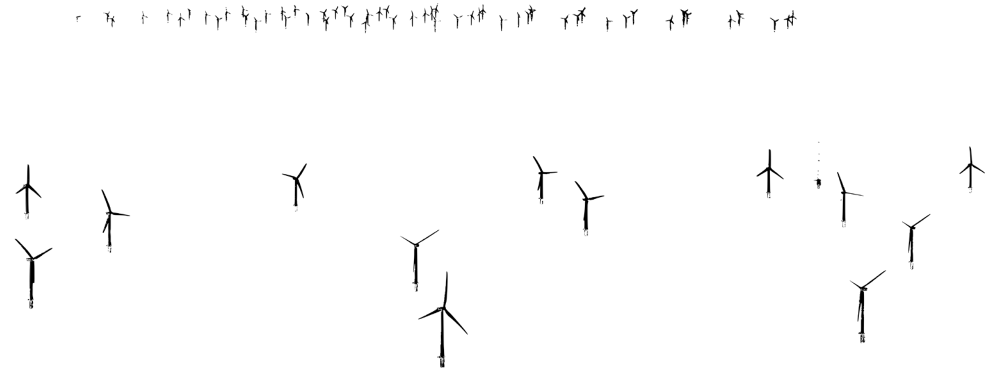
Assessing fatality risk of bats at offshore wind turbines



Author(s): S. Lagerveld[1], C.A. Noort[1], L. Meesters[2], L. Bach[3], P. Bach[3], S.C.V. Geelhoed[1]

[1] Wageningen Marine Research

[2] Wageningen Food & Biobased Research

[3] Bach Freilandforschung

Wageningen Marine Research
Den Helder, March 2020

CONFIDENTIAL no

Wageningen Marine Research report C025/20

Keywords: migratory bats, birds, offshore wind farms, fatalities, barotrauma, collision

DUTCH GOVERNMENTAL OFFSHORE
WIND ECOLOGICAL PROGRAMME

Client: RWS Water, verkeer en Leefomgeving (WVL)
Attn.: Dhr. M. Platteeuw
Postbus 17
8200 AA, Lelystad

Wageningen Marine Research is ISO 9001:2015 certified.

Photo cover: Hans Verdaat

Wageningen Marine Research, an institute within the legal entity Stichting Wageningen Research (a foundation under Dutch private law) represented by Dr. M.C.Th. Scholten, Managing Director

KvK nr. 09098104,
WMR BTW nr. NL 8113.83.696.B16.
Code BIC/SWIFT address: RABONL2U
IBAN code: NL 73 RABO 0373599285

A 4 3 2 V30 (2020)

Contents

Summary

Recent research shows that bats regularly occur offshore, in particular during the migration season. At the same, time land-based studies show that bats frequently become victim of wind turbines, and it is plausible that fatalities occur at sea as well. Given the fast development of the offshore wind sector it is urgently needed to determine the offshore fatality rate in order to assess the impact of offshore wind turbines on bat populations.

On land the methodology for assessing the fatality rate is rather straightforward. This includes regular carcass searching under the wind turbines and adjusting the number of fatalities for causes of imperfect detection. Offshore, however, carcass searching is virtually impossible and therefore a model-based or technical solution may be a more appropriate approach, which may be also applicable for assessing bird fatalities.

This report aims to provide guidance on how offshore fatalities could be monitored in the future. The first option is a model-based approach which assesses the offshore fatality rate by extrapolating onshore fatality rates based on the measured post-construction acoustic bat activity. The main advantages and disadvantages of this solution are:

Advantages
- Relatively easy to implement

Disadvantages
- Possibly biased results:
  - When wind turbines with different dimensions are used for the reference data
  - When reference data is gathered at locations with different species compositions, season and environmental conditions.
- Not applicable for birds

A second option is a more empirical approach, in which fatalities are being monitored using measurement equipment that is able to detect the actual event, as well as the species involved. The application to monitor bat (and bird) fatalities should ideally consist of:
1. A radar, which detects approaching flying objects and identifies the potential relevant ones (bats and birds).
2. Thermal cameras, in order to obtain footage to assess collisions/barotrauma, as well as for the identification of bird species. Furthermore, thermal cameras may be used to record a falling corpse from the Rotor Swept Area (RSA).
3. An ultrasonic detector (bat detector) to record bat echolocation and social calls and subsequently for the identification of individual bat species.
4. A bird sound recorder to record flight calls and subsequently for the identification of bird species.

LIDAR (no clear advantages over radar and less well developed), daylight cameras (not useful at night), near-infrared cameras (possibly change behaviour due to insect attraction because of the needed artificial lighting) and impact sensors (not able to assess barotrauma and most likely not able to assess collisions of bats and small birds as well) should not be part of the technical solution.

After evaluating potentially suitable monitoring techniques as well as the available systems on the market or in development, there seem to be three potential technical applications/solutions that should be able to monitor bat and bird fatalities offshore: MUSE (Multi Sensor), B-finder and TSVA (Thermal Stereo Vision Application). However, none of them is able to perform this task straight away. They all require adjustments and development time. The main advantages and disadvantages per system are:

MUSE

Advantages

- Able to identify potential relevant objects (bats and birds) by radar
- Extensive thermal camera detection range possible (zoom)
- Camera footage aiding species identification
- Few thermal cameras needed per wind turbine
- Operational system and tested offshore
- Applicable for birds as well

Disadvantages

- Underestimation of the fatality rate, due to radar and camera shadow behind the tower, multiple individuals cannot be tracked at the same time and doubtful whether individuals (in particular bats) can be followed during prolonged periods in the Rotor Swept Area (RSA)
- System needs to be modified: the daylight camera needs to be replaced by at least two thermal cameras, and a bat detector and bird sound recorder need to be added and integrated into the system.

B-finder

Advantages

- Specifically aimed to assess fatalities
- The system is able to predict the location of the fallen carcass and this information can be used to assess detection functions to compensate for the number of fatalities missed.
- Applicable for birds as well

Disadvantages

- Currently not suitable for species identification
- Early stage of development
- Not operational and tested offshore
- System needs to be modified, thermal cameras, bat detector and bird sound recorder need to be added and integrated into the system

TSVA

Advantages

- Specifically aimed to assess fatalities
- Camera footage facilitating species identification
- Includes bat detector
- Applicable for birds as well

Disadvantages

- Very early stage of development, not operational and tested offshore
- System needs to be modified, bird sound recorder needs to be added and integrated into the system

1 Introduction

1.1 Background

Research on the occurrence of bats in the North Sea area has shown that bats regularly occur offshore, in particular during the migration season from late March until June and from late August until late October. The most frequently encountered species at sea is Nathusius' pipistrelle *Pipistrellus nathusii*, but there are also records of Common pipistrelle *Pipistrellus pipistrellus*, Common noctule *Nyctalus noctula*, Leisler's bat *Nyctalus leislreri*, Particoloured bat *Vespertilio murinus,* Northern bat *Eptesicus nilssonii* and Serotine bat *Eptesicus serotinus* (Bach et al. 2017, Boshamer & Bekker 2008, Hüppop & Hill 2016, Jonge Poerink et al. 2013, Lagerveld et al. 2014, 2015, 2017B, 2019, Leopold et al. 2014).

As the number of offshore wind farms will increase significantly in the coming years (S.E.R. agreement 2013), and given the fact that bats frequently become victim of wind turbines, due to collision or barotrauma (e.g. Baerwald et al. 2008, Bach & Rahmel 2004, Cryan et al. 2014), further research is needed to assess the impact of offshore wind turbines on bat populations. Offshore bat research was therefore included from 2016 onwards in the Dutch Offshore Wind Ecological Programme (WOZEP), commissioned by Rijkswaterstaat.

When assessing the overall effect of offshore wind farms on bats, several questions are important to answer:
1) Which part of the bat population(s), passing through the Netherlands, migrates over sea?
2) Where and when do (migratory) bats occur at sea?
3) Are bats attracted to offshore wind farms, and if so, from which distance?
4) What is the behaviour of bats in the immediate vicinity of a wind turbine?

The overall effect of offshore wind farms on migratory bats will be largest when (1) a large proportion of the migrating bats occurs at sea, (2) migratory bats occur frequently at sea over large areas, (3) they are strongly attracted to wind turbines, and (4) they spend much time in the vicinity of a wind turbine, thereby running a high fatality risk.

A technical feasibility study was conducted in 2016 at the Energy research center Wind Turbine Test site Wieringermeer (EWTW) as a first step to study the behaviour of bats near wind turbines (4), using a stereoscopic setup consisting of two thermal cameras in combination with a 12 channel batdetector (Lagerveld et al 2017A). During this study tailor-made 3D analysis tools were developed to synchronize the thermal cameras, calibrate the stereoscopic setup, determine 2D tracks in the left and the right view and eventually reconstruct the x, y, z coordinates of bat positions in time. The used stereo configuration and analysis methods proved to be promising, but needed further improvement in order to automatically derive reliable 3D paths. In addition, multiple stereo cameras (8-16) would be needed in order to cover the entire rotor swept area. The expected development and hardware costs would be very high and therefore Rijkswaterstaat doubted whether it was feasible to proceed with the development of the stereoscopic setup. Furthermore, Rijkswaterstaat decided that the aim of further research would be assessing the actual fatality risk, and not the previous goal, assessing flight behaviour of bats around wind turbines (potentially leading to a collision or barotrauma). Therefore, it is not required any more to determine accurate flight paths of bats and their interaction and distance to the rotor blades of wind turbines.

1.2 Problem definition

One of the main issues regarding the effect of offshore wind development on bats is how to determine -or at least estimate- the actual numbers of bat fatalities. Onshore the methodology for assessing the number of fatalities is rather straightforward with regular carcass searching under the wind turbines and adjusting the number of fatalities for imperfect detection of carcasses. Offshore, however, carcass searching is virtually impossible and therefore a model-based or technical solution may be a more appropriate approach, which may be also applicable for assessing the number of bird fatalities.

1.3 Aim of this study

This report aims at providing guidance on how offshore fatalities could be monitored in offshore wind farms future. The specific objectives of this study are:

1. A semi-quantitative suitability analysis of the available tools/technologies to monitor fatalities at offshore wind turbines.
2. A description of the tools/technologies that could be included in the technical solution to monitor fatalities at offshore wind turbines.
3. An exploration of an alternative model-based approach to assess fatalities offshore by extrapolating onshore fatality rates.

The emphasis of the study is on bats, but results can grosso modo be applied for birds as well.

Eventually this should lead to a better understanding of the potential risk of operational offshore wind farms for migratory bat (and possibly bird) populations. The results of the monitoring may also be used to design and apply effective mitigation measures.

1.4 Project team

The project team conducting this study consists of employees of Wageningen Marine Research (Steve Geelhoed, Sander Lagerveld, Bart Noort), Wageningen Food & Biobased Research (Lydia Meesters) and Bach Freilandforschung (Lothar Bach, Petra Bach).

1.5 Reading guide

This report consists of 7 chapters. Chapter 1 provides the problem definition and the aim of the study. Chapter 2 gives a literature review on bat fatality risks at offshore wind turbines. Chapter 3 describes a model based approach on estimating offshore fatalities. Chapter 4 gives an overview of the currently available techniques which may be used to assess fatalities, while chapter 5 describes the evaluated systems and states their performance. Chapter 6 describes the functional requirements as well as the potential system which may meet these requirements. Conclusions and recommendations are given in chapter 7.

2 Bats and wind turbines

Numerous studies on land show that bats are frequently killed by the rotor blades of wind turbines due to collisions or as a result of a barotrauma (Kunz et al. 2007, Baerwald et al. 2008, Grondsky et al 2011, Bach & Rahmel 2004, Brinkmann et al. 2011, Cryan et al. 2014, Dürr 2013, Jones et al. 2009, Lehnert et al. 2014, Rydell et al. 2010a & 2010b). Unlike birds, collisions with static structures like light houses and masts rarely occur (van Gelder 1956, Crawford & Baker 1981).

Not all bat species are affected by wind turbine induced mortality as in general only the open-air foraging species (belonging to the genera *Eptesicus*, *Nyctalus*, *Pipistrellus* and *Vespertilio*) venture into the rotor zone. In Europe most fatalities have been observed amongst the migratory species Nathusius' pipistrelle, Soprano pipistrelle, Common noctule, Leisler's bat and Particoloured bat, but the non-migratory Common pipistrelle is also frequently reported as victim (Rodrigues et al. 2014).

The majority of the fatalities in the northern hemisphere occurs in August and September (Bach & Rahmel 2004, Dürr & Bach 2013, Johnson 2005), coinciding with the timing of the autumn migration of Nathusius' pipistrelle, Soprano pipistrelle, Common noctule, Leisler's bat and Particoloured bat (Dietz et al. 2011). Relatively low numbers of migratory bats become victim during the spring migration period. Some resident species like Common pipistrelle are also affected by wind-turbine induced mortality. Consequently, bat migration cannot be the only single cause why bats become victim of wind turbines (Rydell et al. 2012, Hein & Schirmacher 2016). Several other potential causes like curiosity, misperception, foraging, roosting, flocking and mating opportunities have been hypothesized over the last years (Kunz et al. 2007, Cryan & Barclay 2009), but currently it is assumed that foraging near wind turbines is probably be the most important factor determining the fatality risk (Rydell et al. 2012, 2016).

Foraging opportunities depend on the weather conditions and on the seasonal availability of insects. Most bat activity occurs during nights with temperatures > 12°C and wind speeds below 6 m/s (Arnett et al. 2008, Arnett & Baerwald 2013, Ahlén et al. 2009, Cryan et al. 2014), although Nathusius' pipistrelle seems to be more wind tolerant and is active in higher wind speeds (Bach & Bach 2009, Bach et al. in press A, Limpens et al. 2013). The weather conditions mentioned are known to trigger insect migration in August – September (Chapman et al. 2004, Drake & Reynolds 2012) and therefore bat mortality is suggested to be linked with nocturnal migrating insects (Rydell et al 2010a).

The annual fatality rate in Europe and North America on land is on average 2.9 bats per year per wind turbine, but the variation (0-70 bats) is large (Rydell et al. 2012). A review of the reported mortality at 37 wind farms across north-western Europe (Rydell et al. 2010b) revealed that the local topography and habitat are important factors that determine mortality. It was estimated that the annual number of fatalities per wind turbine is 0-3 in flat open farmland inland, 2-5 in more diverse agricultural landscapes, and 5–20 at the coast and on forested hills and ridges. Considerable regional variation in fatality rates have also been reported from North America (Arnett et al. 2008, Baerwald & Barclay 2009).

Furthermore, mortality depends on the dimensions and the location of the wind turbine within the wind farm (Baerwald & Barclay 2009). The mortality increases with both the tower height and the rotor diameter, but there is no significant relationship between mortality per wind turbine and the number of wind turbines per wind farm and the distance between the rotor and the ground (Rydell et al. 2010b, Mathews et al 2016, Thaxter et al. 2017, Bach et al. in press B).

Bats do not occur exclusively on land. In the Netherlands summer records at sea are occasional but during the migration season bats regularly occur offshore (Figure 2.1). The most common species at the North Sea is Nathusius' pipistrelle, but there are also offshore records of Common pipistrelle, Common noctule, Leisler's bat, Particoloured bat and Serotine bat (Boshamer & Bekker 2008, Lagerveld et al. 2014, 2015 & 2017B, Hüppop & Hill 2016, Bach et al. 2017, Hüppop et al. 2019).

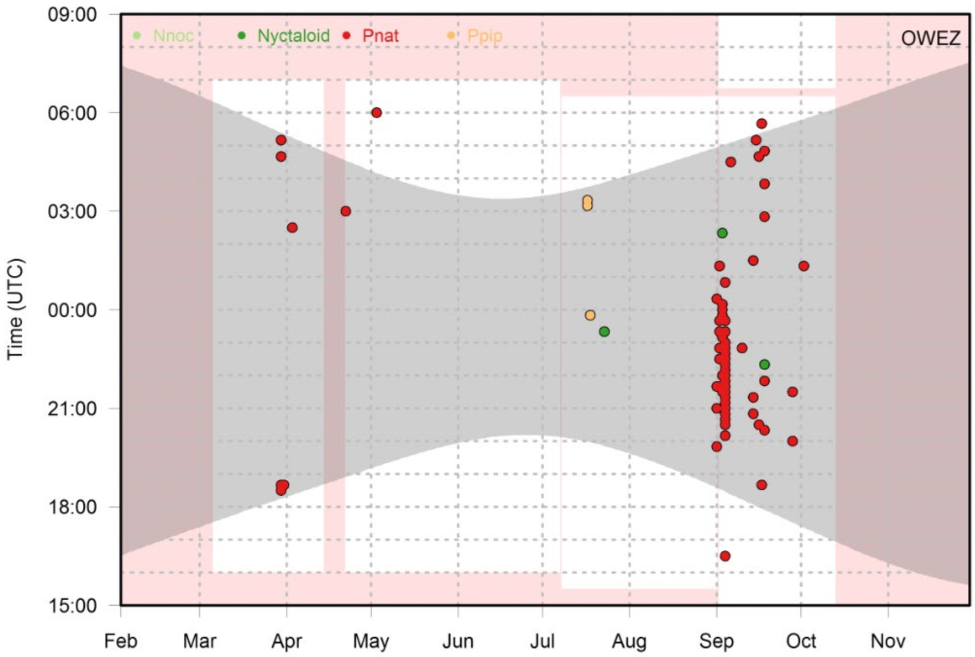


Figure 2.1 Acoustic bat activity at the Offshore Wind Farm Egmond aan Zee (OWEZ) meteo mast in 2014 (reproduced from Lagerveld et al. 2015). The dots represent the presence of bats in 10 minute intervals and their color indicates the species (group): Nathusius pipistrelle (red), Common pipistrelle (yellow), nyctaloid (dark green), Common noctule (pale green). Note that a white background represents the actual monitoring period and pink indicates no monitoring/recorder switched off. The period of darkness is represented by grey.

Apart from migrating over sea, bats are also known to forage around offshore wind turbines, similarly to foraging behaviour around onshore wind turbines (Ahlén et al. 2009), but the offshore fatality risk is yet unknown (Arnett et al. 2016). In addition to the link with foraging behaviour, the fatality risk at sea may also be influenced by the flight height during (directional) migration. Ahlén et al. (2009) observed that all migrating bats over the Baltic Sea usually flew below 10 m, even the species normally flying high like Common noctule and Particoloured bat. Nathusius' pipistrelles seen during ship-based surveys at the North Sea flew at heights between 5-20 m (Lagerveld et al. 2014). Brabant et al. (2018) noted that recorded acoustic bat activity offshore at nacelle height is significantly less than at lower heights. However, high altitude migration over sea has been proven by Hatch et al. (2013) who photographed several diurnally migrating bats during tailwind conditions at altitudes of more than 200 m above sea level off the eastern US. Hüppop & Hill (2016) also suggested that bat migration over sea may also be a high altitude phenomenon. Other factors possibly contributing to the fatality risk at sea is attraction to offshore wind turbines by red aviation lighting (Voigt et al. 2018), intensive exploring behaviour around the nacelle (Ahlén et al. 2009, Bach 2019) and diurnal roosting opportunities (Lagerveld et al. 2017B).

3 Model-based approach to estimate offshore fatalities

An estimation of the number of fatalities at wind turbines can be based on:

- Carcass searches
- Pre-construction acoustic bat activity
- Post-construction acoustic bat activity

3.1 Carcass searches

Over the last years, multiple approaches for fatality estimation on land have been developed based on carcass searching, for example Shoenfeld (2004), Huso (2010), Huso et al. (2012), Perón et al. (2013), Wolpert (2013) and Dalthorp et al. (2018).

The number of carcasses found -by either human observers or by search dogs- is usually much lower than the actual number of fatalities as there are several sources of imperfect detection. The following factors have to be accounted for in order to produce a reliable estimate of the number of fatalities (Dalthorp et al. 2018):

1. Carcasses fall outside the search area
2. Carcasses disappear due to scavengers or by decomposition (carcass persistence)
3. Skills of the observer or search dog (searcher efficiency)
4. Different species groups (bats, birds) and size classes (large, medium, small)
5. Various habitat types
6. Frequency of search efforts

In parallel with the search process, researchers will typically conduct field trials to assess these detection bias factors. For instance the searcher efficiency is estimated by placing marked carcasses in the field for possible discovery during routine carcass surveys. This will also quantify ‘carcass persistence’ , i.e. the probability that a carcass arriving at time 0 will continue to persist until a time t days later. Establishing the detection bias factors is paramount to an accurate quantification of bat fatalities.

Carcass searches on offshore wind turbines are possible at the transition piece (TP) of offshore wind turbines and theoretically these can be used to estimate the number of fatalities when imperfect detection is accounted for (see above). However, the searched area will be tiny in relation to the area where carcasses potentially may land. Furthermore, it seems likely that carcasses will disappear much faster in comparison to land. In addition to scavengers and decomposition carcasses offshore will likely drop down easily through the gratings at the TP and can be blown off easily by the wind. Once in the water they will soon drift away. Carcass monitoring will also be logistically and financially challenging as search intervals are typically 2-3 days, and several wind turbines of multiple offshore wind farms have to be monitored simultaneously in order to obtain a robust data set.

3.2 Pre-construction acoustic bat activity

Pre-construction acoustic bat activity can be used to assess the species-specific presence/absence over time in the area concerned. However, it is not a good predictor for the actual fatality rate. Hein et al. (2013) reviewed fatality data from 12 windfarms in the US and showed that there is no significant relationship between pre-construction acoustic measurements of bat activity and the number of post-construction fatalities, possibly due to attraction to turbines once they are built and/or the changes in site use due to an alteration of the habitat.

3.3 Post-construction acoustic bat activity

Post-construction acoustic bat activity on land is in general a good predictor for the fatality rate (Kunz et al. 2007, Baerwald & Barclay 2009 & 2011). Korner-Nievergelt et al. (2013) developed a model which predicts the number of bat fatalities (irrespective of the species involved) based on wind speed and post-construction acoustic activity measured at the nacelle, using a baseline fatality dataset from 30 Enercon wind turbines with rotor diameters between 66 m and 72 m, across 15 different wind farms in Germany. The model does not use wind turbine dimensions (height, rotor diameter), species composition, season and geographical region as predictors. Korner-Nievergelt et al. (2013) stated that the model can be used to assess the fatality rate of new wind turbines with similar dimensions, as well as the turbine-specific curtailment. However, a model validation in which residual patterns are investigated (Zuur & Ieno 2016) is lacking, and therefore it is unclear whether it was appropriate to ignore other potentially relevant covariates in the model like geographical region, season, species composition, type of bat detector, wind turbine dimensions and other weather variables (e.g. temperature).

In fact, an extensive study by Bach et al. (in press B) in coastal NW Germany showed that the local species composition is an important factor as Nathusius' pipistrelle (82% of the fatalities) produced only 25% of the acoustic activity, whereas Common noctule (20% of the fatalities) produced 60% of the acoustic activity. Therefore, it seems that the relationship between acoustic bat activity and the number of fatalities is species-specific and regional differences in species composition will produce different relationships between the overall acoustic bat activity and the total number of fatalities.

Recently, the Korner-Nievergelt model was updated (Behr et al. 2018). Currently it includes the type of bat detector, and accounts for four different regions in Germany as well as for seasonal differences. Furthermore, it takes into account to some extent the species composition, as the percentage of Nathusius' pipistrelle recordings is now used in the assessment of the number of fatalities.

If the offshore fatality rate has to be deduced from onshore measurement results, it will be necessary to:

- Determine a ratio between the measured bat activity onshore and the number of onshore fatalities (formula 1) and use this factor to deduce the number of fatalities offshore based on the measured bat activity offshore (formula 2).

$$(1) \quad R_{onshore} = \frac{\sum_{i=1}^{i=N_{onshore}} \left(\frac{F_{onshore}(i)}{A_{onshore}(i)} \right)}{N_{onshore}}$$

Where:

$R_{onshore}$	= *mean onshore fatality ratio*
$N_{onshore}$	= *number of onshore wind turbines with measurement results*
$F_{onshore}(i)$	= *average number of estimated fatalities at onshore wind turbine i*
$A_{onshore}(i)$	= *measured average bat activity at onshore wind turbine i*

$$(2) \quad F_{offshore} = R_{onshore} * \sum_{j=1}^{j=N_{offshore}} A_{offshore}(j)$$

Where:

$F_{offshore}$ = *number of estimated fatalities offshore*
$N_{offshore}$ = *number of offshore wind turbines*
$A_{offshore}(j)$ = *measured bat activity at nacelle height at offshore wind turbine j*
$R_{onshore}$ = *onshore fatality ratio*

- Use onshore wind turbines with similar dimensions as offshore turbines.
- Use onshore wind turbines at locations in open landscapes where the species composition reflects the composition at sea, i.c. where migrating bats can be expected and resident bats are rare/uncommon.
- Develop species-specific models (starting with Nathusius' pipistrelle, and possibly at a later stage Common noctule).
- Initially include all potentially important covariates in the model (wind turbine dimensions, location within the wind farm, weather parameters, seasonality, acoustic activity), and simplify the model wherever appropriate.
- Measure acoustic bat activity at various heights (at least two) both onshore and offshore at multiple wind turbines in various wind farms (and with different locations within the wind farm) to assess potential differences in bat activity/flight height.
- Use the same bat detector with identical maintenance schemes and monitor their performance throughout the season (mid-March – late October).
- Perform fatality searches onshore, account for sources of imperfect detection.
- Create a robust dataset.

4 Automated monitoring techniques

Several techniques can be used for automated monitoring of bats and birds near wind turbines. The section camera techniques covers the use of daylight, infrared and thermal cameras. Radar uses reflections of radio waves and Lidar uses reflections of laser light. Acoustics comprises the use of ultrasound recorders (bat detectors) for bats and 'regular' recording equipment (birdsound recorders) for birds. In addition, impact sensors can be used to register an actual collision.

All these techniques generate raw monitoring data which need to be manually or automatically processed. We do not cover the processing of the data since this can be done in many ways including image processing and deep learning techniques.

4.1 Camera techniques

Digital cameras can be equipped in various ways. Most of them have CCD (Charged Coupled Device) or CMOS (Complementary Metal Oxide Semiconductor) sensors. These sensors are sensitive to light with wavelengths in the range from 400 to 1100 nm. The visible spectrum (VIS) of the human eye ranges from approximately 380 to 780 nm (Mangold et al. 2013). The infrared light (higher than 700 nm) can be blocked with special IR cut filters so that only the visible light is transmitted.
These filters are attached in front of a lens or built-in into a digital photo camera such that the colour image appears similar as the one perceived by the human eye. Conversely, a daylight cut filter can be used to block the visible light and transmit the infrared light to the image sensor. In this case only the reflected infrared light is used and converted to produce an image that can be seen by the human eye. Digital cameras cannot operate in full darkness. Image sensors record the reflected light from an object when illuminated by a light source, such as the sun or lamps. At night time, the outdoor light is low and to record an image an additional light source is needed. A well-known example are security cameras, which produce night vision images in the infrared (IR) spectrum. For near-infrared cameras some light needs to be available. If no ambient lighting is available the area surveyed needs to be lit with IR light.

Thermal imaging (Long Wave Infra-Red) makes use of the heat radiation each object produces and produces images based on this. Thermal cameras (also referred to as Forward Looking Infra-Red (FLIR) camera) are sensitive in the mid- or long infrared spectrum, which is not visible to the human eye. The mid wave infrared (MWIR) and the long wave infrared (LWIR) range from 2-15 μm (Dakin 2017). All objects warmer than the absolute zero point (-273 degree Celsius) emit infrared radiation in that range. Thermal cameras detect this radiation and convert the temperature variations to grey scale or color images that produce a heat map that can be seen by the human eye. Cloud cover might lower the performance due to reduced contrast in temperature between animals and the environment (Horton et al. 2015). Thermal cameras can be used day and night, and no light sources are needed to illuminate the surveyed area. In addition, a thermal camera performs better in foggy and rainy conditions in comparison to a daylight camera (Beier & Gemperlein 2004).

Several camera characteristics are important to collect footage at night. These include resolution, frame rate and thermal sensitivity. The resolution of the camera defines the amount of detail a camera image can capture, i.e. at what size and distance objects are still visible. The typical resolution for thermal (Long Wave Infra-Red) cameras is low (320x240 or 640x480 pixels) compared to digital cameras using daylight or near-infrared, and therefore reduces a small or remote object to a few pixels making it harder to track. Increasing the focal length of the camera (higher zoom factor) will increase the detection range but at the same time the field of view (FOV) will decrease, and objects can easily be lost when they fall outside the image (Matzner et al. 2015). The optimal focal length therefore depends on the area surveyed as well as on the size and behaviour of the subject. There are also cameras on the market which have a variable focal length and are able to zoom in and out.

Frame rate defines the temporal resolution. A high frame rate results in a higher temporal resolution. A high frame rate can result in detailed and sharper images of moving objects that would otherwise be a blur.

Thermal sensitivity is indicated as NETD (Noise Equivalent Temperature Difference). NETD changes with the temperature of an object. When the object temperature increases compared to other objects in its surrounding, the NETD decreases leading to a better sensitivity (Rai et al. 2018).

There are active-cooled and uncooled cameras and both of those systems have their own advantages, the details of which are beyond the scope of this report, but in general cooled cameras produce a much better image quality (Matzner et al. 2015) but are more expensive, use more energy and require a "startup-time" to cool down. Uncooled cameras tend to have lower resolution and quality. Uncooled cameras will be sufficient to detect medium to large birds at ranges up until 200 m. Cooled cameras have a higher performance which is necessary to cover the Rotor Swept Area (RSA).

In conclusion, multiple factors contribute to the detection distance of bats and birds:
- Location/orientation of the camera (sea, clouds, objects in view)
- Size of the animal
- Resolution
- Focal length
- Framerate
- Precipitation
- Type of camera (daylight, IR light, thermal, cooled/uncooled)
- Additional light source (for near-infrared cameras)
- Sensitivity (NETD) for thermal cameras

The reported detection distance of bats is up to 100 m (Matzner et al. 2015), 120 m (Lagerveld et al. 2017A) and 150 m (Mollis et al. 2019), using thermal or near-infrared cameras. Medium to large birds can be detected at about 200 m (Matzner et al. 2015). Camera-footage will also include insects, waves, clouds and planes (Flowers & Suryan2014, Hill et al. 2014, Lagerveld et al. 2017A).). Filtering techniques can be applied (to a certain extent) to exclude those other images from the monitoring data.

Cameras are typically applied for recording 2D footage, but can also be used to record 3D footage when applied as a stereoscopic setup or in a Time-of-Flight setup. Stereo vision however is much more complicated as the cameras need to be synchronized and calibrated, and an integration solution is needed when multiple sets of stereo cameras are being used (Lagerveld et al. 2017A). As stereovision is able to assess the actual 3D flight, collisions and barotrauma events are likely to be much better detectable in comparison to the use of single cameras, since abrupt changes in flightpath can be quantified (Lagerveld et al. 2017A). Nevertheless, fatalities have also been documented using single cameras (e.g. https://www.youtube.com/watch?v=mttpX53OCwU).

Bat and bird rotor interactions close to the edge of the frame are very hard (and maybe even impossible) to interpret with certainty (Lagerveld unpublished data). Therefore, it seems likely that collisions and barotrauma events can only be documented with certainty when they occur close to the center of the frame.

The Time-Of-Flight (ToF) technique uses either LED light or laser (3D flash LIDAR) in combination with an imaging sensor (both thermal and daylight / IR). It measures the distance by use of the round trip time of a light signal. LED based ToF devices have a very limited range and are, in their current state, unusable with small animals like bats.

4.2 Radar

Radar (RAdio [Aim] Detecting And Ranging) is commonly used in detecting birds and bird-fluxes, it works based on the principle of transmitting radio waves (pulses) and receiving back the reflections (echoes) of these on the surrounding objects. Based on the elapsed time between transmission of pulses and receiving their echoes, and other characteristics of the echoes, objects can be recognized. Furthermore a radar can identify the distance, height, direction, course, and speed of flying objects. The electromagnetic pulses used for radar are unaffected by darkness and can also penetrate fog and clouds. The wave length of emitted radio waves determines the resolution and detection range of a radar. These wave lengths are classified into bands; bird studies mostly use either the X-band (wavelengths 2.5-3.75 cm), or the S-band (8–15 cm wavelengths).

The X-band has a higher resolution and can thereby detect smaller objects, including insects. The broader range of the S-band is less vulnerable to disturbance by fog or rain, but has a lower resolution than the X-band. The beam of the radar is narrow to facilitate detection of smaller objects, but radar antennas regularly rotate to transmit pulses in all directions, thus enabling detection of objects in a circle around the radar.

In general, four types of radar are being used:

- A horizontal radar which scans across the landscape and provides a "bird’s eye view". It provides information about the direction of flying targets.
- A vertical radar, pulsing perpendicular to the ground, taking a cross section of the airspace and providing information on the flight height of targets.
- Fixed beam radars, where the antenna a fixed angle, and several consecutive pulses are averaged together to reduce the contamination by random noise (Stepanian et al. 2014).
- Phased Array radar, containing of an array of antennas by which information can be obtained through electronically steering the beam and using a Frequency Modulated Continues Wave, this array can be rotated. A beam-width of 60° is achievable.

The advantages and disadvantages of these types are described in Snoek et al. (2016).

Radar does allow for separation of avian and non-avian (e.g. insects) radar signals as well as classification into various sizes classes (Zaugg et al. 2008). In general bats cannot be distinguished from birds with certainty (personal comment S. Gyraud, March 2020). The detection range varies depending on the technical characteristics of the radar and the size of the object. Reported detection ranges of a phased array radar are 10 km and 6 km for ducks/small geese and songbirds respectively, both up to an altitude of 1 km (https://www.robinradar.com/press/downloads).

Close to the wind turbine rotor radar loses track of objects (personal comment S. Gyraud, October 2019) and therefore fatalities cannot be monitored by radar. Furthermore, it detects its own pulses reflected by the waves of the sea and this will generate noise called clutter. The software will need to adequately filter this clutter as well as insects from real targets and this plays an important role in performance (Osadchyi et al. 2016). The performance of radar decreases during heavy rainfall and snow (Technical information sheet Robin Radar).

4.3 Lidar

LIDAR (LIght Detection And Ranging or Laser Imaging Detection And Ranging) works on the same principle as radar: a signal is sent and the subsequently reflected signal will be picked up. The distance to the object is determined by measuring the time that elapses between transmitting a laser light pulse and receiving a reflection from that pulse. The distance to the reflecting object can be calculated by multiplying the elapsed time with the speed of light divided by two (Lefsky et al. 2002). The difference between LIDAR and radar is that LIDAR uses laser light while radar uses radio waves.

Consequently much smaller objects can be detected with LIDAR than with radar. The wavelength of radio waves (2.5-15cm) used in bird radars is higher than that of laser light (between 10 µm and 250 nm) (Prost 2013). At this wavelength, the waves will be better reflected by small objects.
LIDAR is expected to be sensitive to fog, snow and rain due to the laser becoming diffused (Hadj-Bachir & De Souza 2019, Ryde & Hillier 2009).

Studies have been conducted on several species groups, mainly to assess densities in hibernation sites of bats (Azmy et al. 2012) or measuring flight heights in birds (Cook et al. 2018). A feasibility study of the use of LIDAR in bird classification by spectroscopy shows that birds can be classified based on colour up to 100 meter in darkness (Lundin et al. 2011). Malmqvist et al. (2018) showed that LIDAR could discriminate between bats/birds and insects in a test setup. Based on size only, it would not seem to be possible to differentiate between bats and small birds. Because LIDAR is assumed to be affected by reflection on rotating blades, the use of LIDAR near/in the RSA may be to too limited for the detection of hits.

LIDAR is being used in the automobile industry for the development of autonomous cars and in instruments for measuring cloud cover, deforestation etc. The technique is evolving fast and might further improve to be useful in the detection of flying objects by using the Time-Of-Flight technique as described under chapter 4.1. No ready to use LIDAR products in the field of detecting bats and birds are available yet.

4.4 Acoustics

Echolocation calls of bats and flight calls of birds are often species-specific and can be used for species identification. Flight calls of birds usually lie within the frequency band of 1 - 10 kHz (Ronconi et al. 2015) and bat echolocation calls range from 8 - 200 kHz (Adams et al. 2012). However, because of the bat species spectrum at the North-Sea (Boshamer & Bekker 2008, Leopold et al. 2014, Lagerveld et al. 2017B), recordings up to 100 kHz will be sufficient for use in this area.

Several systems incorporate ultrasound microphones or bat detectors. These record the sounds bats produce during navigation, foraging or social behaviour. Ultrasound sounds in general have limited reach, and depending on the species, habitat and weather conditions (Adams et al. 2012, Barataud 2015) and can vary from less than 5 m to 100 m (Barataud 2015). A bat detector will, to a large extent, be able to record sounds that will enable bat-species identification.

To record flight calls of birds, microphones sensitive in the human-hearable frequencies can be used. Warblers and sparrows could be recorded up to 250 meter, while Thrushes were audible up to 1000 meters (Farnsworth & Russell 2007).

Several factors influence the detection range of sone- and ultrasound recorders. Next to the position and the mounting-direction of the microphone, the choice of the recording device (both microphone and recorder) are of great importance. (Adams et al. 2012, Lagerveld et al. 2019). Note that the sensitivity of microphones decreases over time and therefore regular replacement or re-calibration is required.

Analyzing acoustic data is labour intensive. False detection rates in automated analyses (both in birds and bat species) are generally higher than in manual analyses (Hill & Hüppop 2011).

In general it is unlikely that all bats and birds in the RSA can be detected automatically. However, if the recording is triggered with a different technique (radar), the timestamp might make it possible to find a recording in the noise. To quantitatively assess the occurrence of bat species in the RSA, species-specific detection distances of echolocation calls should be determined.

4.5 Impact sensors

Vibro-acoustic impact sensors in the rotor blade can be used to detect an impact signal from a collision (Wiggelinkhuizen et al. 2010), but only objects above a certain weight can be detected. Empty (~57g) and water-filled (~140g) tennis balls were detectable during tests of one of the available systems (Wiggelinkhuizen et al. 2006). It seems unlikely that small bats like Nathusius' pipistrelle (6-15g) are detectable with this type of sensor. A fatality due to barotrauma will evidently never be detected, as no rotor impact occurs.

5 Evaluated systems

An overview of the available systems to monitor bird and bat fatalities & fluxes is given in Collier (2012), Dirksen (2017) and Mollis et al. (2019). In addition the recently developed B-finder system was added to the list of evaluated systems.

Name:	***WT-Bird***
Basic information:	The current WT-Bird system by ECN is based on several impact sensors (accelerometers) in the blades that detect the actual hit. The system is supplemented with near-infrared cameras to verify a collision and for the identification of species.
Sensors used:	Impact sensors & near-infrared camera.
Current status:	One system is in operation in the OWEZ offshore windfarm in the Netherlands. It is not commercially available yet. Limited progress has been made since 2017. However an upgrade of sensors of the system is planned for 2020 since the USA Department of Energy is financing new research on the system. (J.P. Verhoef, personal comment, March 2020)
Performance:	While operational, the system has detected a collision with a feral pigeon. Further information on this has not yet been published. Collisions of smaller bird species (songbirds) are most likely not detected as the actual collision event cannot be filtered out from the background noise (Dirksen 2017). An improvement of the sensory system will be tested in 2020.
References:	Wiggelinkhuizen et al. 2006, Wiggelinkhuizen et al. 2010, Dirksen 2017

Name:	***VARS***
Basic information:	The Visual Automatic Recording System by IfAOe[1] is a camera based system for automatically recording flying birds and bats. The software uses motion detection to trigger the recordings. The recordings need to be manually checked on false triggers (rotors, waves, rain at night, fast-moving aircraft, shooting stars and occasionally clouds). The near infrared cameras are mounted both on the nacelle behind the rotor and on the base of a wind turbine and capture birds and bats in the rotor swept area.
Sensors used:	Near infrared cameras
Current status:	Available
Performance:	It does not cover the whole RSA but was limited to a field of 22°. Within this area under good conditions the detection of small birds is almost hundred percent up to 60m and detection is possible, although not for every bird, up to 80m. No detections of bats are published.
References:	Collier et al. 2012, Dirksen 2017, Mollis et al. 2019

---

[1] Institut für Angewandte Ökosystemforschung GMBH

Name:	***DT-Bird / DT-Bat***
Basic information:	The DT-Bird / DT-Bat system is designed as an early warning system. The user is able to set a trigger on an amount of activity. After reaching this trigger the system either stops the turbine and/or emits signals to deter birds. The system consists of different modules, and can be equipped with visual or ultrasound detectors. The visual component consists of daylight or optionally thermal cameras. The ultrasound detectors are used to detect echolocating bats (in general mounted on the nacelle). It was designed for on- and offshore usage. The system is not designed for registering collisions, it is designed to deter birds and/or bats in the vicinity of the wind turbine or to stop the wind turbine temporally. In order to determine and quantify collisions it is necessary to manually check the recorded videos.
Sensors used:	Daylight or optionally thermal camera’s, batdetectors
Current status:	Available
Performance:	Its thermal cameras are, to a certain extent, able to detect bats and birds and record flight paths and collisions. The reported detection range is 40-60 m at night for a Puffin *Fratercula arctica*. However not the full Rotor Swept Area is covered (personal comment, A. Rioperez, 28 October 2019) The ultrasound (bat) recorders are mounted on the tower and/or nacelle and most likely will not cover the complete RSA for all species.
References:	Deplazes et al. 2015, manufacturer brochures

Name:	***ID-Stat***
Basic information:	The ID-Stat system uses a microphone at the base of each rotor blade to detect impact sounds. The system filters the acoustic signal at the wind farm and detections of collisions are sent to a web based database. It has been tested with objects as little as 2.5 gram in an onshore situation (Delprat & Alcuri 2011). Information on the test-setup is limited.
Sensors used:	Acoustic microphones
Current status:	unknown (developer does not respond)
Performance:	No report available
References:	Delprat & Alcuri 2011

Name:	***ATOM - Acoustic and Thermographic Offshore Monitoring***
Basic information:	The ATOM Acoustic and Thermographic Offshore Monitoring system is a system designed to detect objects with stereo thermal cameras, daylight cameras and acoustic recorders. It is able to detect both bats and birds. The thermal camera system is designed to calculate, record and store direction data and flight altitude of flying objects, but does not record collisions. Since the review by Mollis et al. (2019), an additional daytime camera sensor was added to the setup to give a wider view of almost the entire RSA. The thermal camera view is less-wide and mounted in a fixed position. It is therefore only able to view the whole RSA under optimal wind direction scenarios (personal comment J. Willmott 29 October 2019).
Sensors used:	Thermal cameras, daylight cameras, acoustic (both sone- and ultrasone)
Current status:	Available
Performance:	Birds were detected up to 180 m, bats were not detected in the RSA during tests. The detection range of bat calls with the ba tdetector is less than 20m. The system uses SwisTrack to identify tracks, SwisTrack success rates of bird detections from within the video imagery ranging from below 15% to over 60% (Willmott et al. 2015).
References:	Willmott et al. 2015

Name:	***ACAMS***
Basic information:	The ACAMS (Aerofauna Collision Avoidance Monitoring System) system is developed by Biodiversity Research Institute (BRI, USA) in combination with HiDef Aerial Surveying Limited. It consists of two high-definition 29-megapixel stereo-optic camera systems with fisheye lenses. A 3-D algorithm was developed for object isolation and tracking, but the system was unable to obtain accurate distance measurements. The system was designed with near infrared cameras aided with near-infrared illuminators to possibly also detect bats, but unable to detect a bat flying at a distance of more than 60 meters. Testing with near infrared was discontinued and the research was exclusively focused on daytime monitoring (Adams et al. 2017).
Sensors used:	Daylight cameras
Current status:	Unknown (developer does not respond)
Performance:	Eagles detectable up to 500m, bats undetectable
References:	Adams et al. 2017

Name:	***Robin Radar***
Basic information:	Robin Radar has built several bird and bat detecting radars. The latest addition is the Max Avian Radar of which the software is able to detect both bats and birds, but is (like any radar) unable to identify species (groups). Radar will experience disturbance from turbine blades, as well as from the turbines themselves and might lose the track near the turbines (S. Giraud, personal comment, 30 Oct 2019).
Sensors used:	Radar (phased array)
Current status:	Available
Performance:	• Small-aircraft :15 km range, up to 2 km altitude • Small goose/duck: 10 km range, up to 1 km altitude • Songbird: 6 km, up to 1 km altitude
References:	Information supplied by manufacturer

Name:	***Wind Turbine Sensor Unit for Monitoring of Avian & Bat Collisions***
Basic information:	The Wind Turbine Sensor Unit for Monitoring of Avian & Bat Collisions was developed by Oregon State university. It contains impact sensors (accelerometers and contact microphones) mounted at the base of each blade, visual cameras, infrared cameras and bioacoustics microphones. It is designed to register collisions of animals with the blades. It is triggered by impact so will be unable to detect barotrauma incidents. The system is not in production yet, commercial partners are being sought (D. Dickson, personal comment).
Sensors used:	impact sensors, microphones(for bird species identification), batdetector, visual cameras, infrared cameras
Current status:	Under development, not in production
Performance:	Tested with tennis balls 57g, and 140g
References:	Hu et al. 2018

Name:	***DeTect Merlin Avian Radar System***
Basic information:	The DeTect Merlin Avian Radar System uses automated radar to detect birds and bats passing through the radar swept area to help improve collision risk assessment and provide warning when flocks are approaching. Merlin radars have been used offshore.
Sensors used:	Radar (horizontal)
Current status:	Available
Performance:	Passerines detectable from 135 to 2866 m (species identification was performed visually not with radar), bats unknown
References:	May et al. 2017

Name:	***MUSE (MUlti-Sensor)***
Basic information:	MUSE (MUlti-Sensor) formerly known as Thermal & Visual Animal Detection System (TVADS) is designed and in production by DHI. The current version combines a horizontal radar and thermal and/or daylight cameras. Once the radar detects an object, the camera is automatically aimed at the object and the flight path of the object is recorded. The system without thermal cameras is installed in Offshore windfarm Luchterduinen in The Netherlands as well as in an offshore windfarm in the UK and the US.
Sensors used:	Radar, thermal cameras, daylight cameras
Current status:	Available
Performance:	The system is capable of monitoring four turbines and can detect a "standard seabird" at about 4 km by radar in its current setup. The camera is able to follow the "standard seabird" at a maximum of approximately 1 km and is expected to be able to track a small bat at 150 meter while positioned at the base of a single turbine (Skov, personal comment, 30 October 2019).
References:	Skov, personal comment (30 October 2019)

Name:	***BirdScan MR1***
Basic information:	BirdScan MR1 by Swiss-Birdradar is a radar system for the quantitative long-term monitoring of birds and bats. It uses a vertically directed conically shaped wide aperture beam with a nutating (movement of the primary rotary axis of a revolving object) movement. The system can be placed as close as 150 m away from a turbine, and is able to detect small passerines and bats up to an altitude of 1000 m.
Sensors used:	Radar
Current status:	Available
Performance:	It uses a software which is able to detect a wing flapping pattern to exclude non-birds or non-bats. Identification of bats is not possible.
References:	Birdscan fact-sheet: www.swiss-birdradar.com

Name:	***B-FINDER***
Basic information:	The B-FINDER "automatic bats & birds mortality monitoring for wind power" is a solution based on three rings of thermal cameras mounted on the tower, which detect falling objects. A "positive hit" is an object that is detected by all three sensor rings within a predetermined time-frame. Data are collected and reported including photo & video evidence of the event. The system is not in production yet, sale has started in September 2019. The solution is designed for offshore and onshore usage but not tested offshore. The collected images are unsuitable for species identification (M. Przybycin, personal comment, 13 November 2019). The system predicts the location where the carcass will hit the ground.
Sensors used:	Thermal camera
Current status:	Tested onshore but not offshore and not in production yet
Performance:	Information supplied by manufacturer: • Detection of all bats species up to 50 m from the wind tower (min. 95% efficiency); • Detection of smallest bird species up to 50 m from the wind tower (min. 95% efficiency); • Detection of all bigger bird species up to 100 m from the wind tower (min 95% efficiency); • Detection of all raptor species up to 100 m from the wind tower (min 95% efficiency); Manufacturer expects an increase of range possible by adding cameras and changing optics (bats 100-150 meter) but this needs to be tested. The system is able to predict the location of the fallen carcass on the ground by an precision of about 10m.
References:	Przybycin et al 2019

Name:	***Thermal Stereo Vision Application (TSVA)***
Basic information:	A feasibility study by Wageningen University & Research commissioned by Rijkswaterstaat was performed using a stereo-thermal-video setup in combination with an array of ultrasound microphones positioned at three heights, each containing four microphones to determine bat behaviour around an wind turbine.
Sensors used:	Stereo thermal cameras, ultrasound microphones
Current status:	Proof of concept completed, further development and testing needed.
Performance:	The proof of concept showed that measuring flight-tracking of bats with the stereo camera setup can be used together with the ultrasound microphone array for species identification and assessing the performance of the estimated flight trajectories. Further improvements are needed.
References:	Lagerveld et al. 2017A

Table 5.1 Overview of the sensors used in each system

Nr	*System*	*Radar*	*Lidar*	*Daylight camera*	*Thermal camera*	*Infrared camera*	*Ultrasound detector*	*Birdsound recorder*	*Impact sensor*
1	WT Bird			X		X			X
2	VARS			X		X			
3	DT-Bird / DT-Bat			X	X		X		
4	ID-Stat								X
5	ATOM			X	X		X	X	
6	ACAMS			X					
7	Robin radar	X							
8	WTSU			X		X		X	X
9	Detect Merlin	X							
10	MUSE	X		X	X	X			
11	Birdscan MR1	X							
12	B-Finder				X				
13	Thermal Stereo Vision application				X		X		

6 Application design

In this chapter we provide a conceptual design for an application that can quantify offshore bat as well as bird fatalities, based on the review of available techniques and evaluated systems.

6.1 Functional requirements

Several functional requirements were defined a priori:

1. The application should be able to:
    a. Detect approaching flying objects towards the wind turbine
    b. Identify relevant flying objects (bats and birds, filter out insects)
    c. Record footage of bats and birds in the RSA
    d. Record echolocation calls of bats and record calls of birds
    e. Identify bats and birds as much as possible at species level based on camera footage and acoustics.
    f. Assess collision/barotrauma
2. The application should not change the behaviour / fatality risk of bats and birds.
3. The application should be offshore proof

6.2 Elaboration of the requirements

Detect approaching flying objects

Bats and birds should be detected day and night, as well as under various weather conditions, e.g. rain and fog. The system should be able to track objects approaching the turbine, and particularly a movement towards the RSA. This can be achieved with radar, LIDAR and stereo-cameras (both thermal and infrared). Acoustics (bird sound recorders as well as bat detectors) are not suitable due to the limited detection range. In addition, some bird species do not call at all during flight or call at irregular intervals. Some bats are also known not to echolocate in some cases (Chiu & Moss 2008 Corcoran & Weller 2018).

Radar is the best option to detect approaching flying objects as it performs both by day and by night, in foggy and rainy conditions, has a considerable detection range and there are several well developed systems on the market. LIDAR is also a promising technique given the extensive detection range and its performance during day and night. However, LIDAR will be disturbed by fog and rain (Hadj-Bachir & De Souza 2019, Ryde & Hillier 2009) and is less well-developed in comparison to radar. Near-infrared as well as thermal cameras may be used, but their detection ranges are limited and multiple pairs of zoomed (stereo-vision) cameras are needed in order to cover the area around the wind turbine. In addition, the analysis methods need further improvement so that reliable 3D paths can be derived automatically (Lagerveld et al. 2017A).

Identify relevant flying objects (bats and birds, filter out insects)

Radar does not only detect bats and birds, insects or artifacts (clutter) are also being recorded. Depending on the radar manufacturer filtering can be applied and can be adjusted (Schmaljohann et al. 2008). A feasibility study with LIDAR showed that bats and birds can be separated from insects (Malmqvist et al. 2018). Neither radar or LIDAR can separate birds from bats with certainty. (Malmqvist et al. 2018). A feasibility study of the use of LIDAR in nocturnal bird classification has been explored, and Lundin et al. (2011) showed bird species can crudely be classified up to 100 meter in darkness by using spectroscopy in extended wavelength ranges.

Cameras will record insects in addition to birds and bats. As far as we know there are no automated filtering techniques for insects. Applying stereovision may be a way to get rid of insects as the detection range of insects is very small and therefore it is unlikely that an insect is detected simultaneously on both camera's (Lagerveld et al. 2017A).

Record footage in the RSA

Video footage of birds and bats close to the rotor should be obtained day and night. This can best be achieved with thermal and near infrared cameras. In order to reach the upper limits of the RSA, zoomed cameras have to be applied.

Bats are known to forage around wind turbines which results in complicated flight paths (encircling the tower, sudden turns and loopings). In order to track a foraging bat in the RSA multiple fixed cameras per wind turbine are needed in order to avoid obscuration by the tower, and sophisticated tracking algorithms must be used to follow the movements of a foraging bat, in particular while the wind turbine is operational and when the object can frequently be hidden by the rotor blades. For birds this will likely be not an issue as their flightpaths are less erratic.

Record calls

Echolocation calls of bats can only be recorded with ultrasound recorders (bat detectors). Flight calls of birds should be recorded with a bird sound recorder. Note that the detection distance of some species is rather limited (Adams et al. 2012, Barataud 2015) and therefore multiple ultrasound and regularly placed microphones are needed to monitor bat and bird activity at various tower heights (Lagerveld et al. 2017A, Bach et al. in press A). Even so, it is not likely that the entire RSA can be monitored.

Identify bats and birds at species level

The identification of flying bats is very difficult visually, unless close-up full colour footage is obtained from species which are easy to identify based on morphological characteristics. Therefore, identification of flying bats should in general be done based on the echolocation or social calls. In NW Europe this is rather straightforward for species which belong to the genus *Pipistrellus*, but challenging and often not possible for species which belong to the Nyctaloid group.

Birds are often much easier to identify on camera footage. Bird calls can aid the identification, in particular songbirds like thrushes are easily identified by their calls.

Assess collision/barotrauma

Fatalities can be monitored automatically in two ways. The first option is to register the event of a collision or barotrauma in the RSA. This cannot be done by radar, LIDAR or acoustics. In addition, impact sensors cannot be used as these are not able to register barotrauma events and collisions of smaller birds and bats. Therefore, a collision or barotrauma event in the RSA can only be registered using a camera. Note that using stereoscopic cameras will likely be a more reliable option to register fatalities as these are able to assess the actual flight path (a collision or barotrauma event will cause a sudden change in direction). When single cameras are being used, a human observer should interpret the footage and decide what actually happened. In that case the object must be close to the center in order to interpret the footage adequately.

The second option to assess a fatality is to register the falling corpse when it drops down from the RSA. This cannot be done by impact sensors or acoustic recordings. Tower-mounted cameras, or specially designed radar or LIDAR should be able to perform this task.

The application should not change the behaviour / fatality risk of bats and birds.

The application should not interfere with the 'normal' behaviour of birds and bats near wind turbines. Therefore, it should not emit light or sound which may directly attract/deter birds and bats, or indirectly attract birds and bats due to an increased availability of prey (insects). In addition, the application should not alter the roosting opportunities. It seems that none of the technologies in this inventory will significantly change the behaviour of birds and bats, with the exception of the near-infrared camera. The additional required light source will generate both light and heat and consequently it is likely that it will attract insects (and bats).

Offshore proof

The application should be offshore proof which means that it should at least be able to deal with high wind speeds, precipitation and salt. It seems that all sensors can be applied at sea, although some modifications may be necessary.

Summary requirements

Table 6.1 shows a summary of the suitability of each technique in relation to the requirements.

Table 6.1 semi-quantitative suitability of the various techniques in relation to the functional requirements using a five-point scale

Nr	*Requirement*	*Radar*	*Lidar*	*Daylight camera*	*Thermal camera*	*Infrared camera*	*Ultrasound detector*	*Birdsound recorder*	*Impact sensor*
1	Detect approaching flying objects	++	+	--	+	+	-	-	--
2	Identify relevant flying objects	+	-/+	--	-/+	-/+	--	--	--
3	Record footage RSA	--	--	--	++	++	--	--	--
4a	Record bat calls	--	--	--	--	--	++	-	--
4b	Record bird calls	--	--	--	--	--	-	++	--
5a	Identify bats at species level	--	--	--	-	-	+	--	--
5b	Identify birds at species level	--	--	--	-	+	--	+	--
6a	Assess collision/barotrauma in RSA	--	--	--	+	+	--	--	-
6b	Assess drop from RSA	-/+	-/+	--	+	+	--	--	--
7	Not change the behaviour	++	++	++	++	--	++	++	++
8	Offshore proof	++	++	++	++	++	++	++	++

6.3 Conceptual design

Given the functional requirements (paragraph 6.1) and the appropriate techniques (Table 6.1), the application for bat and bird fatality monitoring should ideally consist of:

1. A radar, which detects approaching flying objects (1) and identifies the potentially relevant flying objects (2).
2. Thermal cameras, in order to obtain footage (3) to assess collisions/barotrauma (6a), as well as for the identification of bird species (5b). Furthermore, thermal cameras may be used to assess a falling corpse from the RSA (6b).
3. An ultrasound detector (bat detector) to record bat echolocation and social calls (4a) and for the identification of individual bat species (5a).
4. A bird sound recorder to record flight calls (4b) and for the identification of different bird species (5b).

LIDAR (no clear advantages over radar and less well developed), daylight cameras (not useful at night), near-infrared cameras (possibly change behaviour due to insect attraction because of the large amount of needed artificial lighting to enlighten the full RSA) and impact sensors (not able to assess barotrauma and likely not to be able to assess collisions of bats and small birds as well) should not be part of the solution.

6.3.1 Radar

Several radar systems are on the market that are able to detect an object of interest (bats and birds) that potentially collide with the wind turbine. The location of the radar needs to be considered well, if the object is in between the radar and the RSA the radar might lose track. Placement close to (or on) the turbine of interest must be considered but creates a "blind-spot" behind it, furthermore limiting the usability of regular fan beam radars since its cone shaped beam is very small close to the radar unit. Recently introduced "bird-radars" using the Frequency Modulated Continuous Wave principle have an increased beam width and height, and have a field of view of 60° upwards to solve the small cone, but leave the "blind-spot".

6.3.2 Thermal cameras

Bats frequently forage around wind turbines e.g. (Kunz et al. 2007, Cryan & Barclay 2009, Cryan et al. 2014) which may result in complicated flight paths (Lagerveld et al. 2017A). In order to track a foraging/passing bat (or bird) in the RSA, high quality thermal cameras are needed. In addition, it seems likely that sophisticated tracking algorithms must be used to follow the movements of a foraging bat, in particular while the wind turbine is operational and when the object is frequently hidden by passing rotor blades. For birds this will likely be less an issue as their flight paths are less erratic.

The distance to the upper reach of the RSA is more than 200 m for modern offshore wind turbines. Bats and songbirds are too small to observe at this distance. The camera to be used needs to be a high-quality camera with a long focal length. With a camera with a long focal length, the angle of view becomes smaller and only part of the RSA can be viewed (Figure 6.1 & Figure 6.2).

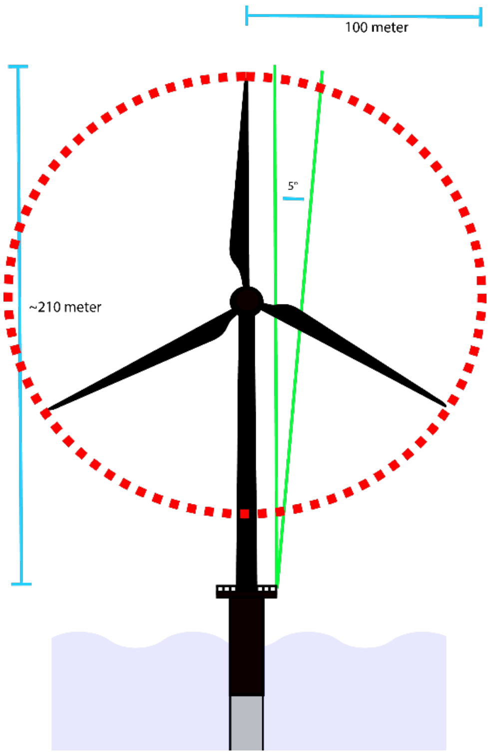


Figure 6.1 Long focal length

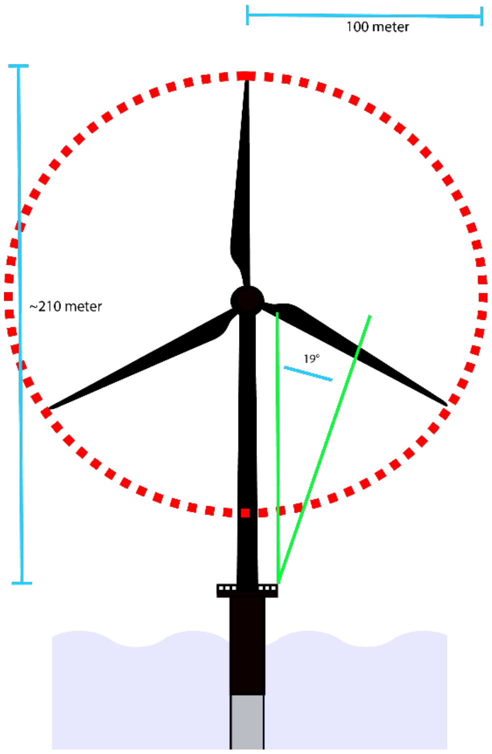


Figure 6.2 Short focal length

The RSA can be monitored in two ways :

- Using multiple cameras (possibly using stereo vision), so that they together cover the entire RSA. The number of cameras needed to cover the RSA depends on the dimensions of the wind turbine. Because a high-quality camera with a long focal length is very expensive, a solution in which the entire RSA is visible will be very expensive.
- Aim the camera at a target and continue to track that target with the camera. By using a set of “point, tilt and zooming” capable high-quality cameras with a long focal length, both the back and the front of the wind turbine can be covered within a camera view. However, with this solution it seems likely that an object is lost more easily by the camera (once lost it will likely stay lost) when it is obscured by moving rotor blades. In addition, collision and barotrauma events will probably be missed when more than one bat or bird is present in the vicinity of the rotor.

Thermal cameras may also be used to asses a drop of an object from the RSA. It seems likely that lower quality cameras can be applied for this purpose.

6.3.3 Bat detector

Due to the limited detection range of the bat echolocation calls (up to 25 m for Nathusius’ pipistrelle), several microphones at various heights should be installed at the tower. In addition, due to the directionality of bat calls, multiple microphones (at least two) at each level should be installed to avoid bats being missed which pass behind the tower.

6.3.4 Bird sound recorder

Analogue to bat detectors, multiple microphones should be installed at the tower and at the nacelle.

6.3.5 System integration

Depending on the choice of system the different sensors should be synchronized with each other and some of them should be the trigger for others. In addition, measurement data must be stored and it should be possible to monitor the performance of the system.

7 Conclusions

For bats post-construction acoustic bat activity is in general a good predictor for the fatality rate. If the offshore fatality rate has to be deduced from onshore measurement results it will be essential to:

- Use onshore wind turbines with similar dimensions to offshore turbines.
- Use onshore wind turbines at locations in open landscapes where migrating bats can be expected and resident bats are rare/uncommon.
- Develop species-specific models (starting with Nathusius' pipistrelle, and possibly at a later stage Common noctule).
- Initially include all potentially important covariates in the model (wind turbine dimensions, location within the wind farm, weather parameters, seasonality, acoustic activity), and simplify the model wherever appropriate.
- Measure acoustic bat activity at various heights (at least two) both onshore and offshore at multiple wind turbines in various wind farms (and with different locations within the wind farm) to assess potential differences in bat activity/flight height.
- Use the same bat detector with identical maintenance schemes and monitor their performance throughout the season (mid-March – late October).
- Perform fatality searches onshore, account for sources of imperfect detection.
- Create a robust dataset

Offshore bat fatalities can also be monitored using a technical solution. The application for bat (and bird) fatality monitoring should ideally consist of:

1. A radar, which detects approaching flying objects and identifies the potential relevant ones (bats and birds).
2. Thermal cameras, in order to obtain footage to assess collisions/barotrauma, as well as for the identification of bird species. Furthermore, thermal cameras may be used to record a falling corpse from the RSA.
3. An ultrasonic detector (bat detector) to record bat echolocation and social calls and subsequently for the identification of individual bat species.
4. A bird sound recorder to record flight calls and subsequently for the identification of bird species.

LIDAR (no clear advantages over radar and less well developed), daylight cameras (not useful at night), near-infrared cameras (possibly change behaviour due to insect attraction because of the needed artificial lighting) and impact sensors (not able to assess barotrauma and most likely not able to assess collisions of bats and small birds as well) should not be part of the solution.

In general it is beneficial to use existing applications in order to minimize lead times and development costs. However, none of the applications taken into consideration (table 5.1) is able monitor offshore bat and bird fatalities without modifications. All available systems require adjustments and development time to meet the functional requirements.

Radars cannot be used stand-alone as they can only measure flux. All applications that use impact sensors as trigger mechanism (WT Bird, ID-Stat & WTSU) are not useful because barotrauma and collisions of bats and small birds cannot be detected. VARS uses near-infrared cameras, of which the lights attract insects and the increased availability of prey may cause biased (higher) fatality rates. ACAMS uses daylight cameras and can therefore not be used at night. ATOM is designed for assessing flux but its detection performance is rather low for birds (15 – 60%) and bats were never detected during field trials. DT Bird/bat is designed to avoid fatalities, by either triggering a deterrent or stopping the wind turbine, but not as an application to monitor fatalities.

MUSE seems to be a promising system as it is able to identify a potential relevant object by radar and subsequently pinpoints a camera on the object to record footage that can be used to assess fatalities and for the identification of bird species. However, MUSE is currently equipped with one radar and individual birds and bats will likely be missed when they approach the wind turbine from behind the tower, in particular when the radar is mounted on the turbine itself. Furthermore, one single camera will miss activity/fatalities behind the tower (but this may be solved by adding an additional camera to the system). In addition, multiple birds or bats may approach the turbine at the same time and the camera can follow only one at the time. Finally, it is not clear whether the system is able to track an individual in the RSA for a prolonged time as it will be frequently hidden by passing rotor blades. This is particularly important for bats as a foraging individual may become victim after some time, whereas most birds will become victim immediately when they pass through the RSA.

The B-finder lacks a lot of the required functionality and is in an early stage of its development. Nevertheless it seems a promising application as it is specifically designed to monitor fatalities. The main issue of this system is that the identification of species is not possible (unless fatality searches (onshore) are executed on the ground). This may be solved by adding thermal cameras to the system facing up in order to collect footage. In addition, a bat detector and a bird sound recorder should be added. The 'ring-cameras' around the tower will not detect all fatalities (small birds and bats are detected up to 50 m whereas bigger birds are detected up to 100 m). Because the system is able to estimate the fall location of the victim it should be possible to determine detection curves for different size classes (Buckland et al. 2001), and these can be used to assess the percentage of fatalities missed (per size class).

TSVA should -in theory- detect fatalities reliably as this application assesses the actual 3D flight paths. It does not need a radar to assess 'incoming' flying objects. However, the development stage of this application is a proof of concept, and it will take time to mature. In addition, it will be an expensive solution as multiple pairs of high-quality zoomed and non-zoomed stereo-cameras are needed to cover the entire RSA. A bat detector is already included in this solution, but a bird sound recorder needs to be added.

8 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. This certificate is valid until 15 December 2021. The organisation has been certified since 27 February 2001. The certification was issued by DNV GL.

References

Adams, A. M., Jantzen, M. K., Hamilton, R. M., & Fenton, M. B. (2012). Do you hear what I hear? Implications of detector selection for acoustic monitoring of bats. *Methods in Ecology and Evolution*, *3*(6), 992–998. https://doi.org/10.1111/j.2041-210X.2012.00244.x

Adams, E., Duron, M., & Goodale, W. (2017). *Stereo-Optic High Definition Imaging: A New Technology to Understand Bird and Bat Avoidance of Wind Turbines*. 1–79.

Ahlén, I., Baagøe, H. J., & Bach, L. (2009). Behavior of Scandinavian Bats during Migration and Foraging at Sea. *Journal of Mammalogy*, *90*(6), 1318–1323. https://doi.org/10.1644/09-mamm-s-223r.1

Arnett, E. B., & Baerwald, E. F. (2013). Impacts of wind energy development on bats: implications for conservation. In *Bat evolution, ecology, and conservation* (pp. 435–456). Springer.

Arnett, E. B., Brown, W. K., Erickson, W. P., Fiedler, J. K., Hamilton, B. L., Henry, TH, Jain A, Johnson GD, Kerns J, Koford R.R., Nicholson C.P., O'Connell T.J., Piorkowski M.D., Tankersley, R. D. (2008). Patterns of Bat Fatalities at Wind Energy Facilities in North America. *Journal of Wildlife Management*, *72*(1), 61–78. https://doi.org/10.2193/2007-221

Arnett, E. B., Baerwald, E. F., Mathews, F., Rodrigues, L., Rodríguez-Durán, A., Rydell, J., … Kingston, T. (2016). Bats in the anthropocene: Conservation of bats in a changing world. *Bats in the Anthropocene: Conservation of Bats in a Changing World*, 1–606. https://doi.org/10.1007/978-3-319-25220-9

Azmy, S. N., Sah, S. A. M., Shafie, N. J., Ariffin, A., Majid, Z., Ismail, M. N. A., & Shamsir, M. S. (2012). Counting in the dark: Non-intrusive laser scanning for population counting and identifying roosting bats. *Scientific Reports*, *2*(July). https://doi.org/10.1038/srep00524

Bach L. & Rahmel U. (2004). Summary of wind turbine impacts on bats—assessment of a conflict. Bremer Beiträge für Naturkunde und Naturschutz 7:245–252.

Bach, L. & Bach, P. (2009). Einfluss der Windgeschwindigkeit auf die Aktivität von Fledermäusen. *Nyctalus (NF) Band*, *14*(1–2), 3–13.

Bach, L., P. Bach, H. Pommeranz, R. Hill, C. Voigt, Ma. Göttsche, Mi. Göttsche, H. Matthes & Seebens-Hoyer, A. (2017). Bat migration in the German North Sea and Baltic Sea in autumn 2016. - Poster at EBRS 2017, Donostia, The Basque Country, 1.-5. August 2017.

Bach, L., P. Bach & R. Kesel (in press a): Akustisches Monitoring von Rauhautfledermaus an Windenergieanlagen: Ist ein zweites Ultraschallmikrofon am Turm notwendig? - In: Evidenzbasierter Fledermausschutz in Windkraftvorhaben (Hrsg. Voigt, C.C.).

Bach, P., L. Bach & R. Kesel (in press b): Aktivitätsverteilung und Schlagopfer der Rauhautfledermaus an WEA im nordwestdeutschen Küstenraum. In: Evidenzbasierter Fledermausschutz in Windkraftvorhaben (Hrsg. Voigt, C.C.).

Bach, L. (2019): Box 8.1 Scope for mitigating risk to bats at offshore wind farms. In: Perrow, M.R. (ed.): *Wildlife and Wind Farms, Conflicts and Solutions. Vol. 4 Offshore: Monitoring and Mitigation*. Publisher: Pelagic Publishing, Exeter, UK: 244-247

Baerwald, E. F., & Barclay, R. M. R. (2009). Geographic Variation in Activity and Fatality of Migratory Bats at Wind Energy Facilities. *Journal of Mammalogy*, *90*(6), 1341–1349. https://doi.org/10.1644/09-mamm-s-104r.1

Baerwald, E. F., Barclay, R. M. R. (2011) Patterns of activity and fatality of migratory bats at a wind energy facility in Alberta, Canada. *Journal of Wildlife Management 75*: 1103–1114

Baerwald, E. F., D'Amours, G. H., Klug, B. J., & Barclay, R. M. R. (2008). Barotrauma is a significant cause of bat fatalities at wind turbines. *Current Biology*, *18*(16), 695–696. https://doi.org/10.1016/j.cub.2008.06.029

Barataud, M. (2015). Acoustic ecology of European bats. Species Identification and Studies of Their Habitats and Foraging Behaviour. Biotope Editions, Mèze; National Museum of Natural History, Paris (collection Inventaires et biodiversité), 340 p.

Behr, O., Brinkmann, R., Hochradel, K., Mages, J., Korner-Nievergelt, F., Reinhard, H., … Nagy, M. (2018). Bestimmung des Kollisionsrisikos von Fledermäusen an Onshore-Windenergieanlagen in der Planungspraxis–Endbericht des Forschungsvorhabens gefördert durch das Bundesministerium für Wirtschaft und Energie (Förderkennzeichen 0327638E). *URL: Http://Windbat. Techfak. Fau. de/Abschlussbericht/Renebat-Iii. Pdf*.

Beier, K., & Gemperlein, H. (2004). Simulation of infrared detection range at fog condition for Enhanced Vision System in civil aviation. *Aerospace Science and Technology*, *8*(1), 63–71. https://doi.org/10.1016/j.ast.2003.09.002

Brabant, R., Laurent, Y. & Jonge Poerink, B. (2018). First ever detections of bats made by an acoustic recorder installed on the nacelle of offshore wind turbines in the North Sea. 2018 WinMon report 2018. Royal Belgian Institute of Natural Sciences, pp 129-132.

Brinkmann, R., Behr, O., Niermann, I. & Reich, M. (2011). Entwicklung von Methoden zur Untersuchung und Reduktion des Kollisionsrisikos von Fledermäusen an Onshore-Windenergieanlagen, *Volume 4 Umwelt und Raum*. Cuvillier Verlag, Göttingen.

Boshamer, J. P. C., & Bekker, J. P. (2008). Nathusius' pipistrelles (Pipistrellus nathusii) and other species of bats on offshore platforms in the Dutch sector of the North Sea. *Lutra*, *51*(1), 17–36.

Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Borchers, D.L. & Thomas, L. (2001)

Introduction to Distance Sampling. Oxford University Press, Oxford.

Chapman, J. W., Reynolds, D. R., Smith, A. D., Smith, E. T., & Woiwod, I. P. (2004). An aerial netting study of insects migrating at high altitude over England. *Bulletin of Entomological Research*, *94*(2), 123–136.

Chiu, C., & Moss, C. F. (2008). When echolocating bats do not echolocate. *Communicative & Integrative Biology*, *1*(2), 161–162. https://doi.org/10.4161/cib.1.2.7107

Collier, M. P., Dirksen, S., & Krijgsveld, K. L. (2012). A review of methods to monitor collisions or micro-avoidance of birds with offshore wind turbines - Part 2: Feasibility study of systems to monitor collisions. *Report Commissioned by The Crown Estate Strategic Ornithological Support Services*, 30 pp.

Cook, A. S. C. P., Ward, R. M., Hansen, W. S., & Larsen, L. (2018). Estimating Seabird Flight Height using LiDAR. *Scottish Marine and Freshwater Science*, *9*(14), 66. https://doi.org/10.7489/12131-1

Corcoran, A. J., & Weller, T. J. (2018). Inconspicuous echolocation in hoary bats (Lasiurus cinereus). *Proceedings of the Royal Society B: Biological Sciences*, *285*(1878). https://doi.org/10.1098/rspb.2018.0441

Crawford, R. L., & Baker, W. (1981). Bats Killed at a North Florida Television Tower: A 25-Year Record. *Journal of Mammalogy*, *62*(3), 651–652. https://doi.org/10.2307/1380421

Cryan, P. M., & Barclay, R. M. R. (2009). Causes of Bat Fatalities at Wind Turbines: Hypotheses and Predictions. *Journal of Mammalogy*, *90*(6), 1330–1340. https://doi.org/10.1644/09-mamm-s-076r1.1

Cryan PM, Gorresen PM, Hein CD, Schirmacher MR, Diehl RH, Huso MM, Behavior of bats at wind turbines. Proc Natl Acad Sci U S A. 2014 Oct;111(42) 15126-15131. doi:10.1073/pnas.1406672111.

Cryan, P. M., Gorresen, P. M., Hein, C. D., Schirmacher, M. R., Diehl, R. H., Huso, M. M., Hayman D.T, Fricker P.D, Bonaccorso F.J, Johnson D.H, Heist K, Dalton D. C. (2014). Behavior of bats at wind turbines. *Proceedings of the National Academy of Sciences of the United States of America*, *111*(42), 15126–15131. https://doi.org/10.1073/pnas.1406672111

Dalthorp, D., Madsen, L., Huso, M., Rabie, P., Wolpert, R., Studyvin, J., Simonis, J., and Mintz, J., (2018), GenEst statistical models—A generalized estimator of mortality: U.S. Geological Survey Techniques and Methods, book 7, chap. A2, 13 p., https://doi.org/10.3133/tm7A2.

Dakin, J. P., & Brown, R. (2017). *Handbook of Optoelectronics: Concepts, Devices, and Techniques (Volume One)*. CRC Press.

Delprat B. & Alcuri G. (2011) Innovative technology for assessing wildlife collisions with wind turbines. Conference on Wind energy and Wildlife impacts (CWW 2011), Trondheim, Norway, 5 May 2011. Norwegian Institute for Nature Research. Retrieved March 2020 from: https://cww2011.nina.no/Portals/CWW2011/Presentations/CWW%20Bertrand%20Delprat.pdf?ver=2012-08-01-195453-807

Deplazes L., Dietrich A., Frey-Ehrenbold A., Märki K., Bantadina F., (2015) Performance of the real-time bat detection system DTBat at the wind turbine of Calandawind, Switzerland, SWILD – Urban Ecology & Wildlife Research, Zürich

Dietz, C., Helversen, O. v., & Nill, D. (2007). *Handbuch der Fledermäuse Europas und Nordwestafrikas. Biologie, Kennzeichen, Gefährdung*. Stuttgart: Franckh-Kosmos.

Dirksen, S. (2017). Review of methods and techniques for field validation of collision rates and avoidance amongst birds and bats at offshore wind turbines. *Sjoerd Dirksen Ecology Report Number SjDE 17-01*, 47.

Drake, V., & Reynolds, D. (2012). *Radar Entomology: observing insect flight and migration*. Cabi, Wallingford, UK.

Dürr, T., & Bach, L. (2004). Bat deaths and wind turbines–a review of current knowledge, and of the information available in the database for Germany. *Bremer Beiträge Für Naturkunde Und Naturschutz*, *7*, 253–264.

Dürr, T. (2013). Fledermausverluste an Windenergieanlagen. Daten aus der zentralen Fundkartei der Staatlichen Vogelschutzwarte im Landesumweltamt Brandenburg. Stand 25.09..2013. www.mluv.brandenburg.de/cms/ media.php /.../wka_fmaus.xls.

Farnsworth, A., & Russell, R. W. (2007). Monitoring flight calls of migrating birds from an oil platform in the northern Gulf of Mexico. *Journal of Field Ornithology*, *78*(3), 279–289. https://doi.org/10.1111/j.1557-9263.2007.00115.x

Flowers, J., & Suryan, R. M. (2014). Design and Initial Component Tests of an Integrated Avian and Bat Collision Detection System for Offshore Wind Turbines. *Proceding of the 2nd Marine Energy Technology Symposium*, (April), 1–10. Retrieved from http://mhk.pnl.gov/publications/design-and-initial-component-tests-integrated-avian-and-bat-collision-detection-system

Grodsky S.M, Behr M.J, Gendler A, Drake D, Dieterle B.D, Rudd R.J, Walrath N.L. Investigating the causes of death for wind turbine-associated bat fatalities. Journal of Mammalogy. 2011;92:917–925. doi: 10.1644/10-MAMM-A-404.1

Hadj-Bachir, M., & De Souza, P. (2019). LIDAR sensor simulation in adverse weather condition for driving assistance development. *HAL Archives - Ouvertes*, (August). Retrieved from https://hal.archives-ouvertes.fr/hal-01998668

Hatch, S.K., Connelly E.E., Divoll T.J., Stenhouse I.J. & Williams K.A. (2013). Offshore observations of Eastern red bats (Lasiurus borealis) in the Mid-Atlantic United States using multiple survey methods. PLoSOne 8 (12): e83803.

Hein, C. D., & Schirmacher, M. R. (2016). Impact of wind energy on bats: A summary of our current knowledge. *Human-Wildlife Interactions*, *10*(1), 19–27. https://doi.org/10.26077/x7ew-6349

Hein, C., Gruver, J., & Arnett, E. (2013). *Relating Pre-construction Bat Activity and Post-construction Bat Fatality to Predict Risk at Wind Energy Facilities: A Synthesis*. https://doi.org/10.13140/RG.2.1.2884.7765

Hill, R. & Hüppop, O. (2011) Zugrufe über der Nordsee – welche Erkenntnisse lassen sich aus einer automatisierten Erfassung gewinnen? Vogelwarte 49: 318–319.

Hill, R., Hill, K., Aumüller, R., Schulz, A., Dittman, T., Kulemeyer, C. & Coppack, T. (2014) Of birds, blades and barriers: detecting and analysing mass migration events at Alpha Ventus. In *BSH & BMU (eds) Ecological Research at the Offshore Windfarm Alpha Ventus: Challenges, results and perspectives.* Wiesbaden: Springer Spektrum. pp. 111–131.

Horton, K. G., Shriver, W. G., & Buler, J. J. (2015). A comparison of traffic estimates of nocturnal flying animals using radar, thermal imaging, and acoustic recording. *Ecological Applications*, *25*(2), 390–401. https://doi.org/10.1890/14-0279.1.sm

Hu, C., Albertani, R., & Suryan, R. M. (2018). Wind turbine sensor array for monitoring avian and bat collisions. *Wind Energy*, *21*(4), 255–263. https://doi.org/10.1002/we.2160

Huso, M.M.P. (2010). An Estimator of Wildlife Fatality from Observed Carcasses. Environmetrics. Wiley Blackwell. DOI:10.1002/env.1052

Huso, M., N. Som, and L. Ladd. (2012). Fatality estimator user’s guide: U.S. Geological Survey Data Series 729, 22 p.

Hüppop, O., & Hill, R. (2016). *Migration phenology and behaviour of bats at a research platform in the south-eastern North Sea Climate change and bird migration phenology View project Bat migration View project*. *59*, 5–22. Retrieved from https://www.researchgate.net/publication/313239319

Hüppop, O., B. Michalik, L. Bach, R. Hill, S. Pelletier (2019): Chapter 7: Migratory birds and bats. In: Perrow, M.R. (ed.): Wildlife and Wind Farms, Conflicts and Solutions. Volume3: Offshore: Potential Effects. Publisher: Pelagic Publishing, Exeter, UK: 142-173

Johnson, G. D. (2005). A review of bat mortality at wind-energy developments in the United States. *Bat Research News*, *46*(2), 45–49.

Jones, G., Cooper-Bohannon, R., Barlow, K. & Parsons, K. (2009). Determining the potential ecological impact of wind turbines on bat populations in Britain. Scoping and Method Development Report, Defra

Jonge Poerink, B., Lagerveld, S., & Verdaat, H. (2013). *Pilot study: Bat activity in the dutch offshore wind farm OWEZ and PAWP*. (20120402), 2–22.

Korner-Nievergelt, F., Brinkmann, R., Niermann, I., & Behr, O. (2013). Estimating bat and bird mortality occurring at wind energy turbines from covariates and carcass searches using mixture models. *PloS One*, *8*(7).

Kunz, T. H., Arnett, E. B., Erickson, W. P., Hoar, A. R., Johnson, G. D., Larkin, R. P., Strickland, M.D., Thresher, R.W., Tuttle, M.D. (2007). Ecological impacts of wind energy development on bats: Questions, research needs, and hypotheses. *Frontiers in Ecology and the Environment*, *5*(6), 315–324. https://doi.org/10.1890/1540-9295(2007)5[315:EIOWED]2.0.CO;2

Lagerveld, S., Poerink, B. J., Haselager, R., & Verdaat, H. (2014). Bats in Dutch offshore wind farms in autumn 2012. *Lutra*, *57*(2), 61–69.

Lagerveld, S., Jonge Poerink B., Vries P. de (2015). Monitoring bat activity at the Dutch EEZ in 2014. Den Helder, IMARES, (Report / IMARES Wageningen UR C094/15).

Lagerveld, S., Kooistra, G., Otten, G., Meesters, L., Manshanden, J., De Haan, D., Gerla. D., Verhoef, H.,Scholl, M. (2017A). *Bat flight analysis around wind turbines – a feasibility study*. 43. Retrieved from http://library.wur.nl/WebQuery/wurpubs/fulltext/417091

Lagerveld, S., Gerla, D., van der Wal J.T., de Vries P., Brabant R., Stienen E., Deneudt K., Manshanden J. & Scholl, M. (2017B). Spatial and temporal occurrence of bats in the southern North Sea area. Wageningen Marine Research (University & Research centre), Wageningen Marine Research report C090/17; 52 p.

Lagerveld, S., van der Wal, J. T., Vries, V., Verdaat, H., Sonneveld, C., van der Meer, J., Brabant, R. & Noort, B., (2019). Bats at the southern North Sea in 2017 & 2018. Den Helder: Wageningen Marine Research. 36 p. (Wageningen Marine Research report ; C062/19)

Lefsky, M. A., Cohen, W. B., Harding, D. J., Parker, G. G., Acker, S. A., & Gower, S. T. (2002). Lidar remote sensing of above-ground biomass in three biomes. *Global Ecology and Biogeography*, *11*(5), 393–399. https://doi.org/10.1046/j.1466-822x.2002.00303.x

Lehnert, L S., Kramer-Schadt, S., Schönborn, S., Lindecke, O., Niermann, I. & Voigt, C. C. (2014). Windfarm facilities in Germany kill Noctule bats from near and far. PLoS ONE 9(8): e103106. doi:10.1371/journal.pone.0103106.

Leopold M.F., M. Boonman, M.P. Collier, N. Davaasuren, R.C. Fijn, A. Gyimesi, J. de Jong R.H. Jongbloed, B. Jonge Poerink, J.C. Kleyheeg-Hartman, K.L. Krijgsveld, S. Lagerveld, R. Lensink, M.J.M. Poot, J.T. van der Wal & M. Scholl 2014. A first approach to deal with cumulative effects on birds and bats of offshore wind farms and other human activities in the Southern North Sea. IMARES Report C166/14.

Limpens, H.J.G.A., M. Boonman, F. KornerNievergelt, E.A. Jansen, M. van der Valk, M.J.J. La Haye, S. Dirksen & S.J. Vreugdenhil, 2013. Wind turbines and bats in the Netherlands - Measuring and predicting. Report 2013.12, Zoogdiervereniging & Bureau Waardenburg

Lundin, P., Samuelsson, P., Svanberg, S., Runemark, A., Åkesson, S., & Brydegaard, M. (2011). Remote nocturnal bird classification by spectroscopy in extended wavelength ranges. *Applied Optics*, *50*(20), 3396–3411. https://doi.org/10.1364/AO.50.003396

Malmqvist, E., Jansson, S., Zhu, S., Li, W., Svanberg, K., Svanberg, S., Rydell, R., Song, Z., Bood, J., Brydegaard, M., Åkesson, S. (2018). The bat–bird–bug battle: Daily flight activity of insects and their predators over a rice field revealed by high-resolution scheimpflug lidar. *Royal Society Open Science*, *5*(4). https://doi.org/10.1098/rsos.172303

Mangold, K., Shaw, J. A., & Vollmer, M. (2013). The physics of near-infrared photography. *European Journal of Physics*, *34*(6), 51–71. https://doi.org/10.1088/0143-0807/34/6/S51

Mathews, F., Richardson, S., Lintott, P., & Hosken, D. (2016). *Understanding the risk to european protected species (Bats) at onshore wind turbine sites to inform risk management*. 127.

Matzner, S., Cullinan, V. I., & Duberstein, C. A. (2015). Two-dimensional thermal video analysis of offshore bird and bat flight. *Ecological Informatics*, *30*, 20–28. https://doi.org/10.1016/j.ecoinf.2015.09.001

May, R., Steinheim, Y., Kvaløy, P., Vang, R., & Hanssen, F. (2017). Performance test and verification of an off-the-shelf automated avian radar tracking system. *Ecology and Evolution*, *7*(15), 5930–5938. https://doi.org/10.1002/ece3.3162

Mollis, M., Hill, R., Hüppop, O., Bach, L., Coppack, T., Pelletier, S., … Schulz, A. (2019). Measuring bird and bat collision and avoidance. *Wildlife and Wind Farms - Conflicts and Solutions. Offshore: Monitoring and Mitigation*, (2), 165–206.

Osadchyi, V. V, Yeremeev, V. S., & Matsyura, A. V. (2016). Mathematical Model Of Bird Species Identifying: Implication Of Radar Data Processing. *Ukrainian Journal of Ecology*, *6*(3), 463–471. https://doi.org/10.15421/2016119

Perón, G., Hines, J. E., Nichols, J. D., Kendall, W. L., Peters, K. A., & Mizrahi, D. S. (2013). Estimation of bird and bat mortality at wind-power farms with superpopulation models. *Journal of Applied Ecology*, 902–911.

Prost, G. L. (2013). *Remote sensing for geoscientists: image analysis and integration*. CRC Press.

Przybycin, P., Przybycin, M., Przybycin, J., Makowski, M. (2019) B-finder system: 24 month test report for t-series.

Rai, M., Maity, T., & Yadav, R. K. (2018). Thermal imaging system and its real time applications: a survey. *Article in Journal of Engineering Technology*, *6*(2), 290–303. Retrieved from https://www.researchgate.net/publication/325685880

Robinson Willmott, J., Forcey, G. M., & Hooton, L. A. (2015). Developing an automated risk management tool to minimize bird and bat mortality at wind facilities. *Ambio*, *44*(4), 557–571. https://doi.org/10.1007/s13280-015-0707-z

Rodrigues, L., Bach, L., Dubourg-Savage, M.-J., Karapandža, B., Kovač, D., Kervyn, T., … Collins, J. (2015). *Guidelines for consideration of bats in wind farm projects: Revision 2014*. UNEP/EUROBATS.

Ronconi, R. A., Allard, K. A., & Taylor, P. D. (2015). Bird interactions with offshore oil and gas platforms: Review of impacts and monitoring techniques. *Journal of Environmental Management*, *147*, 34–45. https://doi.org/10.1016/j.jenvman.2014.07.031

Ryde, J., & Hillier, N. (2009). Performance of laser and radar ranging devices in adverse environmental conditions. *Journal of Field Robotics*, *26*(9), 712–727. https://doi.org/10.1002/rob.20310

Rydell, J., Bach, L., Dubourg-Savage, M.-J., Green, M., Rodrigues, L., & Hedenström, A. (2010a). Bat Mortality at Wind Turbines in Northwestern Europe. *Acta Chiropterologica*, *12*(2), 261–274. https://doi.org/10.3161/150811010x537846

Rydell, J., Bach, L., Dubourg-Savage, M. J., Green, M., Rodrigues, L., & Hedenström, A. (2010b). Mortality of bats at wind turbines links to nocturnal insect migration? *European Journal of Wildlife Research*, *56*(6), 823–827. https://doi.org/10.1007/s10344-010-0444-3

Rydell, J., Engström, H., Hedenström, A., Larsen, J. K., Petterson, J., Green, M. (2012). *The effect of wind power on birds and bats power - a synthesis*. Retrieved from http://mhk.pnl.gov/publications/effect-wind-power-birds-and-bats-synthesis

Rydell, J., Bogdanowicz, W., Boonman, A., Pettersson, S., Suchecka, E., & Pomorski, J. J. (2016). Bats may eat diurnal flies that rest on wind turbines. *Mammalian Biology*, *81*(3), 331–339. https://doi.org/10.1016/j.mambio.2016.01.005

Schmaljohann, H., Liechti, F., Bächler, E., Steuri, T., & Bruderer, B. (2008). Quantification of bird migration by radar - A detection probability problem. *Ibis*, *150*(2), 342–355. https://doi.org/10.1111/j.1474-919X.2007.00797.x

S. E. R. (2013). Economic Council of the Netherlands (2013): Summary of Energy Agreement for Sustainable Growth. Energieakkoord Voor Duurzame Groei), 6.

Shoenfeld, P. S. (2004). Suggestions Regarding Avian Mortality Extrapolation. Prepared for the Mountaineer Wind Energy Center Technical Review Committee.

Snoek, R. (2016). Technisch overzicht radarsystemen offshore windparken (p. 60). p. 60.

Stepanian, Stepanian, P. M., Horton, K. G., Melnikov, V. M., Zrnić, D. S., & Gauthreaux, S. A. (2016). Dual-polarization radar products for biological applications. Ecosphere, 7(11). https://doi.org/10.1002/ecs2.1539

Thaxter, C. B., Buchanan, G. M., Carr, J., Butchart, S. H. M., Newbold, T., Green, R. E., … Pearce-Higgins, J. W. (2017). Bird and bat species' global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. *Proceedings of the Royal Society B: Biological Sciences*, *284*(1862). https://doi.org/10.1098/rspb.2017.0829

Van Gelder, R. G. (1956). Echo-location failure in migratory bats. *Transactions of the Kansas Academy of Science (1903-)*, *59*(2), 220–222.

Voigt, C., Rehnig, C., Lindecke, O., Petersons, G.,(2018), Migratory bats are attracted by red light but not by warm-white light: Implications for the protection of nocturnal migrants

Wiggelinkhuizen, E.J., Rademakers, L.W.M.M., Barhorst, S.A.M, den Boon, H.J. (2006). Bird collision monitoring system for multi megawatt wind turbines WT-Bird; Summary of prototype development and testing.

Wiggelinkhuizen, E.J. & den Boon, H.J. (2010) Moni- toring of bird collisions in wind farm under offshore-like conditions using WT-BIRD system Final report. Research Report No. 09-033. Petten: Energy Research Centre of the Netherlands. Retrieved 26 March 2019 from https://publica- ties.ecn.nl/PdfFetch.aspx?nr=ECN-E--09-033

Willmott, Julia & Forcey, Greg & Hooton, Lauren. (2015). Developing an automated risk management tool to minimize bird and bat mortality at wind facilities. Ambio. 44. 557-571. 10.1007/s13280-015-0707-z.

Wolpert, R. (2013). Appendix B: A partially periodic equation for estimating avian mortality rates. Pages B1–B3 in W. Warren-Hicks, editor. Improving methods for estimating fatality of birds and bats at wind energy facilities. California Wind Energy Association, Berkeley, California, USA

Zuur, A. F., & Ieno, E. N. (2016). A protocol for conducting and presenting results of regression-type analyses. Methods in Ecology and Evolution, 7(6), 636–645.

Zaugg, S., Saporta, G., van Loon, E., Schmaljohann, H., & Liechti, F. (2008). Automatic identification of bird targets with radar via patterns produced by wing flapping. Journal of the Royal Society Interface, 5(26), 1041- 1053. https://doi.org/10.1098/rsif.2007.1349

Justification

Report C025/20
Project Number: 4315100106

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved: Dr. Ir. M.J. Baptist
Senior Researcher

Signature:

Date: 10 april 2020

Approved: Drs. J. Asjes
Manager

Signature:

Date: 10 april 2020

Wageningen Marine Research
T +31 (0)317 48 09 00
E: marine-research@wur.nl
www.wur.eu/marine-research

Visitors’ address
- Ankerpark 27 1781 AG Den Helder
- Korringaweg 7, 4401 NT Yerseke
- Haringkade 1, 1976 CP IJmuiden

With knowledge, independent scientific research and advice, **Wageningen Marine Research** substantially contributes to more sustainable and more careful management, use and protection of natural riches in marine, coastal and freshwater areas.

Wageningen Marine Research is part of Wageningen University & Research. Wageningen University & Research is the collaboration between Wageningen University and the Wageningen Research Foundation and its mission is: 'To explore the potential for improving the quality of life'