo G., Brindley G. & Tardieu P. (2025). Wind energy in Europe: 2024 statistics and the outlook for 2025-2030. WindEurope, Brussels, Belgium. <https://windeurope.org/data/products/wind-energy-in-europe-2024-statistics-and-the-outlook-for-2025-2030>.
- Fijn R.C., Krijgsveld K.L., Poot M.J.M. & Dirksen S. (2015). Bird movements at rotor heights measured continuously with vertical radar at a Dutch offshore wind farm. *Ibis*, 157, 558-566. <https://doi.org/10.1111/ibi.12259>.
- Frémaux A. (2026). Offshore wind in Europe: key trends and statistics 2025. WindEurope, Brussels, Belgium. <https://windeurope.org/data/products/offshore-wind-in-europe-key-trends-and-statistics-2025/>
- Frick, W.F. *et al.* (2017). Fatalities at wind turbines may threaten population viability of a migratory bat. *Biological Conservation*, 209, 172-177. <https://doi.org/10.1016/j.biocon.2016.10.026>
- Furness R.W., Wade H.M. & Masden E.A. (2013). Assessing vulnerability of marine bird populations to offshore wind farms. *Journal of Environmental Management*, 119, 56-66. <https://doi.org/10.1016/j.jenvman.2013.01.025>.
- Happ C., Sutor A. & Hochradel K. (2021). Methodology for the automated visual detection of bird and bat collision fatalities at onshore wind turbines. *Journal of Imaging*, 7, 272. <https://doi.org/10.3390/jimaging7120272>.
- Hüppop O., Dierschke J., Exo K.-M., Fredrich E. & Hill R. (2006). Bird migration studies and potential collision risk with offshore wind turbines. *Ibis*, 148, 90-109. <https://doi.org/10.1111/j.1474-919X.2006.00536.x>.
- Hüppop O., Hüppop K., Dierschke J. & Hill R. (2016). Bird collisions at an offshore platform in the North Sea. *Bird Study*, 63, 73-82. <https://doi.org/10.1080/00063657.2015.1134440>.
- Kleyheeg-Hartman J.C., Krijgsveld K.L., Collier M.P., Poot M.J.M., Boon A.R., Troost T.A. & Dirksen S. (2018). Predicting bird collisions with wind turbines: Comparison of the new empirical Flux Collision Model with the SOSS Band model. *Ecological Modelling*, 387, 144-153. <https://doi.org/10.1016/j.ecolmodel.2018.06.025>.
- Krijgsveld K.L., Akershoek K., Schenk F., Dijk F. & Dirksen S. (2009). Collision risk of birds with modern large wind turbines. *Ardea*, 97, 357-366. <https://doi.org/10.5253/078.097.0311>.
- Krijgsveld K.L., Fijn R.C., Japink M., Van Horssen P.W., Heunks C., Collier M.P., Poot M.J.M., Beuker D. & Dirksen S. (2011). Effect studies offshore wind farm Egmond aan Zee. Final report on fluxes, flight altitudes and behaviour of flying birds. Report 10-219, Bureau Waardenburg, Culemborg, Netherlands.
- Lack D. (1959). Migration across the sea. *Ibis*, 101, 374-399. <https://doi.org/10.1111/j.1474-919X.1959.tb02395.x>.
- Lagerveld S., de Vries P., Harris J., Parsons S., Debusschere E., Hüppop O., Brust V., Schmaljohann H., (2024). Migratory movements of bats are shaped by barrier effects, sex-biased timing and the adaptive use of winds. *Mov. Ecol.* 12, 81. <https://doi.org/10.1186/s40462-024-00520-7>

- 
- Lagerveld S., De Vries P., Rakhimberdiev E., Harris J., Noort B.C.A., Geelhoed S.C.V., Van Langevelde, F., Mathews F., Poot M.J.M., Karagicheva J., 2026. Directional variation and method-specific detection patterns in offshore bat migration: implications for wind farm mitigation. <https://doi.org/10.64898/2026.02.06.704313>
- Lagerveld S., Karagicheva J. & Poot M., 2026. Additional analyses of bat migration across the North Sea; Integration of telemetry and passive acoustic monitoring - WOZEP research programme (2019–2023). Wageningen, Wageningen Marine Research, Report C041/26.
- Liedtke J., Bruneaux M., Girndt A. & Welcker J. (2025). The collision risk of migrating birds at wind farms. BioConsult SH, Husum Germany. (BWO project.)
- Marques A.T., Batalha H., Rodrigues S., Costa H., Pereira M.J.R., Fonseca C., Mascarenhas M. & Bernardino J. (2014). Understanding bird collisions at wind farms: An updated review on the causes and possible mitigation strategies. *Biological Conservation*, 179, 40-52. <https://doi.org/10.1016/j.biocon.2014.08.017>.
- Ozsanlav-Harris L., Inger R. & Sherley R. (2023). Review of data used to calculate avoidance rates for collision risk modelling of seabirds. JNCC Report 732, JNCC, Peterborough.
- R Core Team (2025). R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>
- Review Energy. (2026, January 15). Over 100 wind farms, 30 GW strong: North Sea sets the pace for global offshore wind. <https://www.review-energy.com/eolico/over-100-wind-farms-30-gw-strong-north-sea-sets-the-pace-for-global-offshore-wind>.
- Skov H., Heinänen S., Norman T., Ward R., Méndez-Roldán S. & Ellis I. (2018). ORJIP Bird Collision and Avoidance Study. Final Report, April 2018. The Carbon Trust, UK.
- Skov H., Tjørnløv R.S., Armitage M., Barker M., Jørgensen J.B., Mortensen L.O. & Uhrenholdt T. (2025). High-resolution multi-sensor technology reveals low collision risk to seabirds in offshore wind farms. *Journal of Applied Ecology*, n/a, e70239. <https://doi.org/10.1111/1365-2664.70239>.
- Sovacool B.K. (2009). Contextualizing avian mortality: A preliminary appraisal of bird and bat fatalities from wind, fossil-fuel, and nuclear electricity. *Energy Policy*, 37, 2241-2248. <https://doi.org/10.1016/j.enpol.2009.02.011>.
- SPOOR & BTO (2025). Final report. Review of AI avian monitoring with CCTV cameras on floating wind turbines. SPOOR, BTO, UK. <https://cdn.equinor.com/files/h61q9qi9/global/c4a3e3487044b0280804db9fc9cb4e1d890f374f.pdf?spoor-review-ai-avian-monitoring-cctv-cameras-floating-wind-turbines-equinor.pdf>.
- Voigt C.C., Kaiser K., Look S., Scharnweber K. & Scholz C. (2022). Wind turbines without curtailment produce large numbers of bat fatalities throughout their lifetime: a call against ignorance and neglect. *Global Ecology and Conservation*, 38, e02149. <https://doi.org/10.1016/j.gecco.2022.e02149>
- Weaver S.P., Ritter J.D., Commiskey A.M., Garcia J.D. & Morton B.P. (2025). Testing a bat fatality detection system at wind turbines. *PLOS ONE*, 20, e0334609. <https://doi.org/10.1371/journal.pone.0334609>.
- Welcker J., Liesenjohann M., Blew J., Nehls G. & Grünkorn T. (2016). Nocturnal migrants do not incur higher collision risk at wind turbines than diurnally active species. *Ibis*, 159, 366-373. <https://doi.org/10.1111/ibi.12456>.
- Welcker J. (2019). Patterns of nocturnal bird migration in the German North and Baltic Seas. Technical report, BioConsult SH, Husum, Germany. [https://www.bioconsult-sh.de/fileadmin/user\\_upload/Publikationen/2019/patterns\\_of\\_bird\\_migration\\_in\\_the\\_german\\_north\\_and\\_baltic\\_seas\\_20190923\\_ohne\\_anhangstabellen.pdf](https://www.bioconsult-sh.de/fileadmin/user_upload/Publikationen/2019/patterns_of_bird_migration_in_the_german_north_and_baltic_seas_20190923_ohne_anhangstabellen.pdf).
- Western EcoSystems Technology (2025). A multi-sensor approach for measuring bird and bat collisions with offshore wind turbines (final technical report). Western EcoSystems Technology Inc. (WEST), Netherlands Organisation for Applied Scientific Research (TNO), National Renewable Energy Laboratory (NREL) & National Wind Technology Center at University of Minnesota, Cheyenne United States. Doi: 10.2172/3011525.
- Wiggelinkhuizen E.J., Rademakers L.W.M.M., Barhorst S.A.M. & Den Boon H.J. (2006). WT-Bird: bird collision monitoring system for multi-megawatt wind turbines. Report ECN-E-06-027. Energy Research Centre of the Netherlands.

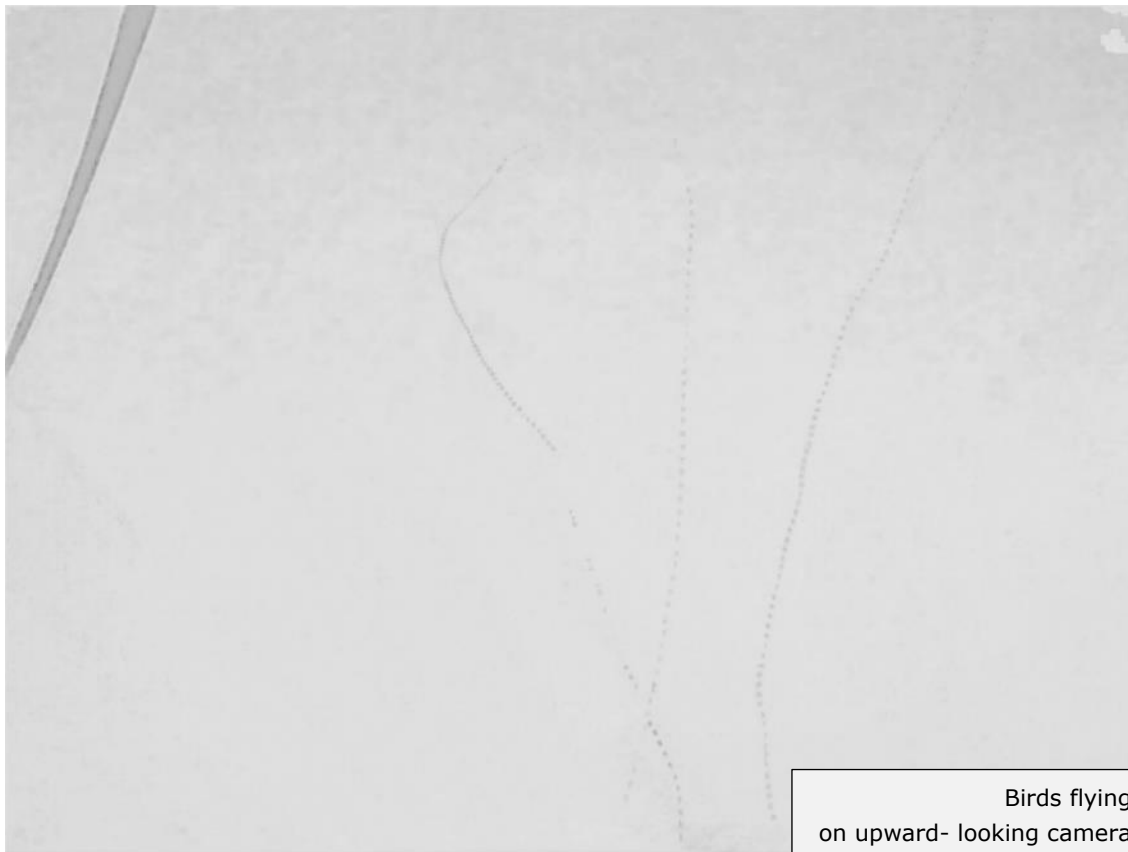
# Appendices



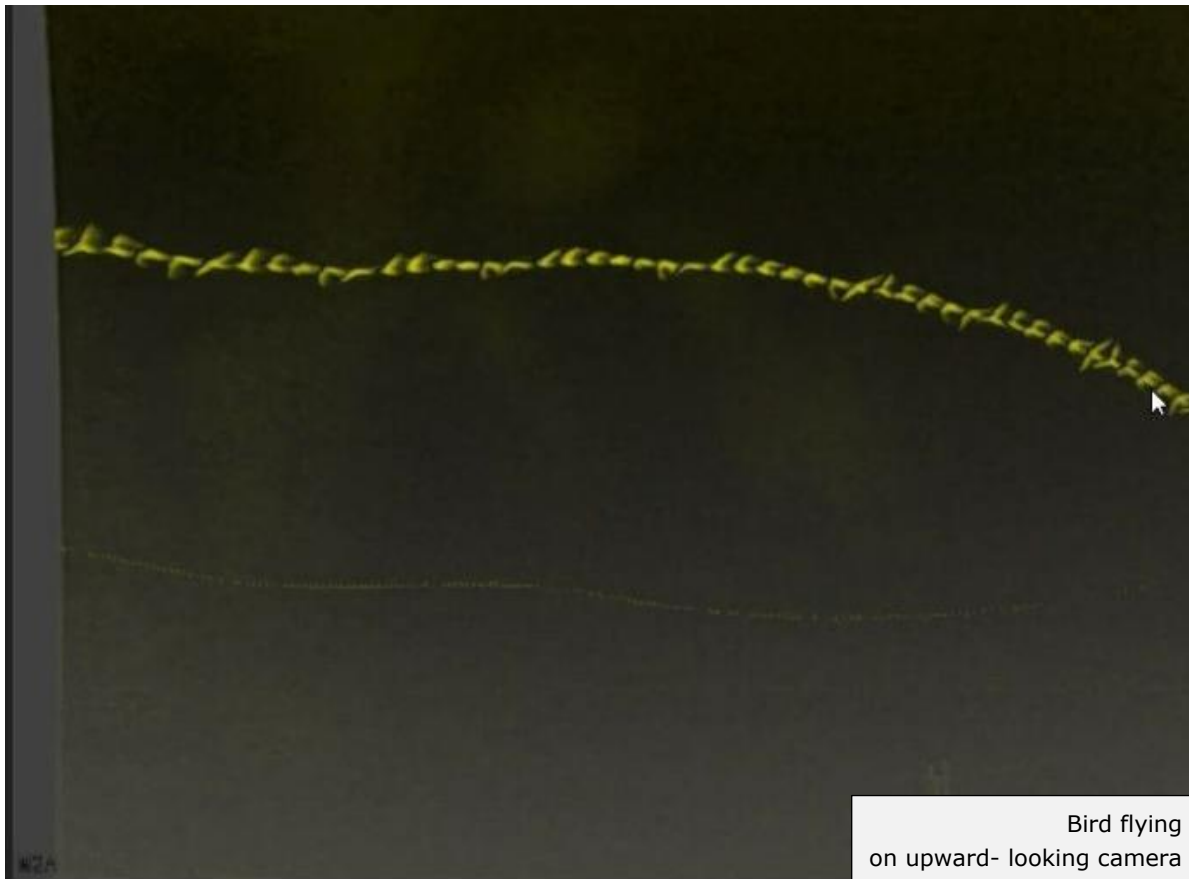
**Figure A1** Schematic view of camera setup on the turbine. Only outward-looking cameras are numbered. Fields of view are not to scale.



**Figure A2** Collage of summary images reflecting typical tracks of insect, flying animal, bird and bat. Colours are inverted from the original image for visual clarity (continued below).



**Figure A2 continued** Collage of summary images reflecting typical tracks of insect, flying animal, bird and bat. Colours are inverted from the original image for visual clarity (continued below).



**Figure A2 continued** Collage of summary images reflecting typical tracks of insect, flying animal, bird and bat. Original image, colours not inverted.

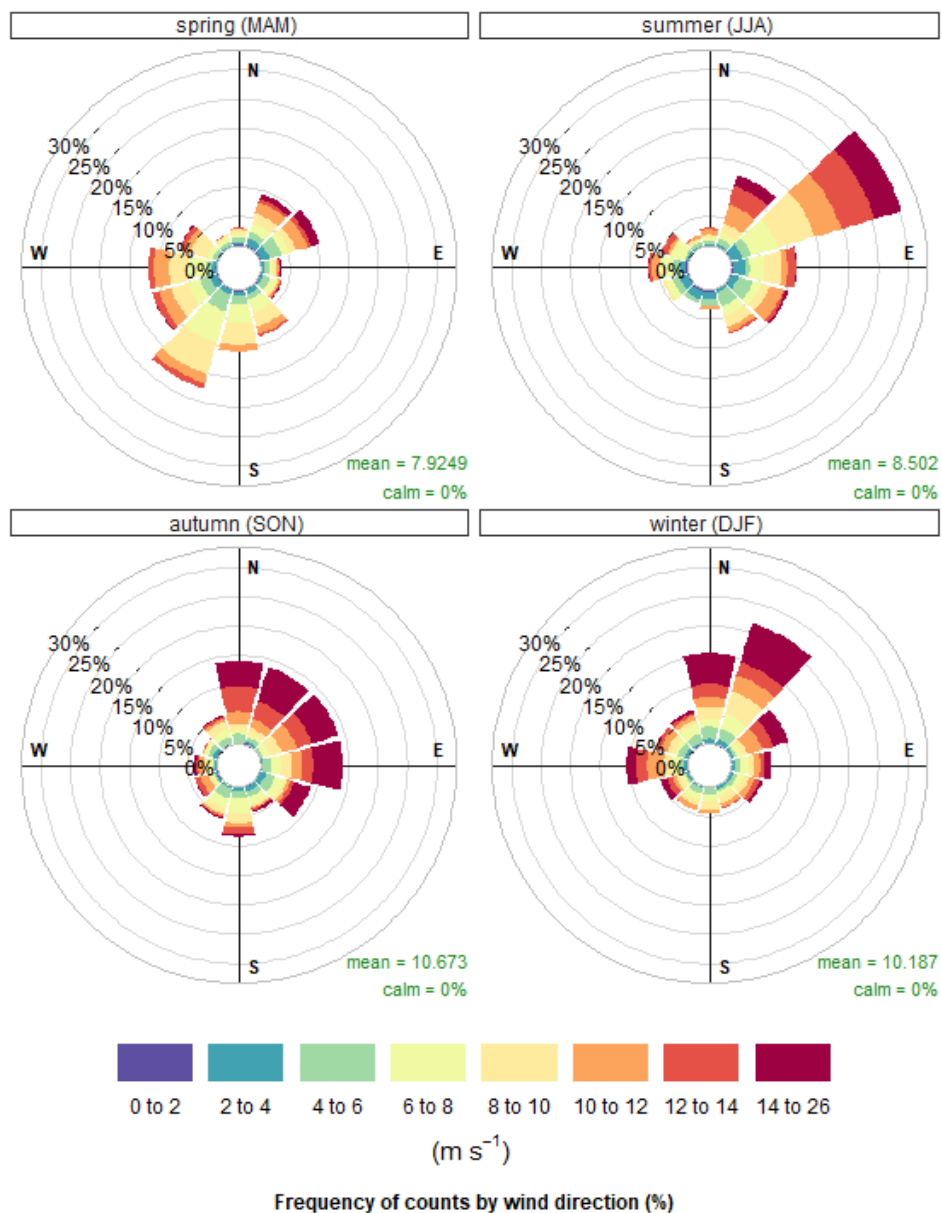
**Table A1** Labelling rules used during the manual evaluation of the tracks. Each label has its own set of rules and rules are weighted from + to +++. To assign a label to a track, the track needs to align with multiple rules. Note that all labels should be considered when evaluating a track, because some rules may apply to several labels (e.g. active flight applies to both animal flying and insect) while others may exclude one of the other labels (e.g. visible wing beats).

| LABEL               | NUMBER | WEIGHT | GROUP                  | DESCRIPTION                                                                                                                                                                                                                |
|---------------------|--------|--------|------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| COLLISION DETECTION | F1     | +++    | Vertical corroboration | <b>activity or direct hit</b> on footage of <b>upward looking cameras</b> within same time window (this counts as a high probability/confirmed collision)                                                                  |
|                     | F2     | ++     | Secondary tracks       | <b>several tracks</b> visible with similar trajectories within the same time window (indicating several pieces). This only applies when rotor is spinning, since sufficient velocity is needed to break apart the carcass. |
|                     | F3     | ++     | Rotation               | object <b>rotating in fall at a constant rhythm</b> , showing as a track that is fading in and out (flickering) and/or with a wave shape to it.                                                                            |
|                     | F4     | ++     | No active flight       | <b>no changes in speed</b> , and object is not moving faster than expected for its size and shape (terminal velocity)                                                                                                      |
|                     | F6     | +      | No active flight       | track is relatively <b>straight</b> ; no sharp/active changes in directions along the track. Note, when rotor is rotating fast the object could be changing direction due to the draft of the blades                       |
|                     | F7     | +      | Appearance             | object is relatively <b>bright</b> (for the size); e.g. small and blurry object with detections close together -> indicating object is further away from the camera but still large enough to be detected                  |

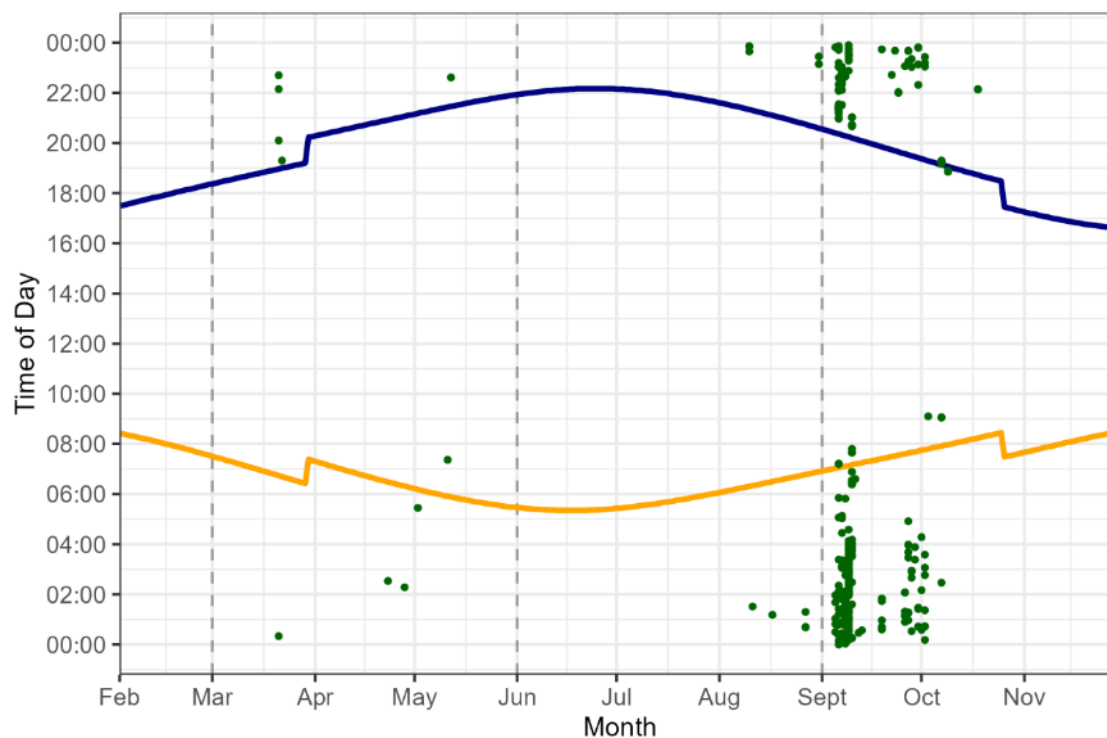
| LABEL         | NUMBER | WEIGHT | GROUP            | DESCRIPTION                                                                                                                                                                      |
|---------------|--------|--------|------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| ANIMAL FLYING | A1     | ++     | Active flight    | track shows a <b>change in direction</b> ; sharp/active direction changes                                                                                                        |
|               | A2     | ++     | Active flight    | <b>distance</b> between detections <b>decreases</b> along the track, possibly also fading at end of track (indicating an object travelling away from the camera or slowing down) |
|               | A3     | ++     | Active flight    | <b>wing beats</b> are visible in the track                                                                                                                                       |
|               | A5     | ++     | Active flight    | <b>distance</b> between detections <b>varies</b> along the track (indicating variation in flight speed or direction)                                                             |
|               | A4     | +      | Appearance       | <b>small detections close together</b> (indicating an object is a fair distance away from the camera)                                                                            |
|               | A6     | +      | Appearance       | Detections are relatively <b>clear in shape and definition</b> (i.e. not blurry)                                                                                                 |
|               | A7     | +      | Appearance       | track is relatively <b>bright</b>                                                                                                                                                |
|               | A8     | /      | Secondary tracks | a <b>single track</b> (no secondary tracks in same direction that occur simultaneously in time)                                                                                  |
| INSECT        | I1     | ++     | Active flight    | <b>erratic</b> movements                                                                                                                                                         |
|               | I2     | ++     | Appearance       | undistinguishable/ <b>blurry</b> object (no clear shape)                                                                                                                         |
|               | I3     | ++     | Active flight    | <b>large distance</b> between detections (indicating that the object is moving very fast and close to the camera)                                                                |
|               | I4     | ++     | Active flight    | <b>direction changes</b> ; away from falling (up or sideways) and/or sharp/active changes in direction                                                                           |
|               | I5     | ++     | Active flight    | <b>distance</b> between detections <b>varies</b> along the track (indicating variation in flight speed or direction)                                                             |
|               | I6     | ++     | Active flight    | <b>distance</b> between detections <b>decreases</b> along the track, possibly also fading at end of track (indicating an object travelling away from the camera)                 |
|               | I7     | +      |                  | <b>moving faster</b> than expected for the size or if it would be falling                                                                                                        |
|               | I8     | +      | Appearance       | <b>fading</b> in lower section screen                                                                                                                                            |
|               | I9     | /      | Secondary tracks | a <b>single track</b> (no secondary tracks in same direction that occur simultaneously in time)                                                                                  |
| UNSURE        | U      | N.A.   | N.A.             | track cannot be confidently assigned to one of the categories (e.g. non of the major rules apply, or too much overlap between categories)                                        |
| OTHER         | O      | N.A.   | N.A.             | track is clearly of a non-living object (e.g. falling water, hoisting up of maintenance materials)                                                                               |

**Table A2** Overview of all collisions identified in the study and additional information: season, day/night, windspeed (m/s), wind direction (in degrees), WIS bird activity (birdseconds/h), flight intensities from the bird radar at Hollandse Kust Zuid (MTR; bird tracks/km/h) and rotor RPM (mean per 10min). \*MTR measured at Luchterduinen. Time is local time.

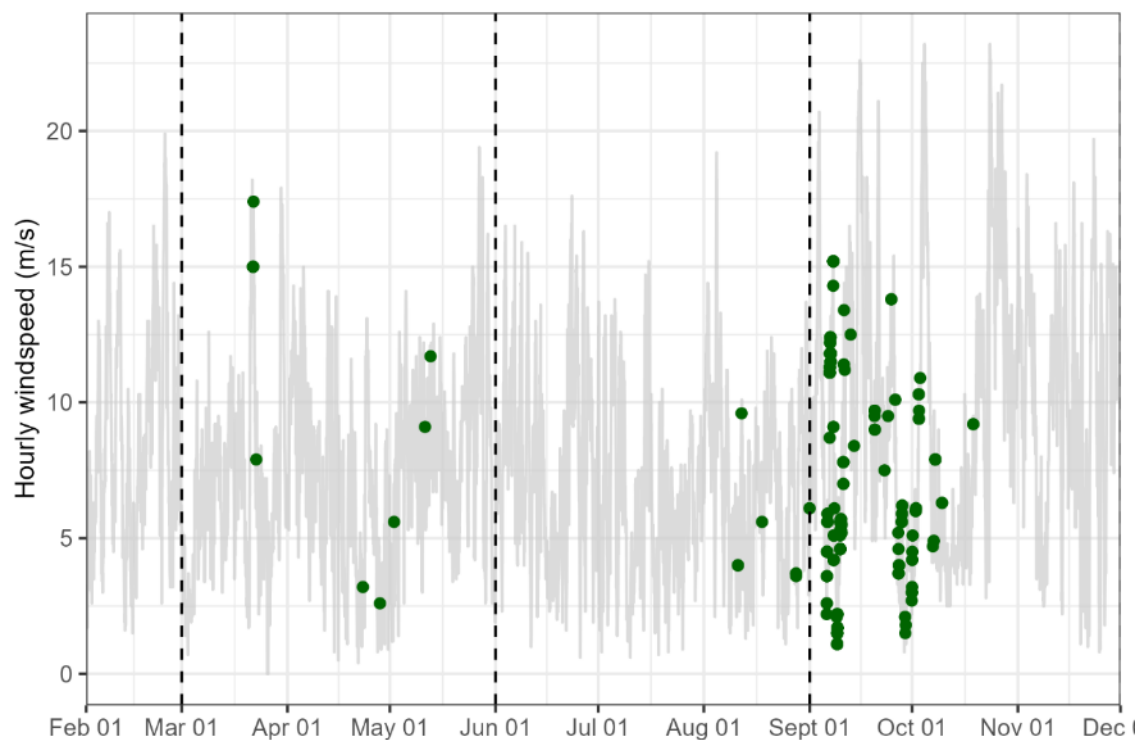
| id | Date and time    | Collision type            | Season | Day/<br>night | Wind-<br>speed | Wind<br>direction | WIS Bird<br>Activity | Flight<br>intensities | RPM |
|----|------------------|---------------------------|--------|---------------|----------------|-------------------|----------------------|-----------------------|-----|
| 1  | 18/03/2025 23:05 | high-confidence collision | Spring | n             | 10             | 115               | 326                  | 17*                   | 8,6 |
| 2  | 14/04/2025 21:35 | mid-confidence collision  | Spring | n             | 9              | 80                | 0                    | 16                    | 8,3 |
| 3  | 15/04/2025 00:03 | confirmed collision       | Spring | n             | 13             | 104               | 20                   | 9                     | 9,0 |
| 4  | 11/05/2025 01:31 | mid-confidence collision  | Spring | n             | 10             | 92                | 135                  |                       | 8,6 |
| 5  | 22/05/2025 19:41 | mid-confidence collision  | Spring | d             | 10             | 319               | 23                   |                       | 8,4 |
| 6  | 02/06/2025 23:08 | mid-confidence collision  | Summer | n             | 4              | 187               | 19                   | 28                    | 4,6 |
| 7  | 16/06/2025 02:31 | mid-confidence collision  | Summer | n             | 4              | 278               | 15                   | 3                     | 4,6 |
| 8  | 16/06/2025 03:27 | mid-confidence collision  | Summer | n             | 5              | 289               | 0                    | 3                     | 4,6 |
| 9  | 21/06/2025 11:20 | mid-confidence collision  | Summer | d             | 4              | 136               | 134                  | 48                    | 5,9 |
| 10 | 21/06/2025 15:21 | mid-confidence collision  | Summer | d             | 3              | 157               | 123                  | 42                    | 5,0 |
| 11 | 21/06/2025 23:14 | mid-confidence collision  | Summer | n             | 7              | 125               | 13                   | 39                    | 5,2 |
| 12 | 01/07/2025 01:37 | mid-confidence collision  | Summer | n             | 12             | 142               | 150                  | 45                    | 0,3 |
| 13 | 02/07/2025 00:14 | mid-confidence collision  | Summer | n             | 3              | 307               | 119                  | 33                    | 4,6 |
| 14 | 10/07/2025 10:30 | mid-confidence collision  | Summer | d             | 1              | 156               | 37                   | 32                    | 0,0 |
| 15 | 10/07/2025 11:33 | mid-confidence collision  | Summer | d             | 1              | 154               | 0                    | 24                    | 0,0 |
| 16 | 10/07/2025 12:50 | mid-confidence collision  | Summer | d             | 1              | 38                | 41                   | 13                    | 0,0 |
| 17 | 02/08/2025 19:23 | mid-confidence collision  | Summer | d             | 10             | 327               | 2                    |                       | 7,3 |
| 18 | 09/08/2025 01:02 | mid-confidence collision  | Summer | n             | 2              | 188               | 24                   |                       | 2,8 |
| 19 | 24/09/2025 00:26 | mid-confidence collision  | Fall   | n             | 9              | 71                | 133                  |                       | 8,6 |
| 20 | 01/10/2025 07:51 | mid-confidence collision  | Fall   | d             | 4              | 125               | 8                    | 26/310*               | 7,1 |
| 21 | 31/10/2025 22:23 | mid-confidence collision  | Fall   | n             | 14             | 189               | 219                  |                       | 9,1 |
| 22 | 22/11/2025 20:52 | confirmed collision       | Fall   | n             | 15             | 196               | 32                   |                       | 9,0 |



**Figure A3** General wind speed and direction during the study, plotted per season.



**Figure A4** Measured *Pipistrellus nathusii* activity through the season. Activity (minutes with echolocation recordings; green points) plotted over the months and time of day, with local sunrise (yellow line) and sunset (blue line) indicated. Vertical dashed lines indicate spring (Mar-May), summer (Jun-Aug) and autumn seasons (Sep-Nov).



**Figure A5** Wind speed in m/s during the minutes with *Pipistrellus nathusii* activity (points) and hourly wind speed (grey line). Vertical dashed lines indicate spring (Mar-May), summer (Jun-Aug) and autumn seasons (Sep-Nov).



To explore  
the potential  
of nature to  
improve the  
quality of life



Wageningen Environmental Research  
P.O. Box 47  
6700 AB Wageningen  
The Netherlands  
T +31 (0) 317 48 07 00  
[wur.eu/environmental-research](http://wur.eu/environmental-research)

Report 3541  
ISSN 1566-7197



The mission of Wageningen University & Research (WUR) is 'To explore the potential of nature to improve the quality of life'. WUR brings together education, fundamental and applied research, and innovation at the intersection of nature, people, and food.

WUR works on solutions to global challenges related to biodiversity, climate, sustainable food systems, and health. Its strength lies in an integrated approach: connecting disciplines, combining scientific depth with practical relevance, and bringing together science, policy, business, and society. Through the collaboration between Wageningen University and Wageningen Research, WUR contributes to knowledge, innovation and impact, and to responsible change towards a world in balance with nature.