OFFSHORE RENEWABLES JOINT INDUSTRY PROGRAMME (ORJIP) FOR OFFSHORE WIND

Review of seabird monitoring technologies for offshore wind farms

May 2022

working to accelerate offshore consenting

INTRODUCTION

ORJIP Offshore Wind

The Offshore Renewables Joint Industry Programme (ORJIP) for Offshore Wind is a collaborative initiative that aims to:

- Fund research to improve our understanding of the effects of offshore wind on the marine environment
- Reduce the risk of not getting, or delaying consent for, offshore wind developments
- Reduce the risk of getting consent with conditions that reduce viability of the project.

The programme pools resources from the private sector and public sector bodies to fund projects that provide empirical data to support consenting authorities in evaluating the environmental risk of offshore wind. Projects are prioritised and informed by the ORJIP Advisory Network which includes key stakeholders, including statutory nature conservation bodies, academics, non-governmental organisations and others.

The current stage is a collaboration between The Carbon Trust, EDF Energy Renewables Limited, Ocean Winds UK Limited, Equinor ASA, Ørsted Wind Power A/S, Red Rock Power Limited, RWE Renewables GmbH, Shell Global Solutions International B.V, SSE Renewables Developments UK Limited, TotalEnergies E&P UK Limited, Crown Estate Scotland, The Scottish Ministers (acting through Marine Scotland) and The Crown Estate Commissioners.

For further information regarding the ORJIP Offshore Wind programme, please refer to the Carbon Trust website, or contact Ivan Savitsky (ivan.savitsky@carbontrust.com) and Oliver Patrick (oliver.patrick@carbontrust.com).

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RPS is a leading global professional services firm, that specialises in six sectors: property, energy, transport, water, resources, defence and government. RPS define, design and manage projects that create shared value by solving problems that matter and making them easy to understand.

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- BioSS
- Joint Nature Conservation Committee (JNCC)
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- Royal Society for the Protection of Birds (RSPB)
- UK Centre for Ecology & Hydrology.

This report was sponsored by the ORJIP Offshore Wind programme. For the avoidance of doubt, this report expresses independent views of the authors.

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Contents

Tables

Figures

Glossary

Term	Meaning
Bird flux rate	Total number of birds crossing an imaginary surface within the airspace expressed as birds / sec or birds / s per m2. The bird flux rate is usually directly estimated from bird density in baseline studies, but also depends on the speed of the bird flights (if birds were stationary, there is no flux).
Empirical avoidance rate	Avoidance rates derived from data collected from monitoring studies. The overall empirical avoidance rate is calculated by combining an empirical macro avoidance rate, an empirical meso avoidance rate, and an empirical micro avoidance rate. The overall avoidance rate would be used within the Band collision risk model.
Empirical collision rate	Collision rate or estimates derived from observations of the occurrence of actual collisions from monitoring studies.
Macro avoidance	Bird behavioural responses to the presence of the wind farm occurring beyond its perimeter, resulting in a redistribution of birds inside and outside the wind farm. Could also be expressed as a barrier to movement.
Meso avoidance	Bird behavioural response within the wind farm to individual turbines, but outside the 'micro-zone' (e.g., within 10 m of the rotor swept zone), resulting in a redistribution of the birds within the wind farm footprint from what would occur in the absence of turbines. May also include responses resulting in a change of flight height above or below the rotor swept zone.
Micro avoidance	Bird behavioural response within or very close to (e.g., within 10 m) the rotor swept zone, considered as the bird's 'last-second action', taken to avoid collision.
Moon watching	Nocturnal migration can be recorded as bird silhouettes passing the moon. These are visible from a telescope when the moon is at its brightest, four days before and four days after the full moon; Krijgsveld et al., 2005.
Nutating	Nodding, swaying motion.

Abbreviations

ACAMs	Aerofauna Collision Avoidance Monitoring System
AROMA	Acoustic Recording of Migrating Aves
ATOM	Acoustic Thermographic Offshore Monitoring
AW	Analyst Workbench
BLE	Bluetooth Low Energy
BPS	Bird Protection System
CDS	Collision Detection System
CFAR	Constant False-Alarm Rate
CRM	Collision Risk Modelling
DAP	Data Analysis Platform
DAPS	Data Acquisition and Pre-processing System
DP	Discretionary Project
DPC	Detection Probability Curve
EESC	German Exclusive Economic Zone
FFT	Fast Fourier Transform
FOV	Field of View
FPGA	Field Programmable Gate Array
GIS	Geographical Information Systems
GLM	Generalised Linear Model
GPS	Global Positioning System
HRSC	High Resolution Stereo Camera

IMU	Inertial Measurement Unit
JNCC	Joint Nature Conservation Committee
MAP	Main Access Platform
MCP	Minimum Convex Polygons
MTR	Mean Traffic Rates
MUSE	MUlti SEnsor
ORJIP	ORJIP Offshore Wind
RSZ	Rotor-Swept Zone
SaaS	Software-as-a-Service
SCADA	Supervisory Control And Data Acquisition
TADS	Thermal Animal Detection Systems
VARS	Visual Automated Recording System
VPN	Virtual Private Network
WFOV	Wide Field of View
WP	Work Packages

Units

Unit	Description
km	Kilometres
m	Metres
cm	Centimetres

mm	Millimetres
%	Percentage
km2	Kilometres Squared
km/h	Kilometres per hour
Bft	Beaufort Scale
°	Degrees
m/s	Metres per second
g	Grams
MHz	Megahertz
Hz	Hertz
SD	Standard Deviation
lumens/m2	Illuminance level
Mbps	Megabits per second

Executive summary

This ORJIP study has been carried out in order to provide information on current and planned monitoring technologies/systems that allow for collision and avoidance behaviour within the vicinity of turbines to be recorded. Data on seabirds and how they react to the presence of a wind farm is required to help address evidence gaps around empirical collision rates and reduce consenting risks for the offshore wind industry.

Within our review we looked at monitoring devices currently deployed at offshore wind farms globally, but also reviewed devices installed at onshore wind farms which have the potential to be deployed offshore following modifications. Our review involved a literature search while also holding interviews with eight different suppliers and wind farm developers utilising monitoring technology/systems, obtaining more information than available in published literature. Including planned monitoring technology/systems, 25 monitoring devices were reviewed (three additional systems were reviewed during report updates and added within Appendix 4). Monitoring technology can be radar, cameras and acoustic, with combined systems (combination of cameras, radar and acoustic) also existing.

Information on each technology/system has been provided under six different subheadings:

- **System design**: Information relating to the objective of the monitoring system (what was/is it aiming to monitor); scale of deployment if it has been deployed offshore or onshore, and details on how the system worked such as calibration or validation.
- **System functioning**: Information relating to the spatial coverage - monitoring capacity relative to turbine structure(s) and beyond of the technology/system, its temporal coverage and what parts of the structure were visibly monitored beyond the turbine blades/rotor swept area, if it can monitor collisions, its species identification capability and the amount of false negative and false positive rates.
- **Hosting/logistical requirements**: Information relating to the type and format of data recorded/stored and retrieved, the equipment and turbine requirements for hosting the technology/system and the logistical requirements – e.g., power, communications, maintenance frequency.
- **Data collection**: Information relating to the rate of bird movement – e.g., flux/ density, data on bird flight reactive behaviour and bird flight parameters – e.g., height, speed, direction.
- **Data processing and data analysis**: Information on data extraction and format, the processing methods, automation and analytical approaches applied to the data, if the system can derive empirical collision rate estimates, CRM parameters (e.g., flight heights and flight speed etc.), if the system can obtain data on within-wind farm avoidance rates, Macro-avoidance rates, if the technology/system can categorise bird flight behaviour preceding collision/avoidance, if the technology/system can obtain data to allow estimation of flux rates through individual turbines and/or wind farm, and if any additional analyses can be envisaged for the processed data.
- **Recommendations**: The final subheading aims to put forth any recommendations that could be undertaken to improve the technology/system to allow for more data to be recorded.

From this review, it was revealed that no one system can monitor all seabird behaviours (macro, meso and micro) as well as collisions. Additionally, from reviewing monitoring campaigns at offshore wind farms to date, no current study is being undertaken with the sole purpose to utilise monitoring technology/systems to obtain empirical collision rates, with majority of monitoring campaigns focusing on avoidance behaviour.

The contents of this document will be used to help inform a power analysis and will be used to help outline a scope of works for a future development project at an offshore wind farm. This report forms part two out of four work packages.

1. Introduction

The Paris Agreement, adopted at COP 21 in Paris in 2015, binds the majority of global governments into a treaty to limit global warming to well below 2°C, ideally 1.5°C above pre-industrial levels. To achieve this goal, Parties to the agreement aim to reach global peaking of greenhouse gas emissions as soon as possible and reach a state of neutrality ("net zero") by the middle of the century. As a result, there is a global drive towards decarbonisation of the energy sector in the growing fight against climate change.

The European Green Deal strives to place Europe as the first continent to reach net zero emissions by 2050, targeting at least 55% reduction by 2030 compared with 1990 levels. In the UK, the 2019 Climate Change Act commits the UK to net zero by 2050; while England, Wales and Northern Ireland are committed to net zero by 2050, Scotland has pledged to reach net zero by 2045. The UK government announced the Offshore Wind Sector Deal in 2019, which seeks to achieve 30GW of generating capacity by 2030, with the target updated to 40GW in 2020. Offshore renewable energy technology will therefore play a prominent role in helping the UK Governments decarbonise the energy sector by 2050, with future energy scenarios predicting between 70 – 113GW installed by 2050.

While offshore wind farms can provide many positive benefits (e.g., securing reliable and affordable energy supplies, helping tackle climate change and potentially yielding biodiversity dividends (Inger et al., 2009)), they also have the potential to adversely impact the marine environment. Despite the aspiration of the offshore wind industry to mitigate any deleterious impacts, we still have a poor grasp of how the construction and operation of such developments will impact biodiversity (Green et al., 2016; O'Brien et al., 2021). Therefore, more applied research is required by the offshore wind sector and stakeholders to ensure expansion of the industry without compromising the integrity of the natural environment. By improving our understanding, it will enable the UK, European and global Governments to make informed decisions based on the best available evidence, reducing the risk to the consenting process for offshore wind developments.

The Offshore Renewables Joint Industry Programme ("ORJIP") for Offshore Wind is a collaborative R&D programme between The Carbon Trust, EDF Energy Renewables Limited, Ocean Winds UK Limited, Equinor ASA, Ørsted Wind Power A/S, Red Rock Power Limited, RWE Renewables GmbH, Shell Global Solutions International B.V, SSE Renewables Developments UK Limited, TotalEnergies E&P UK Limited, Crown Estate Scotland, The Scottish Ministers and The Crown Estate Commissioners (the latter 12 collectively referred to in this document as "ORJIP Offshore Wind Partners").

The objective of ORJIP Offshore Wind is to improve the evidence base, in respect of the overall impact that offshore wind projects have on the marine environment. Plus, other uses of marine areas, better informing consenting authorities, offshore wind farm developers and other relevant stakeholders on the environmental risk associated with planned and existing offshore wind projects.

To achieve this objective, ORJIP Offshore Wind provides a framework to identify, develop, initiate and conduct impactful, relevant and strategic research and development projects aimed at reducing consenting risk, project maturation time, cost, and the environmental impact of offshore wind projects. Research is undertaken under areas chosen as priority focus areas for ORJIP Offshore Wind each year of the programme.

1.1. The ORJIP SBMon Project

Seabirds represent a key consenting risk for offshore wind farms for a number of reasons. First, turbines and wind farms may have non-lethal effects such as displacement and barrier effects, or lethal effects via collision (Thaxter et al., 2018, O'Brien et al., 2021). Second, the UK supports internationally important communities of breeding and non-breeding species which are not only subject to legal protection but are also flagship species in some instances (Lescroel et al., 2016). Finally, many seabird populations are undergoing steep declines, not only in European waters, but also across the globe (Croxall et al., 2012) due to pressures from a series of threats. A global assessment on the threats to seabirds highlighted the top three threats to all 359 seabird species worldwide were invasive alien species (45.96%), bycatch (27.86%) and climate change/severe weather (26.74%) (Dias et al., 2019). It is important therefore that additional pressures from emerging threats, such as offshore wind energy development, do not place them under further severe strain (Furness et al., 2013; Dias et al., 2019).

Uncertainty around cumulative impacts on seabirds from existing and consented offshore wind developments, and how to assess in-combination impacts from future proposals is recognised as a significant risk to offshore wind expansion (e.g., Black et al. 2019, Gibson et al. 2017). For several species of seabird that interact with offshore wind farms around the UK, collision with moving turbine blades is thought to be an important impact pathway. Some species are particularly vulnerable to collision mortality due to their flight behaviour (e.g., foraging patterns, flight speed, manoeuvrability and altitude; Furness et al., 2013), though quantifying these rates is challenging (Spiegel et al., 2017).

To quantify risk during the assessment process, collision risk models (CRM) are used to make predictions regarding the magnitude of impact to seabird populations that utilise any proposed site (Masden and Cook, 2016). Collision risk models rely on the parameterisation of key inputs such as species-specific avoidance rates, nocturnal activity, flight heights and flight speed. However, these models do have a layer of precaution built in due to the lack of robust empirical data on these parameters in the context of the offshore environment (Green et al., 2016; Ornithology Specialist Receptor Group, 2018). Given the uncertainty in these parameters, it is not known the extent to which assessments of adverse impacts may be over-precautionary, but there is a risk that adverse impacts are overestimated. This uncertainty therefore can restrict the development of offshore wind installations. Additionally, although understanding the adverse effects from an individual wind farm towards seabird populations is important, the cumulative adverse effects from multiple wind farms are of particular concern due to the uncertainty around cumulative impacts, and how to assess in-combination impacts from future developments. The better the understanding of seabird behaviour through strategic wind farm monitoring campaigns (to date, no actual collision rates are known for offshore wind farms; Kleyheeg-Hartman et al., 2018), the more accurate prediction models can be, with our ability to accurately assess likely collision levels from future proposals improving.

As the number of offshore wind projects in UK waters increase, with the Round 4 and ScotWind 1 leasing rounds in-progress, with the upcoming INTOG leasing round, Celtic Sea floating wind and future ScotWind 2 round, it is pivotal that evidence on the behaviour of seabirds in the vicinity of offshore turbines is obtained. Several strategic research projects are currently underway with the aim of addressing the known knowledge gaps surrounding bird behaviour near and within offshore wind farms.

ORJIP Offshore Wind (OSW) launched its second stage in July 2019 with the objective of identifying, prioritising and selecting research to reduce consenting risk for offshore wind. As part of the project identification process, a 'call for project ideas' was issued to the ORJIP OSW Advisory Network in November 2019 with submissions being discussed at the ORJIP Forum in December 2019.

As part of this process, the need for further strategic monitoring of seabird behaviour within operational wind farms was identified as a key research topic. Subsequently, the ORJIP OSW Steering Group selected this initial piece of work to determine the extent of any future Discretionary Project (DP) to conduct seabird monitoring at an operational wind farm(s).

There are various technologies and systems (combination of different technologies e.g., camera and radar system) which exist that can collect behavioural information needed for collision risk models and/or the detection of seabird collisions and flight behaviour. However, it is recognised that each of these have their own inherent limitations. As a result, there is a need for a full monitoring campaign which combines the best available technology to record reactive behaviour, helping to reduce uncertainty in future collision estimates and ensuring data collection is consistent across sites. Collecting accurate and standardised data across multiple offshore wind farms is critical if cumulative impacts are to be assessed.

RPS, in partnership with APEM and Heriot-Watt University (together, 'the Project Team'), have been commissioned by The Carbon Trust to carry out this review, known as "SBMon". The project reviewed completed, operational and planned monitoring studies and emerging monitoring technologies to assess the capacity of their (actual, planned or likely) outputs to: a) inform empirical collision estimates; and b) quantify reactive (and other relevant) behaviours for seabirds within offshore wind farms. The measurement of observed (empirical) collision rates can provide information of the actual scale of risk from offshore wind farms and improve our understanding of the wind farm and wind turbine characteristics and bird ecology that influence the risk. Power calculations were used to quantify uncertainty in estimates of actual collision rates and behavioural parameters associated with a range of different monitoring study designs and sample sizes. The results of this work will inform the scope of a future Discretionary Project in line with the Project Expert Panel's (PEP) and ORJIP Steering Groups expectations.

1.2. Work packages

The SBMon project consists of four Work Packages (WP), with information gathered during each WP used to feed into the WP that follows. These four WPs and their respective goals are:

WP1 Kick Off Workshop: Organisation of a workshop with the PEP and ORJIP Steering Group to discuss project aims and objectives. It aims to ensure the Project Team fully understands the intentions for this project and how it can inform the understanding of seabird collision risk and reactive behaviour from current and future offshore wind farms. WP1 was completed in July 2021.

WP2 Review: Review of completed, operational and planned monitoring studies for both fixed and floating offshore wind farms or turbines, including a review of emerging technologies. Understand what information is feasible to collect, and how this information can/should be used to assess the ability of outputs to inform empirical collision estimates and quantify reactive behaviours to support the development/ improvement of collision risk models. WP2 is scheduled for completion by April 2022.

WP3 Power Calculation: Quantify the levels of uncertainty in key quantities of interest (including empirical collision rates and any other key biological parameters that emerge from the review in WP2) that could realistically be achieved by a monitoring study, using different monitoring technologies, wind farm characteristics (e.g., different bird densities and turbine densities) and lengths of monitoring study. The objective of doing this would be to see which technologies lead to the greatest information gain (e.g., lowest levels of uncertainty) regarding collision risk, and to identify the length and design of monitoring study that is likely to be needed to reduce the level of uncertainty to an acceptably low level. WP3 is scheduled for completion by February 2022.

WP4 Project Scoping: Following recommendations from WP2 and WP3, inform a scope of work for a seabird monitoring study within an operational wind farm(s) with recommendations from the PEP and ORJIP Steering Group that will support the creation of an ORJIP Offshore Wind Discretionary Project to deliver this scope. WP4 is scheduled for completion by April 2022.

This report was prepared to meet the goal of WP2: Review of completed, operational and planned monitoring studies for both fixed and floating offshore wind farms or turbines, including a review of emerging technologies. The contents of this review will be utilised during the power analysis in WP3, with the work carried out in WP2 and WP3 required to meet the goal of WP4.

1.3. Objectives

The objective of this work package report is to identify completed, ongoing and planned offshore seabird monitoring campaigns within operational offshore wind farms globally and to provide a comprehensive list of the monitoring technology/systems used within these campaigns.

For each monitoring device mentioned, information on the following elements are provided (the amount of detail included within each of these topics for each monitoring technology/system is dependent on the amount of information available at the time of review):

- Study design;
- Reference projects;
- System functioning;
- Hosting/logistical;
- Data collection;
- Data processing;
- Data analysis;
- Indicative costs; and
- Other relevant information.

In addition to the literature search, engagement with relevant experts involved in monitoring campaigns has been undertaken. This allows for additional information on the monitoring technology/system used to be obtained if it is not available in published or grey literature. Such experts include:

- Equipment manufacturers/providers;
- Developers hosting or who have considered hosting monitoring equipment;
- Developer Engineers who may be able to give a better understanding on the logistics, planning and challenges of installing and maintaining offshore equipment;
- Regulators and relevant nature conservation advisors who may have views on appropriate equipment, information and analyses of such data;
- Data analysts and those using CRMs (e.g., consultants, statutory advisors, academics and researchers).

2. Methods

An initial SBMon Kick-off Workshop (WP1) was held on 22 April 2021, with attendees including The Carbon Trust, the Project Team, ORJIP Steering Group (RWE Renewables, SSE Renewables Developments UK Limited, Marine Scotland, Shell Global Solutions International B.V, TotalEnergies, Ocean Winds and Marine Consent Advisors from The Crown Estate), Project Expert Panel (BioSS, RSPB Scotland, Ørsted, Centre for Ecology and Hydrology, JNCC, Marine Scotland Science, NatureScot, EDF Renewables, Natural Resource Wales and Natural England), and 3rd Party Consultants (British Trust for Ornithology and DHI). The meeting was held primarily to discuss methods and also to identify potential monitoring systems unlikely to appear in the literature.

Based on this discussion and subsequent web searches (see section 2.1 for further details regarding repeatability of searches), the following collision and avoidance monitoring technologies/systems were identified:

- VARS (Visual Automatic Recording Scheme)
- MUSE (Multi-sensor Bird Detection)
- DT-Bird
- WT-Bird
- Robin Radar
- BirdTrack
- IdentiFlight
- B-Finder
- ATOM (Acoustic and Thermographic Offshore Monitoring)
- ACAMS (Aerofauna Collision Avoidance Monitoring System)
- Multisensory System (Oregon State University)
- Camera Technology
- Thermal Tracker Software
- Spoor Bird Monitoring System
- GPS tracking
- Radar

Following the kick-off meeting, a strategic literature review was carried out before interviews with suppliers of the different monitoring technologies/systems were held where possible. Interviews with wind farm developers implementing monitoring campaigns were also undertaken.

2.1. Literature review

A scientific literature search using Google Scholar, Web of Science and Google Search and the terms “bird collision offshore wind farm monitoring”, “bird strike monitoring technology”, “bird avoidance wind farms” and “bird collision monitoring” was carried out by two individuals at RPS between June 2021 and August 2021 and searches were sorted by relevance. As searches spanned over the course of three months, multiple search runs were conducted, resulting in 31 search runs for Google Scholar, 6 search runs for Web of Science and 43 search runs in Google Search, respectively (Pozsgai et al., 2021). Materials by Collier et al., (2011), Collier et al., (2012), Dirksen (2017), and Molis et al., (2019) were also cited: these studies provided a review of known technologies and monitoring systems already in use at offshore wind farms.

The information taken from the studies identified during the literature review can be divided into six broad areas and are outlined in Table 1.

Table 1 Overview of information sought during the literature review

Study Design	System Functioning	Hosting/Logistics
Objective of the monitoring system (what was/is it aiming to monitor)	Spatial coverage - monitoring capacity relative to turbine structure(s) and beyond	Type and format of information recorded/stored and retrieved
Scale of deployment	Temporal coverage	Equipment and turbine requirements for hosting
Case studies with information on calibration or validation	What parts of the structure are visibly monitored beyond the turbine blades/rotor swept area	Logistical requirements – e.g., power, communications, maintenance
	Method for monitoring collisions	
	Species identification capability	
	Detectability/ false negative and false positive rate	
Data Collection	**Data processing / Data Analysis**	**Other Information**
Rate of bird movement – flux/ density	Data extraction and format	Indicative costs per unit
Bird flight reactive behaviour	Processing methods, automation	Any information regarding how locations/sites selected/agreed, risks, difficulties, lessons learnt
Bird flight parameters – e.g., height, speed, direction	Analytical approaches applied to the data	
	Empirical collision rate estimation	
	CRM parameter estimation (flight heights and flight speed etc.)	

	Within-wind farm avoidance rate estimation, behaviour/error
	Macro-avoidance rate estimation
	Categorisation of bird flight behaviour preceding collision/avoidance
	Estimation of flux rates through individual turbines and/or wind farm
	What additional analyses can be envisaged for the processed data?

Within each of the criteria outlined above we identify alternative approaches and assess both the benefits and limitations of data collection to help to improve our understanding of the effects of collision, displacement and/or barrier effects, as well as the confidence in the results. A critical aspect of WP2, in relation to WP4, will be the identification of where each method could be enhanced by combining it with another to form a complementary approach that will better answer the questions posed.

The review has focussed on the capability of systems to operate in the context of fixed offshore wind turbines, and then for each device an assessment is made of its applicability to floating offshore wind turbines and whether this will impact its functionality.

2.2. Interviews

As information relating to bird monitoring technology/systems (and how effective they are in collecting data on bird behaviour in the vicinity of turbines) is not always publicly available, interviews (accompanied by a questionnaire) with project managers utilising the devices and/or developers of the technology/system were carried out. If interviews could not be held, only the questionnaire was sent instead. This allowed for information not published in literature or on developers' websites to be obtained. The following were contacted for an interview and sent a questionnaire:

- Spoor – developer of Spoor AI Bird Monitoring System
- DHI – developer of MUSE
- Strix – developer of BirdTrack
- Normandeau Associates – developer of ATOM
- BSH – developer of MultiBird
- Oregon State University – developer of Wind Turbine Sensor Array
- IdentiFlight Team – developer of IdentiFlight
- Bioseco – developer of Bird Protection System
- BSH – developer of MultiBird I-III

- B-finder Team – developer of B-finder
- Bertrand Delprat – contact at ID-Stat
- Liquen Consultoría Ambienta, S.L – developer of DT-Bird
- Rijkswaterstaat – company involved in the monitoring of Luchterduinen using Robin Radar
- WPD energy – company involved in monitoring at Yunlin offshore wind farm

The developers listed above were chosen due to their mention in either previous published monitoring reports by Collier et al., (2011), Collier et al., (2012), Dirksen (2017), and Molis et al., (2019), or during WP1 Kick Off Workshop.

Interviews were conducted during June – November 2021, with the completed questionnaire returned to the interviewee to approve the content recorded and provide any additional information not already covered. The questionnaire was designed to obtain information needed to address the 26 questions outlined in the ORJIP Scope of Works (Table 1) and the full questionnaire that was sent can be viewed in Appendix 1.

3. Results

Information provided within this section has been extracted from peer-reviewed articles, interviews and publicly available monitoring reports. In total, 45 different reports were reviewed for details of the types and effectiveness of the monitoring devices used to collect data on collision rates and bird flight behaviour in the vicinity of turbines. Additionally, the information obtained from interviews and any associated websites has been incorporated into the appropriate section. A list of all the scientific articles and published reports consulted is provided within Appendix 2. Appendix 4 outlines the type of information extracted from each article in the context of the 26 questions within the Scope of Works laid out in Table 1. Blanks within the spreadsheet in Appendix 4 relate to where no relevant information could be extracted from each piece of literature cited when addressing specific Scope of Works questions. Additionally, within Appendix 4, all interview responses have been included within separate worksheets.

Different types of monitoring methods (e.g., cameras, radar, GPS tracking) are shown in section 3.1, while specific types of device (e.g., Merlin radar, Robin radar) are detailed. Section 3.2 outlines monitoring systems currently available and in use (e.g., MUSE, ATOM).

For each technology/system, its application, strengths and weaknesses in relation to various parameters being investigated such as species or species groups, the scale over which it may operate (e.g., micro, meso, macro) and any recommendations to further enhance the technology/system capability are discussed.

Not all technology or project developers responded with information; in such cases, information provided within the technology/system review is limited to what is available in publications or marketing material. It is intended to continue updating this section if new material becomes available during the WP2 review process and as WP3 and WP4 progress.

3.1. Monitoring technology

We found four primary approaches for monitoring bird collision risk at wind farms: (1) radar, (2) camera, (3) acoustics, and (4) bio-logging. Information provided within this section has been taken from publicly available literature, and with additional information provided by a personal communication with a wind farm developer utilising Robin 3D Radar. See Table 2 below for a list of sources cited for each technology.

Table 2 Cited literature for each technology described within Section 3.1 Monitoring technology

Technology	Information sources
Merlin Avian Radar	Krijgsveld et al., 2005, Krijgsveld et al., 2011, Fijn et al., 2015, Skov et al., 2016
SCANTER Radar	Skov et al., 2018, manufacturer's website
LAWR Radar	Skov et al., 2018, manufacturer's website

Robin 3D Radar	Niemi and Tanttu, 2020, personal communication de Visser, 23 August 2021, manufacturer's website
BirdScan	Neumann et al., 2009, Hill et al., 2014, manufacturer's website
Video and Thermal Imaging Systems	Drewitt and Langston, 2006, Desholm, 2005, Desholm and Bertelsen, 2003
VARS	Hill et al., 2014
Microphone	Krijgsveld et al., 2011, Hill and Hüppop, 2009, Hill et al., 2014, Molis et al., 2019
Impact Noise	Kang and Kang, 2017
Radio-Tagging	Votier et al., 2011, Votier et al., 2006, Perrow et al., 2006, Loring, 2016, Seward et al., 2021, Thaxter et al., 2016, Bodey et al., 2018, Paton et al., 2021, Bridge et al., 2011, Brzustowski, 2015, Taylor et al., 2017
GPS	Peschko et al., 2020, Thaxter et al., 2015, Vanerman et al., 2020, Garthe et al., 2017a, Campion et al., 2020, McKinnon and Love, 2018, Liu et al., 2018, Thaxter et al., 2016, Thaxter et al., 2018, Borkenhagen et al., 2018

3.1.1. Radar

Radar systems most commonly used for estimating bird–wind turbine collision rates include: (i) doppler, (ii) tracking and (iii) surveillance radar (Desholm et al., 2006). Surveillance radars can be used to map individual trajectories of moving targets (e.g., birds), with low powered radars capable of detecting individual birds within a range of a few kilometres and flocks of birds within 10 kilometres (Gauthreaux and Belser, 2003). Their echo trail feature allows each echo to be visible for a given amount of time and they can measure the density and distribution of multiple targets (Desholm et al., 2006). By using a combination of horizontal and vertical radar surveillance systems, flight height and flight direction information can be obtained (Drewitt and Langston, 2006). Doppler radar can detect small differences in target positions and can detect and quantify bird movements at ranges well beyond the coverage of surveillance radars (Gauthreaux et al., 2018). Doppler radar is also less susceptible to clutter from rain and sea (Desholm et al., 2006). Tracking radar can only track a single target at any given time and requires the target to be monitored for a series of wing beats in order to provide data on ground speed and heading (Desholm et al., 2006). It is stated that surveillance radar are the most appropriate radars for studying bird behaviour in relation to wind farms due to cost, versatility and availability (Desholm and Kahlert, 2005; Desholm et al., 2006).

Radar is especially effective because it can record continuously, regardless of the time of day, over large spatial scales and can operate in most weather conditions (although radar can be affected by clutter from fog, waves, turbine blades, vessels and helicopter activity; Drewitt and Langston, 2006; Kunz et al., 2007). Conversely, radar is not able to reliably detect collisions and the level of taxonomic resolution is imprecise (Urmy et al., 2017) although this can be improved by using other methods such as acoustics and visual technology.

We consider the five most commonly used radar for ornithological research at offshore wind farms below. Tracking radar has not been included within the review below as it only tracks one target at a time and requires targets to be located manually by an operator whereas all other radar discussed can be operated remotely.

3.1.1.1. Merlin Avian Radar

System design

This system was developed by DeTect Inc, and uses Furuno radar with horizontal S-Band and X-Band vertical rotational capabilities to detect moving objects such as birds, rain, ships and waves. The literature study revealed four published studies at the Dutch Offshore Wind Farms Rodsand II and Egmond aan Zee (Krijgsveld et al., 2005, Krijgsveld et al., 2011; Fijn et al., 2015; Skov et al., 2016) that have used the Merlin software effectively. Within these studies, two radars were used and linked to the Merlin software, with the Merlin system at Egmond aan Zee in operation for several years (2007 – 2010). At Egmond aan Zee, the horizontal radar monitored six turbines, while the vertical radar gathered data on birds within range of four turbines (Egmond aan Zee has a total of 36 turbines).

System functioning

The radars can automatically record echoes continuously, which provides very detailed temporal coverage regardless of time of day, with data used to generate estimates of flight direction, speed, and altitude of flying birds (Skov et al., 2016). At Egmond aan Zee during the deployment, the radar successfully collected data for 976 out of the 1,086 days (90%). The gaps in data collection were due to maintenance, technical failure and instances where weather conditions were too harsh (strong winds above 7 Bft and heavy rain) for the radar to operate effectively (heavy rain occurred c. 8.7% of the research period).

At Egmond aan Zee, the radars were set to scan a horizontal area within the wind farm up to 5.6km and a vertical coverage up to 1.4km (Krijgsveld et al., 2005; Krijgsveld et al., 2011). These ranges were chosen at Egmond aan Zee to allow the horizontal radar to record flight paths in the wind farm area as well as beyond the wind farm. At the Dutch offshore wind farm, the radars were set to record echoes up to 11km away, with a maximum altitude range of approximately 5km (Fijn et al., 2015). The radar is capable of recording flight paths from a variety of different bird species (including small seabird species such as terns). Radar alone cannot identify species, however.

The most direct test to determine the performance of the Merlin bird detection system is by comparing the numbers of tracks visible on the Furuno computer (raw radar) and the numbers of tracks on the Merlin screen within the same time span. Simultaneous recording of flight movements observed on the Merlin screen and on the Furuno screen gives detection chances of Merlin compared to visual detection from ‘raw’ radar, of which on average around 80-90% of bird tracks are correctly detected by Merlin (Krijgsveld et al., 2005; Krijgsveld et al., 2011; Fijn et al., 2015). The radar system can detect all birds, even fast-flying species at 100km/h flying perpendicularly through the beam.

Incorrect detections are usually split in two conditions. First, detection failure can account for around 9% of error cases. This occurs when a bird is seen on the Furuno screen but not recorded by Merlin. Second, observer failure occurs when a track recorded by Merlin was not seen on the Furuno screen, which can account for 12% of error cases (Krijgsveld et al., 2005; Krijgsveld et al., 2011).

The detection of targets deteriorates quickly with increasing rain, with it being recommended that data recorded during this time not be included within any analysis due to the increase in error. Moreover, radar may be damaged in winds above force 7 on the Beaufort scale requiring the radar to be shut down.

Hosting/logistical requirements

The radars are mounted on the meteorological mast (but in other cases can be mounted onto the turbine platform) and all signals are sent to a computer located near the radar device (offshore), so information can be digitised. This information is then sent to a second computer for data processing (the second computer would be located onshore), where the Merlin tracking software is used to identify the signals that belong to birds (or bats), while simultaneously removing as many false tracks (clutter from waves etc.) as possible. This is done using an algorithm developed specifically for the registration of bird echoes based on the size of the echo, speed and heading (Fijn et al., 2015). All tracks identified as birds are stored within a database, with those identified as belonging to the same object are given a unique trackID, enabling analysis of the flight path to be undertaken.

The Merlin technology is fully remote controllable and networkable through TCP/IP, wireless wide area network (WAN) and other protocols. All equipment is industrial-grade and designed for use in outdoor and extreme environments with exceptionally high reliability (see Figure 1 for an overview of the system).

At both Egmond aan Zee and the Rodsand II offshore wind farm, the Merlin Radar was installed after the turbine was constructed, with no reported negative impact to the metmast or turbine platform.

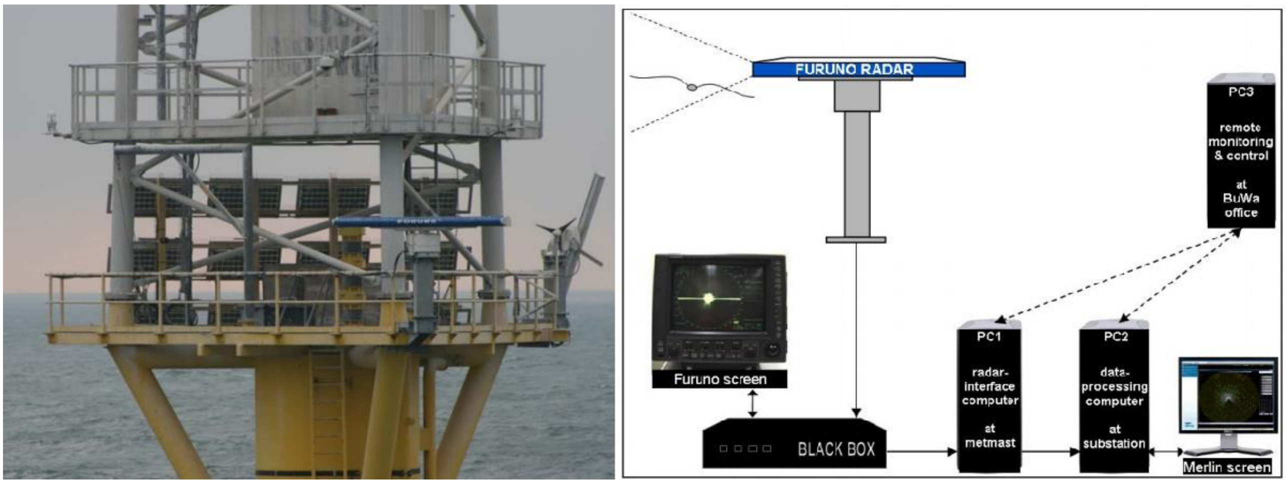

Figure 1 (left) Horizontal and vertical radars installed at Egmond aan Zee; (right) Schematic overview of the radar equipment used (images taken from Krijgsveld et al., 2011).

Data collection

This technology can be used to obtain data on macro-avoidance and meso-avoidance behaviour and can obtain flight heights for species paired with in-field observations. As the radar system operates continuously 24/7, it can obtain data on diurnal, nocturnal and seasonal variability. As species specific information can be obtained through associated visual observations, individual species avoidance rates at the macro and meso-scale could be estimated. Flux rates and proportion of birds at collision risk height can also be estimated. Estimates of direct empirical collision rates cannot be collected by this technology.

Data Processing and Data Analysis

As the system only logs the echoes encountered, together with the characteristics of these echoes, echoes need to be identified as belonging to certain species groups or individual species. This is carried out using the "flagging" method.

Flagging involves the radar signal being linked through simultaneously watching the bird during visual observation surveys. Through direct communication by means of portable radios between a field observer and an observer behind the radar screen, the echo of an object (bird) that was sighted visually can be identified and flagged on the radar screen, and vice versa where an object generating a radar signal can be located by the field observer and identified.

To allow analysis of flight paths in relation to the wind farm, all data on flight paths is assigned to grid cells covering the entire wind farm area, with tracks provided in 2-D. With regards to resolution, by reducing the range of the radar, the resolution of the recorded data can be increased. The entire Merlin screen is built up from 1,024 pixels in both vertical and horizontal direction. At a range of 5.6km, one pixel reflects 11m, whereas at a range of 1.4km, one pixel reflects only 3 m (Krijgsveld et al., 2011). A similar difference occurs with the echoes. Detection is more detailed therefore at smaller ranges. Data can then be analysed using PostgreSQL, QuantumGIS, R and SPSS. QuantumGIS is typically used to visualise flight paths, with SPSS and GenStat used for statistical analysis.

Recommendations

The radar technology needs to be combined with visual observations to obtain information on species composition. The developer website (Avian Radar System | Bird and Bat Mortality Mitigation Radar (detect-inc.com)) also states that custom configuration can be provided where the radar technology is integrated with additional sensors such as thermal cameras, bat detection systems, insect detectors and acoustic monitors, thus allowing for more information (during nocturnal hours for example) on individual species to be obtained. Additionally, the Merlin detect and deter system can be implemented where, based on custom defined control parameters, the Merlin software can trigger deterrent devices and on-demand shut-down of turbines if required, for example if detected birds are deemed to be at risk of collision.

3.1.1.2. SCANTER Radar

System design

SCANTER radar is a fan beam and solid-state radar with Doppler with an enhanced detection capability capable of suppressing sea clutter and rain. Extensive documents relating to the Thanet offshore wind farm off the coast of Kent, England, detail the use of a SCANTER-5000 radar (Skov et al., 2018). One SCANTER-

5000 radar was installed on one of the platforms of the outside turbines, with several turbines within its range and operated from July 2014 to August 2016, with the radar recording bird tracks during 81% of the study period. Down-time for the study was due to occasional faults within the equipment (Skov et al., 2018).

System functioning

The radar can record bird tracks continuously, however tracks obtained cannot be assigned to individual species/species groups unless combined with some form of visual or acoustic survey (e.g., visual surveys and moon watching). Targets can be subsequently identified to species level within a maximum of 2km from the observer, depending on species.

SCANTER radar is typically set to 12km to allow optimal detection within 6km from where the radar is installed, with detection probability close to 100% within the whole scanned range, and only slightly dropping after 5km. At Thanet, outside the wind farm birds around the size of Northern Gannets (mean length: 94cm, mean wingspan: 172cm) and Black-legged Kittiwakes (mean length: 39cm, mean wingspan: 108cm) could be tracked from distances as far as 6.7km, while large gulls could be tracked from distances as far as 5.2km. Inside the wind farm, Northern Gannets could be tracked from distances as far as 3.7km, while tracking of Black-legged Kittiwake and large gulls was usually limited to distances of up to 3km (Skov et al., 2018).

Up to 10 radar tracks can be followed at a time, requiring the de-selection of targets when this amount is exceeded. Birds cannot be tracked in a blind sector caused by shading of the turbine tower (if mounted on the turbine platform), and birds flying at <10m altitude within 45m of the radar cannot be detected (Skov et al., 2018). The maximum height at which flying seabirds can be detected at 1km distance is 385m both inside and outside the wind farm.

The SCANTER radar is better suited compared to other radars (LAWR for example) at collecting information on birds at distances over 5km or under rainy conditions due to the use of Doppler. The sensitivity of the SCANTER radar can be affected by poorer weather conditions at distances over 5km (Skov et al., 2018). It is mentioned within the Skov et al., (2018) study however, that sea clutter was still an issue, causing a high number of false positives despite SCANTER radar being in operation.

Hosting/logistical requirements

The radar is typically paired with observer-aided tracking (with use of rangefinders) during daylight hours from the turbine platform (Figure 2) to obtain species specific information. The SCANTER radar can produce bird echoes and bird tracks of significantly higher resolution and small size, allowing instant recording of track details.

The following filters are applied to the SCANTER radar during operation:

- Coherent Doppler-based processing, used to reduce or eliminate signals from slow moving and stationary objects.
- Constant false-alarm rate (CFAR) filters, used to reduce sea waves, precipitation, and noise, as well as to reduce time-side lobes from the pulse compression.
- Sea Clutter Discriminator, used to detect small targets normally hidden in sea clutter.
- Interference filter, used to reduce noise from other electromagnetic sources nearby.

Figure 2 SCANTER-5000 Radar installed on Turbine G01 at Thanet offshore wind farm (image taken from Skov et al., 2018)

Similar to the Merlin Avian Radar, the SCANTER technology was installed at Thanet for the ORJIP Bird Collision Avoidance study (https://www.carbontrust.com/resources/bird-collision-avoidance-study) after the turbine was constructed, with no reported negative impact to the metmast or turbine platform.

Data collection

This system can be used to record macro-avoidance and meso-avoidance behaviour as well as bird flight speed, height, and direction. This means updated estimates of displacement rates/barrier effects for individual species could be generated as tracking data in the vicinity of a wind farm and would be available for analysis. Within the Thanet study, the SCANTER-5000 radar highlighted that there was a very high avoidance rate for the target species of Northern Gannets and gulls.

This technology does not obtain data in close proximity to turbines (i.e., within the rotor swept zone) due to shading, but information collected (such as updated flight height and speeds) could be used in collision risk models. Empirical collision rates cannot be obtained when using this technology.

Data processing and data analysis

The radar software consists of a Tracker and Doppler Enhanced processing software, coupled with a BirdTracker GIS-based software, which enables real-time 2-D tracking and geo-referencing of up to ten different bird targets at a time. These are followed on background video images on a PC.

The PC screen visualising the radar images is used to select targets both inside and outside the wind farm. The observer responsible for operating the radar can follow up to 10 tracks at a time by tracing the radar track on screen. Each track has several nodes, representing the location of the target (birds) over time. In addition to the start and the end-point, directions are calculated automatically for all tracks by the radar. In the occasions that the number of tracks detected by the radar exceeds 10 tracks, a decision needs to be made by the technician on which tracks to follow using a list of prioritised species.

When a target generating a potential bird track is being followed and comes within the visible range (within 1.5-2km distance depending on species), its identity to species level can be determined visually by a field observer or through cameras recording and subsequent analysis. When confirmed, the targets' identity together with its associated parameters (e.g., numbers of birds, age groups, behavioural activity and visually estimated flying altitude) are calculated using a rangefinder device. Observer estimation or camera angle can be recorded by the technician.

Recommendations

This radar provides very good information on bird tracking over large distances in and around a wind farm, but on its own cannot provide species identification. Visual observation is required by observers or cameras in order to obtain species specific information when paired to radar tracks. Paired visual/camera observations may also be used to provide information on micro-avoidance behaviour and collision rates, which the radar is unable to achieve. There may be some detection issues with scatter and during poor weather.

3.1.1.3. LAWR Radar

System design

The LAWR radar is a magnetron-based radar sensitive to sea clutter in sea states higher than Beaufort 2. LAWR radar also relies on the cross-correlation with known bird radar signatures in order to ensure a high-resolution classification of bird signals, reducing the risk of turbines and rotors interfering with the tracking of birds (Skov et al., 2018).

Extensive documents relating to the Thanet offshore wind farm off the coast of Kent, England, detail the use of LAWR 25 radar (Skov et al., 2018; Figure 3). Three LAWR 25 radars were installed within the wind farm, one of which was installed on one of the platforms of the peripheral turbines. The radars recorded bird tracks during 94% of the study period and had several turbines within the field of view. Additionally, LAWR radar has been used in post-construction monitoring in Belgium (Vanerman et al., 2013), Horns Rev 1 and 2 (Skov et al., 2012) and at Egmond aan Zee (Krijgsveld et al., 2011).

System functioning

Multiple species can be detected using LAWR radar, however this system is susceptible to higher false positive rates due to clutter sensitivity (filters outlined below do not eradicate all instance of clutter).

Due to the shape of the detection probability curve of the LAWR radar, the scanning range of the radar is usually set at 6km (Skov et al., 2018). However, to aid with clutter suppression, the LAWR radar with a reduced detection range (up to 3-4km), coupled with the capacity to suppress sea clutter is seen as beneficial. The radar has a variable theoretical detection probability curve (DPC), with high detection (>0.67) between 1,250 and 3,000m from the radar. In general, it is not possible to detect bird tracks on the LAWR radar at distances beyond 8km.

Because of the vertical angle of the radar beam, Skov et al., (2018) suggests that low-flying seabirds (<10m) cannot be detected closer than 85m from the LAWR radar. For the same reason the maximum height at which flying seabirds can be recorded at 1km distance is 175m. Up to 10 targets can be followed at any one time, with detection of seabirds typically possible within 5km, with species identification possible by visual observation within 2-1.5km.

Limitations in detection occur with increasing distance, with a potential under-representation of bird movements within 1.2km / beyond 2.7km of the sensor both inside and outside the wind farm (Skov et al., 2018). The performance of the radar system is also limited during windy conditions that can lead to small sample sizes being collected. The radar has a blind sector caused by the turbine tower if mounted on the turbine platform.

Hosting/logistical requirements

Data (i.e., screen dumps from the radar) are automatically stored within an external hard drive (installed alongside the radar), with the hard drive collected periodically during scheduled equipment and turbine maintenance, or alternatively, remote access may be facilitated to download data.

To help reduce instances of clutter, settings are applied to optimise clutter suppression and detection of birds. These settings are:

- Improved antennas with a horizontal beam width of 10° only, from 0° to +10°, which places all the power above the horizon, minimising the amount of sea clutter pick up, and applying more power to the area of interest
- Sea filter (suppression of noise due to waves): 30
- Rain filter (suppression of noise due to rain): 30
- Gain (increased visualisation of bird echoes): 75
- Echo stretch (enlarged bird echoes): 2
- Trail (number of seconds old radar echoes are shown on screen): 30

Figure 3 LAWR 25 Radar installed on turbine G05 at Thanet offshore wind farm (image taken from Skov et al., 2018)

Data collection

LAWR radar can record horizontal meso-avoidance behaviour, with the results from the Thanet monitoring study indicating that the majority of recorded seabirds avoided the turbines (96.8%) by flying between the turbine rows, while 3.2% displayed meso-avoidance by adjusting flight height (by associated visual observations) to fly below the rotor-swept zone (Skov et al., 2018). Data on bird behaviour (flight height, flight speed and flight direction) can also be obtained due to the radars tracking abilities and associated visual observation. It is not possible to obtain data on empirical collision rates or micro-avoidance behaviour using this radar technology alone, although such data may be collected through paired visual observations using observers or cameras.

Data processing and data analysis

Data recorded using the LAWR radars include geo-referenced 2-dimensional record (GIS geodatabase) of seabird tracks identified at the species level by observers (or cameras), storing the different entries into a BirdTracker database.

The data acquisition hardware for the LAWR system used at Thanet has been developed by DHI and includes ancillary hardware linked to the systems, allowing 24 hour operation and remote control, with the automated download of screen dumps taking place once every 2 minutes. The total number of recorded bird echoes per km^2 in each distance bin from the LAWR radar is then calculated and divided by the area scanned by the radars in each bin in order to get a comparable measure of the density of echoes recorded from each radar over distance.

In most cases, the LAWR radar is operational to support the selection and tracking of targets by an observer operating a rangefinder, and therefore the PC screen visualising the radar images is used to select targets, with some of the targets followed by a rangefinder operator (as instructed by the technician operating the radar). The rangefinder can only be used to follow one target at a time within approximately 1.5km of the observer position.

Recommendations

Within the Thanet monitoring study, LAWR radar was paired with a thermal camera and deployed on two different turbines within the wind farm, providing additional information on meso-avoidance behaviour but also allowing micro-avoidance behaviour to be recorded. This combined system is referred to as the Thermal Animal Detection Systems (TADS). This system has since been updated to MUSE (see section 3.2.1). It is recommended that a similar combination could be deployed if LAWR radar is chosen for a future monitoring project, as nocturnal flight activity can be estimated together with monitoring of flight behaviour during daylight and nocturnal hours within the micro-zone. As information is obtained on bird behaviour within the rotor swept zone, these estimates and flight parameters could be used to improve collision risk modelling. In theory, observers would be capable of collecting data to inform empirical collision rates, but in practice the amount of observation time required would likely be prohibitively expensive because collisions are typically rare events. Cameras used in fixed positions on turbines might overcome the issue, although multiple cameras (and associated analysis of footage) would be required to cover a sufficient sample of turbines within a wind farm facility.

3.1.1.4. Robin 3D Radar

System design

The Robin 3D radar has both a Furuno horizontal radar (magnetron-based S-band radar), which monitors the birds in two dimensions and a Furuno vertical radar (magnetron-based pulse X-band radar) which adds height information to give a 3D image of the bird flight trajectories.

Robin radar has been installed at Luchterduinen offshore wind farm, and two in Borssele wind farm, one in the middle and one at the edge of the wind farm (personal communication, de Visser, 23 August 2021), at the Gemini offshore wind farm, both off the coast of the Netherlands, and at Tahkoluoto offshore wind farm off the coast of Finland (Niemi and Tanttu, 2020). At Luchterduinen, the radar is installed at one wind turbine near the edge of the turbine array, allowing several turbines to be within view.

System functioning

The radar allows for continuous monitoring during the day and at night, and can also operate in bad weather conditions (however, the performance of the radar does decrease during heavy rainfall and snow).

Species groups can be identified based on flight velocity (m/s), however the radar system would need to be paired with visual observations/camera devices in order to identify to species level.

The horizontal radar emits signals through 360° round, but in order to protect the wind turbine from damage, at Luchterduinen wind farm a blank sector was created at the turbine. The blank sector ranged from 275° to 346°, thus in total 71°: 19.4% of the complete circle around the radar was not monitored (de Visser, pers. comm.). The vertical radar works in a similar way to the horizontal radar, but is tilted 90°, which results in a rotation of the radar in the vertical plane and a narrow vertical beam.

Reported detection ranges of the horizontal radar vary between 10km for ducks and small geese and 6km for songbirds. The vertical radar can detect birds up to an altitude of 1.5km radar (de Visser, pers. comm.). Information inside and outside the wind farm can be gathered if installed on the outside turbines and the radar is capable of monitoring several turbines simultaneously.

Based on the results of the validation at Luchterduinen, the horizontal radar rarely detected bird echoes farther than 5.5km and most of the observations occurred at 3-4km from the radar (de Visser, pers. comm.).

Poor weather conditions (rain, waves) create a lot of clutter, which can be corrected using heavy clutter filtering, however this can cause bird tracks to also be filtered out. The radar can operate well in conditions below sea state 4.

Hosting/logistical requirements

The technology can be installed on the platform of the turbine or on a separate structure and can be either fixed or flexed, flexed allowing for detection in a configurable direction compared to fixed (Figure 4**)**.

The system can also be combined into a single sensor, 'Max' which collects full 3D information with the horizontal radar having 360° rotation and can gather data to at least 1km altitude.

The radar at Tahkoluoto is free standing (it is not attached to the turbine or turbine platform) and has been deployed after development of the turbines was completed.

Figure 4 Robin Radar installed at Tahkoluoto wind farm, Finland (image taken from Robin Radar, 2021)

Data collection

Data on macro and meso-avoidance, flight height and flight speed and direction are all obtained. Data is fairly accurate, but can be limited due to certain weather conditions (de Visser, pers. comm.). Information on species-specific flux rates at rotor height can also be estimated if radar data is combined with observational surveys. This data could be used as species specific input parameters for CRMs. As with all other radar systems, the radar alone cannot detect collision events and so cannot be used to obtain empirical collision rates.

All data recorded can be viewed within a developed interface provided by the manufacturer, allowing for all information to be easily accessed.

Data processing and data analysis

Radar information can be downloaded remotely and can be viewed in ArcGIS (Niemi and Tanttu, 2020). For the purposes of analysing the radar data at Luchterduinen, a 100 x 100m grid cell is created in and around the wind farm. Within these grid cells, the mean track length, representing the density of birds within a cell and the mean flight direction per cell is calculated. A change in mean flight direction dependent on distance from the wind farm can be statistically tested and a significant result can indicate macro-avoidance (de Visser, pers. comm.)

Another method to quantify macro-scale avoidance (this method can also be used to estimate meso-scale avoidance) is based on changes of flight direction within unique tracks of birds or bird flocks measured by the horizontal radar. The method first predicts whether an individual or flock will traverse the wind farm (macro-scale) or wind turbine rotor area (meso-scale) if keeping the initial orientation. Using only individuals/flocks that are predicted to cross the wind farm, it can be determined whether the individual/flock has entered or circumvented the wind farm (macro-scale) or the wind turbine rotor area (meso-scale) at the end of its track.

Based on the recorded position of the birds when flying towards and through the wind farm, relative to the position of the wind turbines, species-specific meso-avoidance behaviour can be recorded, both in the horizontal, as well as in the vertical plane (de Visser, pers. comm.).

Meso-avoidance can be quantified by bird flight density at different distances from the rotor-swept zone (RSZ) plus buffer area, based on the mean track length per unit area. A lower mean track length closer to the RSZ could indicate meso-avoidance. For this purpose, any shading effects of turbines on the radar detection probabilities have to be taken into account, and hence only areas can be used that are comparable regarding such turbine shading.

For the same reason of turbine shading, meso-avoidance can be estimated by calculating fluxes along a virtual line drawn in front of a row of turbines. If this line is drawn in front of the rotor-swept zone (incl. 10 m buffer) of the first line of turbines relative to the radar that are also of approximately at the same distance from the radar, the effect of shading and different detection losses can be excluded. These fluxes can be translated in a simple and straightforward way into meso-avoidance rates by comparing the number of tracks that cross this line right along the RSZ with the number of crossings in between the RSZ of the turbines after correcting for line length.

To detect any meso-avoidance in the vertical plane, flight height data of birds along a distance gradient from turbines can be utilised. Based on the vertical radar data, the proportion of birds flying at rotor height at distance segments of 100 m measured from a turbine can be determined. Subsequently, a GLM analysis can be used to determine whether the proportion of birds at rotor height is significantly different along the distance gradient. Meso-avoidance may be indicated by a lower proportion of birds at rotor height closer to turbines.

A comparison between fluxes inside the wind farm and outside the wind farm can be made by drawing flux lines at equal distances from the radar inside and outside the wind farm. These flux lines are drawn in areas where the horizontal radar has the highest detection probabilities. Subsequently, Mean Traffic Rates (MTRs: birds/km/h) can be calculated using the number of tracks that cross these flux lines. Similarly, flux lines can be drawn at equal distances in both beams of the vertical radar in order to determine the MTRs at different altitudes inside and outside the wind farm.

The visual and camera observations are focussed on determining species composition inside and at different distances from the wind farm. In order to determine species-specific fluxes inside and outside the wind farm, the recorded species composition can be applied to the MTRs measured by the horizontal radar. Ultimately, these species-specific fluxes can be corrected for false positive and false negative radar measurements as defined during the validation field campaign, in order to gain a more realistic measure of the flux rate.

Finally, based primarily on the laser range finder measurements and additionally on the visual and camera recordings, a species-specific flight height distribution can be calculated. Subsequently, the fluxes measured by the vertical radar can be attributed to species, resulting in species-specific fluxes at rotor height.

It is stated that this type of analysis can be applied to other radar system data and are not specific to Robin Radar.

Recommendations

This radar technology is capable of generating 3D flight data in the macro- and meso-space. It would have to be paired with observational technology (e.g., cameras or observers) or acoustics to obtain species-specific data. Robin radar can be integrated with camera technology as seen at Tahkoluoto offshore wind farm (the software for controlling the camera and for steering the video to allow for automatic bird detection was developed by Niemi and Tanttu, 2020). However, Niemi and Tanttu (2020) do state that more research into the application of the software is required and that it was only used to classify the one species, white-tailed eagle: a more complicated image classifier is needed to identify similar species such as gulls.

3.1.1.5. BirdScan

System design

BirdScan is a purpose-built pencil-beam radar based on a conventional ship radar receiver and a parabolic antenna derived from the Swiss ‘Superfledermaus’ military tracking radar (Neumann et al., 2009). The radar includes a pulsed X-band radar which can quantify birds that fly through the radar beam, with the radar range three times larger than conventional ship radars using the same power unit (Hill et al., 2014).

BirdScan has not been used widely at offshore wind farms, however a single unit has been used to monitor migratory birds at the Alpha Ventus offshore wind farm in Germany (Hill et al., 2014). BirdScan radar is incorporated into the MultiBIRD project being developed at FINO1 as part of a comprehensive method for bird monitoring (see Section 3.2.11).

System functioning

As BirdScan uses an X-band radar, it can detect small birds, such as small passerines (e.g., starlings and thrushes) and bats up to 1,000 m away and can detect large birds such as gulls up to 2,000 m away (Hill et al., 2014).

The BirdScan radar can be placed as close as 150 m from the turbine and can operate continuously throughout the day and year, with hundreds of thousands of echoes per month being recorded.

The radar system emits a short pulse several hundred times per second and measures the echoes that it receives (pulse-echo method). Birds are detected using pulsed radar that emits beams vertically across a conically-shaped field from a corrugated Horn-antenna with a wide aperture angle. The height and distance of an object can be calculated from the time the echo needs to return. The radar can be deployed for several years with low maintenance (Hill et al., 2014).

BirdScan radar can become limited during the day by the regular occurrence of bird flocks which can prevent individual echo classification, rending data collected when multiple birds are present unusable. The radar functions better during nocturnal periods when most night-migrating birds accomplish their journeys in solitary flights.

Like for any radar, a rotating blade within the measurement range would produce strong disturbances and would make it hard to properly detect all birds. For this reason, the technology was installed outside the wind farm at Alpha Ventus, on the FINO 1 research platform.

Hosting/logistical requirements

It uses a vertically directed, conically shaped, wide aperture beam with nutating movement (Figure 5). This setup allows recording of the following information:

- Precise recording of target's height above ground
- Wing flapping pattern, which is necessary to exclude non-bird and non-bat echoes, like insects
- It allows classification of bird echoes into sub-groups
- Precise knowledge of surveyed volume, which is necessary to estimate the number of birds aloft per volume, i.e., to compute Migration Traffic Rate for specific altitude layers (birds / horizontal km * hour)
- Flight direction and speed of target is obtained from the nutating beam
- Shape of target (long vs. round) is obtained from circularly polarised beam.

To detect migratory birds at different elevations, the parabolic antenna is set to three different angles on either side for distinct time periods to allow for a larger horizontal range to be monitored simultaneously. These evenly balanced, alternating measurements, make it possible to detect spatiotemporal differences in bird numbers caused by behavioural responses (avoidance and/or light-induced attraction to turbines within range). The radar can detect echoes using four operational modes: static short-pulse, rotating short-pulse, static long-pulse, and rotating long-pulse. Data on flight behaviour are only retrieved under rotating mode (Nilsson et al., 2018).

BirdScan consists of a transmitter/receiver unit, a computer and analysis unit. The system can be monitored remotely if connected to the internet.

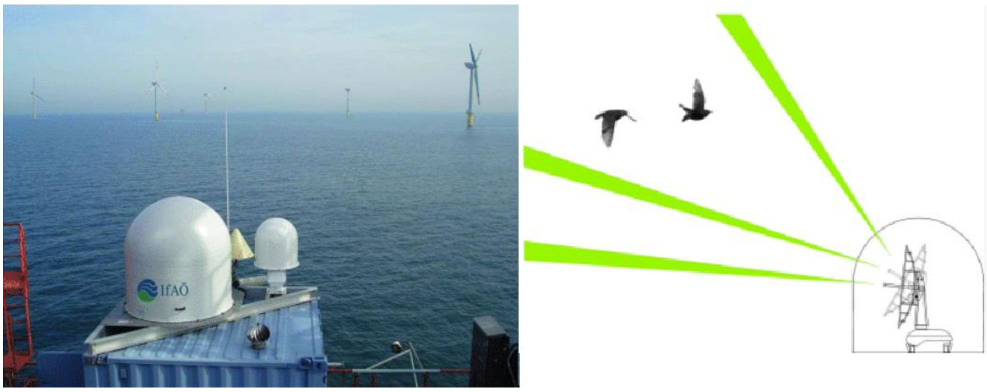

Figure 5 (left) BirdScan Radar installed on the FINO1 research platform just outside of the Alpha Ventus wind farm (right) inside view of the BirdScan radar and how the radar tilts to capture flight height (images taken from Hill et al., 2014)

Data collection

BirdScan can measure the flight directions of individual birds and bats, due to its beam nutation. BirdScan radar systems provide a precise estimation of altitude above ground of each detected bird or bat allowing analysis of the Migration Traffic Rate (flux) for specific altitude layers.

Within Alpha Ventus, the BirdScan radar showed that bird migration took place throughout the whole year and was more pronounced at night than during the daytime. In all seasons, the highest intensities were measured in the lowest 200 m, meaning a large part of migration over the sea occurred at an altitude that would bring birds within the reach of wind turbines (Hill et al., 2014).

This radar system can be used to obtain data on macro and meso-avoidance which could then be used to estimate displacement and/or barrier effects. As flight heights and flight speed information are obtained on species within the wind farm, this information could be used to inform CRM parameters. However, data on empirical collision rates cannot be obtained using this technology without integrating other sensor types.

Data processing and data analysis

BirdScan radar systems emit hundreds of pulses per second and a flying target is illuminated several hundred times. The resulting echo is a short signal which contains information of fluctuations in a target's reflectivity. For birds and bats the wing-flapping pattern can be reconstructed from the signal. This information is exploited by SBRS Analytics Modules to classify targets (e.g., bird, passerine-bird, wader-bird, insect, ground-clutter) and to estimate the wing-flap frequency (Hill et al., 2014).

The results can be expressed as a migration traffic rate (MTR), defined as the number of bird echoes crossing a fictive horizontal line of one kilometre length per hour. The beam of BirdScan radars performs rotational scanning of the surveyed volume. As a result, the horizontal position of targets can be calculated, then for moving targets such as birds and bats, the flight direction and speed can be estimated. Flight direction and speed are estimated and stored in real-time by BirdScan's processing module.

Recommendations

BirdScan can be paired with a horizontal marine radar, providing more information on flight direction and flight behaviour, both outside and through the wind farm. Like in the Alpha Ventus monitoring campaign, the

BirdScan Radar was situated next to a microphone and two camera systems (one camera system was a thermal device allowing for nocturnal activity to be recorded), which allowed for species specific information to be obtained. Where it was possible to do so, depending on the image quality and distance from the camera, birds recorded during nocturnal periods could occasionally be identified down to species level (Hill et al., 2014) using their silhouette and approximate size.

Additionally, a visual automated recording system was installed on one of the turbines within Alpha Ventus and paired with the radar systems (such as BirdScan and horizontal marine radar). These technologies installed on the platform nearby enabled micro-avoidance behaviour to be recorded.

3.1.2. Camera

Video cameras may be employed for the automated documentation of bird activities during the day, and at night using thermal imagery. The choice of focal length is a compromise between magnification and angle of view. If the focal length of the lens is in the range of a short telephotographic lens, the field of view is relatively large, but only large birds will be seen in the recorded images (Hüppop and Hill, 2007). Distant birds may not to be recognisable with such a small resolution. If the camera lens has a large focal length with a correspondingly low shutter speed, nearby bird can be recorded as well as birds hundreds of meters away. This comes with a compromise, resulting in a smaller field of view. Systems such as MUSE make use of zoom and motion-tracking facilities to improve identification rates (through closer zoom on the target) and follow a target for longer periods within the surveyed area.

Through the development of Artificial Intelligence (AI), detection software is continuously being developed which allows for birds to be detected within video images. This reduces the amount of effort required from ornithologists, as thousands of videos clips taken do not need to be reviewed to confirm if a bird has been recorded. Instead, only videos flagged by AI as containing a bird would need to be checked (e.g., Japan Weather Association, 2021; MUSE).

Most recent monitoring studies (e.g., Alpha Ventus, onshore wind farms in Hokkaido Japan and the Nysted offshore wind farm in Denmark) have used a combination of daylight and thermal camera software, allowing for continuous bird monitoring to take place. These camera systems are detailed below.

3.1.2.1. Video and Thermal Imaging Systems

System design

Video cameras can be used for continuous recording of bird activity up to hundreds of metres away, depending on the bird’s size. Video and thermal cameras have been used at several onshore and offshore wind farms (e.g., Thanet offshore wind farm (ORJIP BCA study)), the European Offshore Wind Deployment Centre (RPS / DHI MUSE), Nysted, Alpha Ventus and, onshore in Hokkaido Japan). It appears that increasingly, camera systems are paired with radar to obtain data on bird movements over larger areas than the camera can achieve alone. This results in the camera only turning on and recording movement when a bird has been triggered by the radar (or by motion detection), reducing the amount of data collected. Motion detection and artificial intelligence (AI) functions also enable cameras to follow the object, collecting continuous movement data.

System functioning

Thermographic cameras can allow for bird species to be identified based on their silhouette and approximate size (Drewitt and Langston, 2006). However, this requires good quality images.

It is possible with cameras to monitor the turbines 24 hours a day, all year. However, the weakness of optical systems is their limited range in bad weather, with more water droplets in the air causing reduced visibility.

Using computers, images can be captured and processed to create two separate peak-storage images, one image containing only the brightest pixels (peak), the other only the darkest. This can reveal flight tracks against both dark and light backgrounds. It can also provide information on approximate directions, plus the species group and flock size.

Cameras can record and store thousands of sequences of video over a short period of time, most of which will contain false positives, if a trigger type software (e.g., radar) is not incorporated into the system. Even with a radar-camera combined system, there is no guarantee only target birds (or bats) will trigger the software. For example, at Nysted offshore wind farm, where a thermal camera with radar operation was installed on one of the turbines, 1,944 thermal video sequences were recorded. However, only five were triggered by birds passing the field of view (Desholm, 2005). This meant 1,983 video sequences contained "false positives". Most of these were drifting clouds (45.5%) and turbine blades (32.0%) (Desholm, 2005). Recent improvements in automatic image screening and AI functions have helped to improve the filtering of false positives (e.g., RPS / DHI MUSE at EOWDC).

Hosting/logistical requirements

The video camera(s) can be installed either by mounting on the side of the turbine tower, on the turbine platform, on a survey platform, or on the nacelle. Depending on the lens type used, different information can be obtained.

The cameras may be automatically controlled by system software or can be remote-controlled from onshore via the internet. Observation and photographic documentation with a high temporal and spatial resolution can occur. Thermal imaging camera systems can utilise detection thresholds, which trigger the video capture, thus limiting the amount of data recorded to relevant time periods when birds are present within the range of the camera (Desholm and Bertelsen, 2003). However, the problem with thermal technology is infrared radiation can be absorbed by water and cloud cover; thermography is significantly less effective therefore at detecting objects in high humidity and rainy conditions (McCafferty, 2012; Matzner et al., 2015).

Figure 6 Daylight camera and thermal imaging camera installed on the transformer station outside the Alpha Ventus wind farm. Cameras are positioned in such a way as to monitor the Rotor Swept Zone of the turbine (images taken from Hill et al., 2014).

Data collection

Depending on where the camera systems are installed, for example if they are installed within the wind farm, information on meso-avoidance behaviour can be obtained. If the camera is installed on a separate platform outside the wind farm and a large portion of the wind farm is within view, it is possible that macro-avoidance behaviour could be recorded, although detecting and identifying birds over such scales would be challenging. Installing the camera in such a way (e.g., on the turbine) that the rotor swept zone of one or more turbines is within the field of view, mean instances of micro-avoidance behaviour and collision events can be recorded. Information on flight height, flight paths, direction and speed can only accurately be estimated if the camera system is paired with radar software, although new developments in generating bird tracks from twinned camera systems are also capable of generating this data. In doing so, this information can then be used within CRM.

Data processing and data analysis

Software for the automated capture of images at peak storage technique/mode can be utilised. This way the incoming video data stream from the camera, converted by a video capture card in the PC, can be summed over a defined time period by a computer (e.g., Desholm, 2005).

For each individual pixel, the brightest and/or darkest pixel (peak) is then stored in each case in the form of two separate pictures over the course of the entire time period. Thus “flight tracks” develop from the birds’ motions, which also contain information about approximate directions and flock sizes (Hill et al., 2014). Even distant birds, or birds flying directly over white crest waves or breaking waves may be registered.

Recommendations

It is recommended that camera systems are paired with surveillance radar in order to obtain species specific information, such as flight height, flight speed and macro, meso and micro-avoidance behaviour.

Use of AI detection software could also be used to either programme the system to detect a specific species (for example, the AI software developed by the Japan Weather Association was programmed to detect and record instances of white-tailed eagles and Steller’s sea eagles, and had a 94% detection rate (Japan Weather Association, 2021)). It can also be programmed to separate images containing birds from clips containing false positives (Yoshihashi et al., 2015). This method requires the camera system to be trained with thousands of images beforehand to ensure success.

3.1.2.2. VARS

System design

VARS (Visual Automated Recording System) is a camera system for the automatic detection of flying birds during day and night.

The Alpha Ventus wind farm in Germany appears to be the only wind farm with published documentation on the effective use of VARS and obtaining bird behavioural information in the vicinity of turbines (BSH - Startseite, with Hill et al., (2014) providing further information on the type of data recorded by the device).

System functioning

The system can detect small species, such as thrushes, as well as larger birds, such as large gulls. With thermal images, species groups can be distinguished based on their silhouette. An angle of 20° to 30° is typically chosen to ensure a sufficient recognition of small passerines along the length of the rotor blades. Large birds are visible over much larger distances.

Mechanical loads/vibrations or other offshore conditions do not typically cause VARS to fail. Birds detected by VARS (with data stored) can mostly be assigned to bird groups, but identifying targets down to species level can be difficult, due to the narrow field of view and detection range. Depending on the positioning of the camera, it can also allow for the detection of birds even under low-visibility conditions (such as fog and drizzle).

Problems in distinguishing birds may arise at greater distances from the camera, especially at night and during harsh weather conditions when resolution decreases even further.

Hosting/logistical requirements

The motion analysis software only records a video sequence when one or more objects move through the image section. In the dark, the use of infrared technology allows for the detection of birds and bats (Figure 7). Through a specially developed process, the camera system generates a very small volume of data per recorded event (Hill et al., 2014).

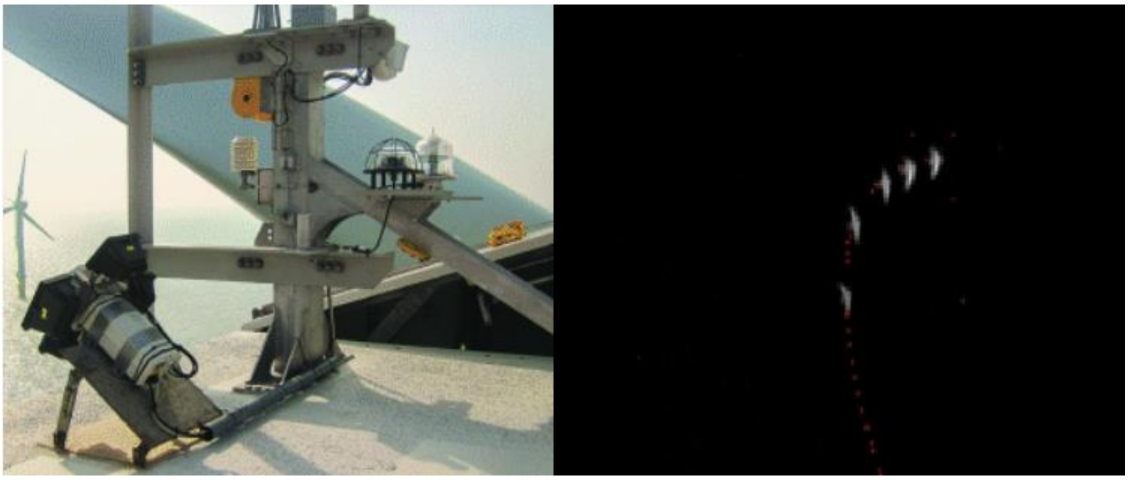

Figure 7 (left) Image of VARS installed on the nacelle of a turbine within the Alpha Ventus wind farm. (right) thermal video sequence of a bird recorded near the turbine (images taken from Hill et al., 2014)

Data collection

Bird collisions recorded by VARS can be treated as purely stochastic events on the basis of established collision models (Hill et al., 2014). By comparing the frequency of birds measured in the rotor-swept zone with the extent of migration measured with radar (such as pencil beam radar) it is possible to quantify micro-avoidance at the site the system is deployed at.

At Alpha Ventus, where the camera system was installed inside the wind farm from 2004 to 2012, numerous birds were recorded flying high above the wind farm (mostly gulls). Around 130 birds (approximately 50% at day and night) where recorded within the rotor-swept zone (irrespective of turbine activity). Of all the recorded events, 91% could be assigned to individual birds, due to the high image quality. The acquired images provide direct evidence for the range of potentially affected species and after excluding gulls from the analysis, songbirds dominated the species list (when the camera was installed on the nacelle, 92% of all birds recorded were songbirds, while data from the platform deck showed songbirds accounted for 88% of all records; Hill et al., 2014).

Birds recorded with VARS can be assigned into broad species groups, while accurate classification at species level is achieved only to a limited extent. However, the acquired images provide direct evidence for the range of potentially affected species.

Data processing and data analysis

The purpose-programmed motion analysis software saves the incoming video streams only when one or more objects move through the image. In darkness, infrared light (in an active system) enables the system to record birds and bats.

Recommendations

If combined with radar, VARS can obtain robust daytime and nocturnal data on species specific bird behaviour within the rotor swept area, with estimates produced used to populate collision risk models. If there are instances that cause the video quality to decrease (e.g., during times of fog or bad weather), to aid with species identification a microphone device could be installed, allowing for all data obtained by the radar to be used if video footage cannot identify the species recorded.

The Hill et al., (2014) monitoring study highlights the benefits of using two VAR devices for monitoring bird behaviour as multiple observations of the same individual can be obtained, with bird activity in the area above the platform being recorded. Despite instances of collision being recorded, the technology has not been used to estimate empirical collision rates.

3.1.3. Acoustic

Acoustic monitoring has the ability to continuously record bird activity (specifically during adverse weather conditions and/or at night) when human observations are not possible (Krijgsveld et al., 2011). Additionally, sensors installed on the rotor blades can pick up vibration signals and can register when a collision event has occurred.

These monitoring technologies have not been used widely within the offshore environment, however, do offer potential if paired with other monitoring systems. It is advised that sole acoustic data collection is not suitable for the quantification of bird activity around wind turbines as some species, especially during migration, utter no calls and would go undetected (Alerstam, 1990; Hill and Hüppop, 2009). Impact events using vibration sensors may also be missed due to the strength of the impact by the bird or bat (Hu et al., 2017).

3.1.3.1. Microphone

System design

Although the quality of recordings can be degraded by strong wind noise and rain, the development of the AROMA (Acoustic Recording of Migrating Aves) software enables the automatic detection and registration of calls and recognises bird calls by their characteristic narrow sound spectrum. This allows for wind and rain noise to be filtered out (Hill and Hüppop, 2009).

Microphones have been installed at Egmond aan Zee offshore wind farm and at Alpha Ventus, integrated alongside other monitoring devices such as radar and camera systems.

System functioning

Recordings of bird calls are subsequently matched to species (Hill et al., 2014). Individuals registered by the sound detection system may be recorded more than once. As a result, call rate data should be thought of as a relative measure, rather than an absolute number of calling birds. Flight calls cannot provide information regarding gender or age.

The range of the microphone varies between species and weather conditions. Typically, it has been installed outside the wind farm on a separate structure/platform.

Typical calls of thrushes, like blackbird and redwing, are detected up to 100m (Hill et al., 2014). Using automatic identification software (AROMA) also enables calls to be detected which are not recognised by the human ear (Hill and Hüppop, 2009).

Depending on where the microphone is positioned (e.g., near the turbines), background noise can become more pronounced, resulting in the application not functioning well. The microphone should be placed away from the sea and at such a distance that it would not cause interference (Krijgsveld et al., 2011).

The disadvantages of using detection software, however, is that the false positive rates can increase due to wrongly identified detections (these rates are generally higher than in manual analysis (Molis et al., 2019)).

Hosting/logistical requirements

At Egmond aan Zee, a microphone was installed on the turbine platform, close to the turbine tower, whereas at Alpha Ventus, the microphone was installed outside the wind farm on a separate platform (FINO1).

Data collected at Alpha Ventus showed that it was beneficial to fit a wind barrier to the microphones to help reduce background noise (Figure 8).

Figure 8 Microphone (and bat detector) with windshield and microphone muff installed at FINO1 near the Alpha Ventus wind farm (image taken from Hill and Hüppop, 2009)

Data collection

Using sound technology makes it possible to pick out temporal patterns that enable the seasonal and daily periods of high activity to be identified. This could feed into mitigation strategies (e.g., the shutdown of turbines when mass migration events occur) (Hill et al., 2014).

Results from monitoring studies using microphone technology, such as the study at Alpha Ventus, show that by using sound detection software, instances of collision can, on occasion, be explained by migration events due to the high frequency of bird call rates recorded. This data can be used to provide further insight into migration and identify the type of conditions that result in increased collision events (e.g., strong wind changes and decreasing visibility).

Data processing and data analysis

Recordings are stored as WAV-files and a bandpass filter within an additional identification software (e.g., Praat 4.6 Praat: doing Phonetics by Computer (uva.nl): a software for speech and acoustic analysis) can be used to improve the detection probability by reducing noise at other frequencies. For example, the detection rate of Redwing calls increased to 80% when the automatic identification software was used.

Using software such as AROMA (which separates calls from background noise) allows for the analysis of species composition in combination with weather effects (Hill et al., 2014, Molis et al., 2019).

Recommendations

This software could be used to supplement other monitoring technologies to collect data on bird activity (Ronconi et al., 2015) and can be used to obtain detailed taxonomic information and allow species identification to take place, especially during times when camera technology may not be in operation due to low light, heavy fog or rain.

Additional programs (such as MATLAB applications) can be used that enable birdcalls to be matched with a pre-established flight call library using an algorithm based on a set of seven acoustic parameters: call duration, highest frequency, lowest frequency, loudest frequency, average bandwidth, maximum band width, and average frequency slope. This can help speed up identification (about 30 times faster than real time; Krijgsveld et al., 2011), however still requires all acoustic data to be reviewed to ensure maximum accuracy.

3.1.3.2. Impact noise

System design

Using paint-type sensors on wind turbine blades may allow for impact events to be detected without the need for more costly impact detection systems (Kang and Kang, 2017). Piezoelectric paint (0-3 piezoelectric composite) is suitable for this application due to its self-powering characteristic, operating without an external power source (Choi et al., 2015; Han et al., 2014).

This technology has yet to be deployed offshore or at a project-scale, with the only published study carried out by the National Research Foundation of Korea (Kang and Kang, 2017).

System functioning

This monitoring technology has yet to be tested outside of a laboratory setting. During the test, a pellet with a mass of 0.12g and size of 6mm was used which is much smaller than any typical bird found at offshore wind farms (Kang and Kang, 2017).

The blade is divided into six electrode parts. The detectability rate can be affected by the thickness of the paint, caused by spray coating and so can vary along the curved shape of the blade. Additionally, the difference in the specific gravity between the powder and the resin can also result in sensitivity deviations (Kang and Kang, 2017).

Even though the sensitivity of the sensors may differ along the blade and between each blade, as the paint is designed to measure impact events and not the magnitude of the impact, the sensor is still capable of detecting impact signals, which means it would not affect collision monitoring.

Hosting/logistical requirements

The 0-3 piezoelectric composite is coated on the length of the rotor blades (Figure 9), with a wireless collision monitoring system that transmits impact signals from the rotating blades to a stationary base, such as the wind turbine tower or ground station, developed to aid in quickly identifying an impact event. The bird collision signal is generated by the 0-3 piezoelectric composite sensor applied to the wind turbine blades, and this signal is impedance-matched and amplified through a signal conditioning circuit.

The paint can be fitted anytime, however is recommended that it is done on land before deployment of turbines to reduce cost.

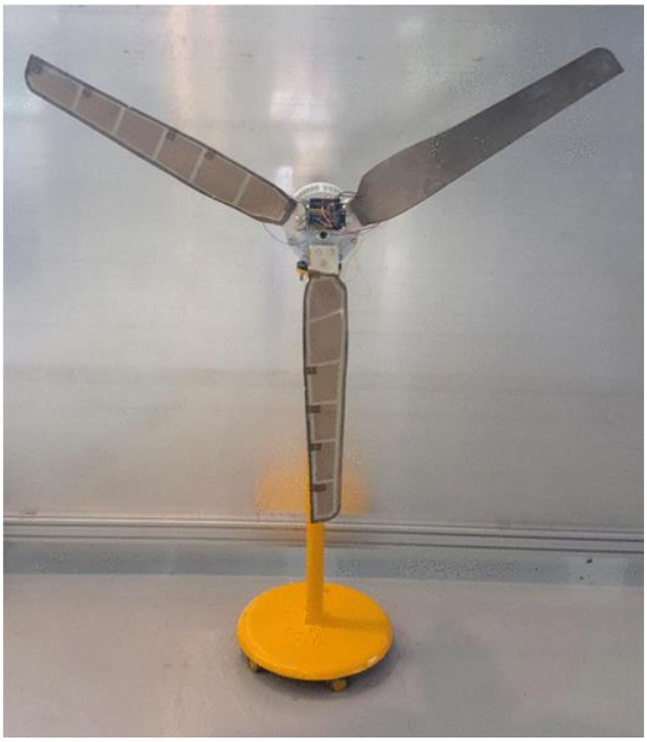

Figure 9 Turbine blades coated with 0-3 piezoelectric composite sensors (image taken from Kang and Kang, 2017)

Data collection

The experiment carried out by Kang and Kang (2017) demonstrated that the 0-3 piezoelectric composite sensors had a 100% detection rate. However, this is based on a laboratory experiment using a small sample of 30 impacts and small-scale model turbine. This technology would have to be paired with additional technologies (e.g., camera and radar) in order to estimate species specific empirical collision rates and obtain data leading up to the collision event.

Data processing and data analysis

The signals from the 0-3 piezoelectric composite sensors are acquired and converted by the ADC of the development board (embedded system installed at the turbine) with the converted data transmitted by wireless ZigBee communication (Kang and Kang, 2017). The receiver sends the received data to the PC (onshore) via serial communication with results viewed in MATLAB. Impacts are therefore displayed on the monitor as the sensor is impacted with little delay.

Recommendations

It is unclear how well this system would function in adverse weather conditions such as those found offshore (i.e., in rainy or icy weather). However, it does show potential and could obtain data on the occurrence of bird collisions. Significant further research on this technology in an offshore setting would be required for its integration into an operational monitoring project.

3.1.4. Bio-logging (animal tracking)

Animal tracking gives insight into individual movement and behaviour (i.e., flight height and flight speed) and can allow for data on bird habitat use across an individual's home range. There are a wide range of different bio-logging devices which have been attached to free-living birds, but those most commonly associated with monitoring potential collision with offshore wind farms are GPS loggers and transmitters (Wade et al., 2014; Thaxter et al., 2015a; 2018; Garthe et al., 2017a; 2017b; Peschko et al., 2020). These devices provide precise coordinates of instrumented individuals and may also provide information on flight height if the sampling interval is frequent enough (Ross-Smith et al., 2016). Loggers are archival and therefore must be recovered whereas transmitters have the advantage of uploading fixes via satellite uplink and could therefore be used to determine collisions.

Not every bird can be fitted with a GPS device due to the weight, with devices weighing about 1g upwards. Radio-tagging offers an alternative solution for small-bodied species (<100g), with tags weighing below 1g (Perrow et al., 2006; Ponchon et al., 2012). In some instances, bird behaviour has been influenced by the presence of a tag (Thaxter et al., 2015b; Seward et al., 2020), with some individuals also spending less time at nesting sites (Seward et al., 2020). As both systems have been utilised effectively in the offshore environment, both are discussed below.

3.1.4.1. Radio-tagging

System design

The emitted signals from radio tags can be detected either by hand-held devices or a base-station (Loring, 2016). This allows information on, for instance, colony attendance (Votier et al., 2011) and also at-sea movements based on triangulation to be recorded (Votier et al., 2006), although at relatively low precision. Radio-tagging has been used to assess Little Tern habitat use within the development zone for Scroby Sands offshore wind farm in the UK, although this involved following instrumented birds with a high-speed RIB to identify foraging locations (Perrow et al., 2006). A more general study by Paton et al., (2021) provides detailed information on the different types of antennas that can be used and their benefits.

System functioning

Generally, to avoid causing potential adverse effects to the bird tagged, tags should be between 1 – 2% of the bird's body mass (Loring, 2016; Seward et al., 2021). However, some species may still respond negatively to tagging (Thaxter et al., 2016) and careful consideration should be given to other important factors such as device shape, position, attachment methods and avian biology (Bodey et al., 2018).

If using hand-held devices to collect data from the radio tags, the tagged bird must be within range. Perrow et al., (2006) reported that the range of the tags used had to be within 1km of the recording device. The detection range of the antenna depends on its height and type, with antennas capable of having a detection range of 2-20km (Paton et al., 2021).

Location fixes can be recorded every two minutes when tracking with hand-held receivers, with automated radio telemetry stations allowing for birds to be monitored continuously as long as the individual is within range (ten to hundreds of signals per minute can be received; Bridge et al., 2011). Conducting regular telemetry surveys by boat or plane is an effective way to supplement locations collected by the automated radio telemetry towers and relocate individuals that may have moved outside the range of the radio antenna (Loring, 2016).

Signals emitted by the transmitters travel within line-of-sight, and so factors such as topography, vegetation, and electronic noise can block, reflect, or attenuate the signal (Kenward 1987). Additionally, poor weather and technical failure of the receiver and tags can limit data collection.

Hosting/logistical requirements

The attachment method of the tag needs to be lightweight and able to withstand high-impact foraging strategies, but also must be attached in such a way to not negatively impact the bird. For example, attaching tags to leg bands can result in leg injuries, reduced body mass and reduced inter-annual return rates (Nisbet et al., 2011; Mostello et al., 2014). Back-mount techniques result in less apparent adverse effects on behaviour (Perrow et al., 2006) and have been used in several studies on small species such as terns (Hill and Talent, 1990; Becker et al., 1993; Whittier and Leslie, 2005; Perrow et al., 2006).

The average life span of a back-mounted tag (Figure 10) before the tag falls off or after the battery expires can vary depending on the species and material used, however can be extended using a combination of adhesive and subcutaneous structures (Warnock and Takekawa, 2003; Hawkins, 2004) and larger battery sizes where it is safe and appropriate to do so (Loring, 2016).

Figure 10 Back-mounted radio tag fitted to an adult Little Tern (image taken from Perrow et al., 2006).

Data collection

Data collected from radio-tagging can be used to assess the species' risk of collisions as information on their habitat use, avoidance, flight altitude and speed can be obtained. This information can only be obtained if the tracked bird is followed on a boat, which can be difficult if fast flying species are the tracked species. If antennas are used inside the wind farm, data on meso-avoidance behaviour could be obtained over extended periods of time via triangulation (Paton et al., 2021). By using multiple devices, movements throughout the diel period and during all types of weather conditions can be monitored (Kunz et al., 2007; Burger and Shaffer, 2008). This information can be used to assess demographic variation in use of offshore areas, including species, breeding population, age, and sex (Montevecchi et al., 2012; Loring, 2016).

Data collected can be used within CRM, however empirical collision rates cannot be estimated using this technology. Information obtained from radio-tagged individuals can provide insight into macro and meso avoidance behaviour (Perrow et al., 2006; Loring, 2016).

Data processing and data analysis

Programs such as ArcGIS and R Studio are capable of analysing tracking data, with packages such as “sensorgnome” allowing for raw detection data to be processed and data that is valid to be separated (Brzustowski, 2015; Loring, 2016).

Birds’ positions can firstly be recorded by plotting the bearing and estimated distance from the receiver of each fix onto a dGPS plotter and then subsequently to a GIS database. Data from all birds can be pooled, and tests such as Mann–Whitney U-tests can be used to test for differences between periods of time and for the different parameters (Perrow et al., 2006).

Additionally, Ranges software can be used to plot 100% minimum convex polygons (MCPs) around fixes collected for each bird, which are then used to estimate the tagged bird's range (Perrow et al., 2006). Maximum range area and range span can be calculated.

Basic outputs from analysed data are:

- percentage of time spent in different activities – at nest, foraging, loafing and flying above the beach typically as a result of disturbance of varying sorts;
- number and duration of foraging bouts per hour;
- total estimated distance travelled in a foraging bout – also converted to flying speed (km/h); and
- minimum, maximum and mean distance (m) of fixes from shore (Perrow et al., 2006).

Recommendations

Radio-tagging can allow for additional data on bird movement across a geographical location to be obtained and could be used to complement other monitoring technology. By tracking individual behaviour, robust data on avoidance rates can be fed into modelling and can improve the overall accuracy of the results (Green et al., 2016).

Within Paton et al., (2021), it is stated that if antennas are to be used, multiple antennas would need to be installed on the turbines and in a configuration that allows for adequate coverage of a wind farm, with four antennas required to provide maximum coverage in all directions. However, it is advised that omnidirectional antennas in the offshore wind farm environment are not used as they perform poorly at detecting radio signals (omnidirectional antennas have a much more limited range of around 500m; Taylor et al., 2017).

In addition, if antennas are a part of the Motus network, individuals tagged for other studies can also be detected by the radio towers (the Motus Wildlife Tracking System is a research approach and involves the development and collaboration of radio-tracking via a programme network stations; Taylor et al., 2017). This system could be useful in helping record macro-avoidance behaviour and potentially has application in assessing differential survival rates between birds that use wind farms (or home ranges containing wind farms) and birds that do not (or have low encounter rate with wind farms).

3.1.4.2. GPS

System design

GPS tags provide high precision location information on instrumented birds enabling a detailed understanding of behaviour and movement. Tags either transmit data (via satellite or GSM uplink) or archive information which is recovered from a base-station at a focal point or by re-catching the bird. The smallest GPS devices are still relatively heavy (>1g) and are therefore unsuitable for use on small-bodied (<100g) birds (Seward et al., 2021). They have, however, been used widely on a number of larger-bodied species.

System functioning

A large number of seabirds have been tracked using GPS tags, including studies in relation to offshore wind farms such as Guillemots (Peschko et al., 2020), Lesser Black-backed Gulls (Thaxter et al., 2015a; Vanerman et al., 2020) and Northern Gannets (Garthe et al., 2017a).

Devices can be set to record fixes at a wider range of intervals from multiple times per second upwards and have variable duty cycles to optimise coverage of important periods of time. This can generate very large datasets depending on the attachment method (i.e., long-term or short-term deployment) and power source (i.e., steady state batteries or solar panels).

Factors such as tags detaching and battery depletion can cause GPS tags to fail, with studies such as Campion et al., (2020) recording a mean failure rate of 30%, ranging between 7–60% across individuals; out of the 1799 collected fixes, 76% were accurate. Tag failure does not always occur, however as a precaution, a reasonable number of birds should be tagged in order to ensure robust data can still be collected if some transmitters do not successfully transmit data (e.g., in Peschko et al., 2020, 13 Guillemots were tagged, with 12 successfully recording information on 204 individual foraging trips).

Hosting/logistical requirements

Depending on the size of GPS-logger used, some can be installed with technologies such as ultra-high frequency (UHF) radio, built-in ZigBee transceiver with whip antenna and Global Systems for Mobile Communications that allow for remote download (Bouten et al., 2013; Masden, no date). Smaller GPS tags simply store the data and require the bird to be recaptured and the tag retrieved (Molis et al., 2019).

Tags can have an operational lifespan of 1 – 2 years (McKinnon and Love, 2018), but can be fitted with a solar panel to allow the battery to recharge (expanding the lifespan of the tag). They can have an accuracy of within 10m (McKinnon and Love, 2018; Liu et al., 2018), however the location accuracy can be negatively influenced by factors such as the environmental conditions and movement intensity of the tagged bird.

Trackers can be attached to body feathers such as the back and tail using Tesa tape or cable ties. This approach is favoured for short-term deployments since the tag falls off during moult or because the attachment fails. Long-term deployments can be achieved by using a harness or surgical implants. However, while harnesses work well for some species, they are not appropriate for others as they can lead to very high levels of mortality (Thaxter et al., 2016).

Data collection

GPS devices record the date, time, and position (latitude, longitude) within the scheduled sampling interval. The device can obtain data on flight height and speed, allowing for behaviour to be reported (e.g. if the bird was foraging, resting or travelling). Information on macro-avoidance behaviour can also be obtained and seasonal patterns in habitat use can be estimated. For example, Thaxter et al., (2015a) reported that Lesser Black-backed Gulls used the offshore wind farm area more during the pre-breeding season compared to during the incubation period, before activity within the offshore wind farm increased again during the chick-rearing period. This information can allow for the times of increased (and decreased) activity within the site to be identified, allowing for the appropriate avoidance rate to be incorporated into modelling depending on seasonal behaviour.

Another study by Garthe et al., (2017) highlighted the benefits of conducting post-construction GPS monitoring, showing that Northern Gannet activity within the wind farm decreased with the tagged individuals exhibiting clear avoidance behaviour. These results indicated that direct mortality from collisions would be lower than initially estimated.

Thaxter et al., (2018) reported that it was also possible to estimate meso-avoidance behaviour from data transmitted from GPS tagged individuals.

Data processing and data analysis

A large range of analytical tools have been developed to extract biological inference from animal tracking data. They are too varied to be discussed effectively here (see papers by Thaxter et al., 2015a; Borkenhagen et al., 2018; and Peschko et al., 2020), but they can be used effectively to quantify movement responses to wind farms and therefore provide a more detailed understanding of any potentially deleterious impacts.

Recommendations

Repeated tracking of the same individuals may help identify changes in birds' responses over time to existing wind farms and therefore provide information on species specific macro-scale avoidance. Tracking can provide data to describe bird behaviour more accurately within operational wind farms, allowing the modelling of bird flight speed, height and distribution in relation to seasonal, environmental and wind farm operational parameters. This is of particular interest in the case of breeding birds that may become accustomed to wind farms over long periods of time, in contrast to migrating birds which may only encounter the same wind farm sites a few times per year (Garthe et al., 2017a). This technology may also provide further information on the impacts of barrier to movement and identify areas where species disperse to if disturbed by the wind farm. The combination of tracking data with other multi-sensor monitoring studies of collision risk offers the potential to improve parameterisation of models and validate estimates of collision risk.

3.2. Review of monitoring systems

As discussed within section 3.1, many of these individual monitoring technologies can be enhanced by combining them into an integrated system, allowing for reliable and valuable quantitative data on bird avoidance responses and/or instances of collision events to be obtained (Desholm et al., 2006; Plonczkier and Simms, 2012; Dirksen, 2017; Molis et al., 2019).

Several monitoring systems have been developed that utilise different combinations of visual daytime observational, thermal imaging, radar, acoustic recording and tracking technology (such as those described in section 3.1) in order to optimise data collection and enhance the quality of information gathered. Previous studies by Dirksen (2017) and Molis et al. (2019) have provided an overview of these systems, with this section building upon those descriptions and incorporating technical information gathered from published monitoring reports, developers' websites and interviews in order to highlight their strengths and limitations.

Due to time constraints, if contacts did not respond to the request for interview by September 2021, no further contact was made and information presented within each monitoring systems section was gathered from publicly available literature and from websites only. Appendix 4 contains all interview responses.

During the review process in November 2021, additional monitoring systems that are relatively new were flagged for inclusion within this literature review, however due to time constraints they have not been included within the main body of this document. Appendix 4 provides further information that was publicly available from developers' websites on these three additional systems.

Table 3 below details the sources where information within each system's section has been taken from.

Table 3 Cited literature and named contacts for each monitoring system described within Section 3.2 Review of monitoring systems

Monitoring system	Information sources
MUSE	Skov et al., 2018, Tjørnløv, 2021, personal communication Armitage, 10 August 2021
WT-Bird	Verhoef et al., 2004, Lagerveld et al., 2020, Wiggelinkhuizen et al., 2006a, Dirksen, 2017, Wiggelinkhuizen et al., 2006b, Verhoef et al., 2003, Krijgsveld et al., no date
DT-Bird	Harvey et al., 2018, May et al., 2012, Aschwanden et al., 2015, manufacturer's website
ATOM	Willmott et al., 2015, Willmott & Forcey, 2014, personal communication, Willmott 19 November 2019
Wind Turbine Sensor Array	Suryan & Polgaye, 2016, Hu et al., 2017, Albertani et al., 2018, Clocker et al., 2021, personal communication, Albertani 23 December 2021
IdentiFlight	McClure et al., 2018, McClure et al., 2021, manufacturer's website
Spoor AI	Personal communication Coronado-Garcia, 26 August 2021
ACAMS	Adams et al., 2017, Mellor & Hawkins, 2013, Albertani et al., 2018, Dirksen, 2017

B-finder	Przybycin et al., 2019, Lagerveld et al., 2020, manufacturer's website
ID-Stat	Delprat & Alcuri 2011
MultiBird	Manufacturer's website
Bird Migration and Collision Monitoring System	Personal communication Schorcht, 13 October 2021, personal communication Nanninga, 26 November 2021
Birdtrack®	Tome et al., 2017, personal communication Goncalves, 27 October 2021, manufacturers website
Bird Protection System	Kielanska et al., 2020, Gradolewski et al., 2021, personal communication Gradolewski & Jaworski, 25 August 2021, manufacturer's website

3.2.1. MUSE

Developer	DHI Group
Contacted	Yes
Responded	Interview held with Mike Armitage, 10 August 2021. Questionnaire returned 11 August 2021. Details checked by Henrik Skov April 2022.

System design

The MUlti SEnsor (MUSE) system combines both radar types (horizontal and vertical) and pan-tilt camera technology and utilises a high-speed processing software that allows birds detected by the radar to be automatically targeted by the cameras 24/7. The camera tracks the bird using motion detection and AI technology and can record seabird moments over an extended period of time. Thermal capabilities can also be included to allow for daytime and night-time tracking.

MUSE is currently installed at the Aberdeen European Offshore Wind Deployment Centre, Luchterduinen and Block Island USA. The system is based on the system deployed at Thanet offshore wind farm for the ORJIP Bird Collision Avoidance study (Skov et al., 2018).

System functioning

MUSE is capable of identification to species level with the daylight camera systems in operation. At Aberdeen, the system utilises two pan-tilt cameras with strong zoom - one daylight camera and one combined daylight-thermal camera.

Cameras can be hampered by poor weather and it can be difficult to identify to individual species level from data collected by the thermal camera. Species group may be identified based on approximate size.

Depending on how many cameras and radar systems are installed, all turbines within a facility can be covered. At the Aberdeen offshore wind farm for example, nine other turbines are within the field of view by the combined radar and pan-tilt camera system.

A series of theoretical (modelled) tests of the radar detection probability of different sizes of birds (radar cross sections) demonstrated good detection of passerines to 3km, of gulls to 4km, of gannets to 5km and of large flocks of birds to 6km during sea state 0. Seabirds cannot be detected by the radar closer than around 30m from the radar due to the angle of the radar beam and the height of where the system is installed above sea-level. Using the camera, the range at which movements of seabirds can be tracked is approximately 1km, and the minimum distance is approximately 50m.

The system has an operational performance of between 80-98%, however can be affected by technical and mechanical failure. The Aberdeen monitoring program reported an overall mean performance rate of the radar of 61% during the 2020 monitoring season, with down-time due to power-outages and occasional hardware failures, compounded by inaccessibility of the equipment during movement restrictions imposed as a result of the coronavirus pandemic. It is mentioned that after updated configurations, the system is set to have a 95% performance rate going forward (Tjørnløv, 2021).

Not all tracks are picked up by the camera and not all videos have radar tracks. Due to the use of efficient clutter filters the radar has very low levels of false positive bird detections. On average false negative detection rates occur <15% of the time. The radar does not record the fine scale movements of birds within the RSZ of turbines due to being affected by clutter from the rotor blades.

Hosting/logistical requirements

MUSE utilises the Furuno FAR-3000 radar due to its clutter suppression and bird tracking capacity. The radar is oriented horizontally and movements of birds in the wind farm area are tracked automatically. The radar processor samples at 100MHz and performs real time filtering of standardised echo sizes based on calibrated dB-values from the radar.

The radar software package used for running the automated radar tracking within the wind farm is subdivided into a data acquisition and pre-processing module and a software package MUSE for controlling the data processing. MUSE ensures that radar track data are stored with the camera data. A time delay of up to several deci-seconds may be introduced between the radar detection and the initiation of the camera tracking.

The system has been deployed on the turbine platform (Figure 11) with the control unit stored inside the turbine. To date, there has been no attempt to install the system anywhere else besides the turbine platform. The system requires little maintenance and can be deployed for several years.

Figure 11 MUSE system installed at Aberdeen European Offshore Wind Deployment Centre (images taken from DHI MUSE website)

The control cabinet for the system plugs into the turbine power system and so cabling is required between different equipment, and a Wi-Fi link to communicate between equipment is needed. At Aberdeen, additional Wi-Fi capability was installed for communication because it was not logistically possible to access the fibre cable network of the facility. Equipment can be installed on existing turbines after construction. There is reportedly no impact to the performance of the turbine due to the presence of the monitoring equipment.

Data collection

MUSE aims to measure bird flight behaviour and avoidance around the turbines and collects reliable information on flight speed, flight height, meso-avoidance and micro-avoidance. As the cameras are not just monitoring the RSZ however, but rather are guided by the radar to detect and record bird flight behaviour. The system at Aberdeen has not been designed to monitor collision rates, but to provide continuous and representative samples of seabird flight behaviour at different distances to turbines.

Avoidance rates can be estimated based on observed avoidance behaviour which can be used within CRM. Data from the thermal camera also provides information that may help inform nocturnal activity rates. Updated information on flapping/gliding behaviour in the presence of the rotor blades could be obtained. In summary, the MUSE system is capable of gathering accurate data on bird behaviour which could improve collision models.

The MUSE system does not aim to estimate flux rates, however it could be adapted by using a fixed camera on a turbine position to measure flux at the turbine scale and to monitor collision rates.

Data processing and data analysis

Radar tracks and video clips are recorded and all stored locally on the control unit. They are copied to an external hard drive, which is retrieved by the site team every 2-3 months. However, remote access to data is also possible. The MUSE system also automatically stores radar screen images every two seconds. Radar data is displayed within ArcGIS, with bird behaviour logged within an excel database which can be put through R mixed model analysis.

Flight height can be estimated by triangulating the radar and video recordings of the same individual in close to real time for selected species. The estimated flight height can then be added to the video track data. The resolution of the 3-D tracks is similar to the 2-D tracks (approximately 30m between track nodes) which is sufficient to generate good statistics on flight heights (Tjørnløv, 2021).

To estimate seabird flight speeds in the wind farm from the radar tracks, the mean speed per segment of a track rather than the mean speed measured over the whole track is used. Flight directions can be assessed from the radar tracks by calculating the direction of a bird relative to the orientation of the rotors at that time (Tjørnløv, 2021).

Recommendations

The MUSE system has been used to research bird flight avoidance behaviour at nine operational wind farm sites in the US, Europe and Asia. At Aberdeen, this has been limited to the micro- and meso-scales. However, there is additional capability to assess species-specific flight behaviour at the macro-scale if cameras are positioned to record activity beyond the wind farm boundary. However, for large sites this might require numerous cameras to be integrated in the system. To aid with species identification of thermal imagery, microphones could be installed onto the platform. Additionally, visual or vibration sensors could be linked to detect collision events (e.g., piezoelectric paints - noting early developmental stage of this technology - B-Finder, WT- Bird, or the Wind Turbine Sensor Unit developed by Oregon State University). The system could also be adapted by integrating cameras fixed onto adjacent turbine rotor swept zones to collect empirical collision rates but has not been installed or tested with this purpose to date. The advantage of the MUSE system for this method is the associated radar tracks for birds recorded by cameras and the ability to move cameras to fix on a sample of different turbines to improve spatial coverage within the wind farm using a smaller number of cameras.

3.2.2. WT-Bird

Developer	Energy Research Centre of the Netherlands.
Contacted	Yes. First email sent 10 August 2021. Second email sent 13 September 2021.
Responded	Developer did not respond to either email. Due to time constraints, no further attempts to arrange a call were made.

System design

WT-Bird aims to identify bird impacts by noise monitoring, utilising a camera system to identify the specific species that collided with the turbine. The system has been installed offshore at Egmond aan Zee. Testing of the system has occurred since 2004 (Verhoef et al., 2004), with updates to the system and further testing commencing in 2020 (Lagerveld et al., 2020). Results from this testing are yet to be published and the system is not yet commercially available.

The number of installed cameras can vary, with four near-infrared camera devices installed at Egmond aan Zee in order to monitor the full rotor-swept area (Wiggelinkhuizen et al., 2006a; Dirksen, 2017).

System functioning

The near-infrared cameras allow for species identification to take place. Monitoring reports from Egmond aan Zee suggest that medium and large sized birds can be easily detected by the sensors, however registered collision events from smaller birds such as songbirds can be missed (Wiggelinkhuizen et al., 2006b; Dirksen, 2017).

WT-Bird aims to record and gather data on bird behaviour within the micro-zone and so the system directly records the rotor swept area only.

During testing, it was reported that all hits to the turbine blades were registered and data recorded (Verhoef et al., 2003). Detection is based on acoustic monitoring, with the turbine monitored 24/7 and sound signals analysed automatically to detect any abnormalities against the normal turbine noise. When an abnormality is registered, images from the camera and recorded sound are stored.

The intensity of background noise can influence detection probability and a peak in the sound level is the initial trigger for the image recording system. The way the bird collides with the turbine also affects the system's ability to detect collision events. It has been reported that five to ten false triggers per day due to background noise can be recorded (Wiggelinkhuizen et al., 2006b).

Hosting/logistical requirements

Sensors are installed onto the blades of the turbine (typically two per blade), along with microphones (mounted on the turbine hub and another installed at the bottom of the turbine) and camera devices (Figure 12). Acoustic impacts are recorded, along with visual footage of the minutes prior to, during, and after the impact, thus providing information on collisions and species involved.

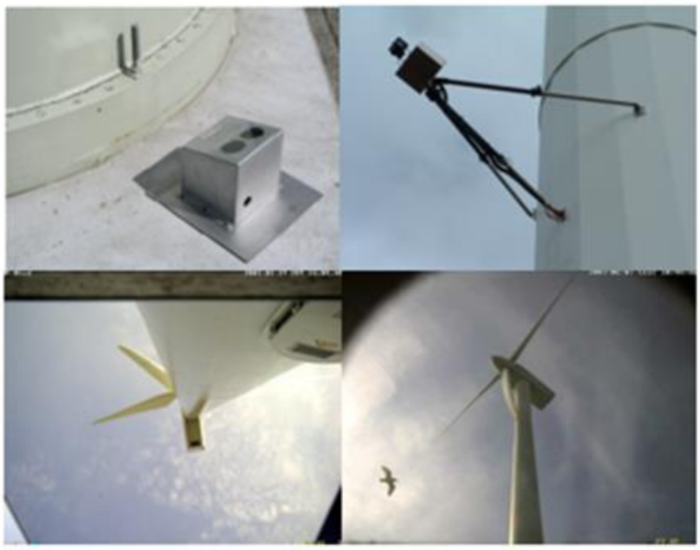

Figure 12 WT-Bird system installed on a wind turbine in Den Helder (images taken from Verhoef et al., 2004)

Data collection

Currently the results from the Egmond aan Zee testing are not publicly available, however it is stated that information on the number of collisions, seasonal and diurnal distribution of collision events, bird species involved, bird fluxes at the time of the event, and flight patterns can all be estimated from using the WT-Bird system (Krijgsveld et al., no date). Results obtained from WT-Bird could be used to improve the accuracy of

CRM estimates and the system could be used to derive empirical collision rates at the individual turbine scale.

Data processing and data analysis

The images from the camera and the recorded sound fragment are stored on the local disk on a PC located in the tower base or can be sent directly via the network to a PC onshore (Wiggelinkhuizen et al., 2006b). All registered collision events are checked to identify the species and record, where possible, the fate of the impacted bird.

Sound measurement can be analysed using noise analysis techniques like the well-known FFT technique (Fast Fourier Transform). However, it is still unclear how effective this method is at producing good results.

Recommendations

The WT-Bird system collects collision data and, potentially, flux data at the individual turbine scale. Multiple units would be needed to deploy at a wind farm scale to sample at multiple turbine locations. The system could be integrated with other systems that record flight trajectory (e.g., radar, or other radar-integrated systems) to obtain additional data about the birds' movements at the meso- and macro-scale beyond the rotor swept zone.

3.2.3. DT-Bird

Developer	Liquen Consultoría Ambienta, S.L, Madrid, Spain.
Contacted	Yes. First emailed June 2021
Responded	Developer responded, however no further information was provided

System design

DT-Bird is designed to help mitigate collisions at wind farms by implementing up to three mitigation measures. The first mitigation measure is an acoustic warning signal that is triggered when a bird is approaching a wind turbine (module "warning") within a given detection range. On a second level, if the bird is still approaching the wind turbine an acoustic deterrent signal is triggered by the system (module "dissuasion"). Finally, on a third level, if the acoustic signals do not lead to a reaction of the bird, the wind turbine can be stopped on demand (module "stop")

The system has been widely deployed at over 80 onshore and offshore wind farms in 14 countries and for the purposes of this review, information about its use has been collated from onshore wind farms in California, Smøla, Norway and Haldensteind at Chur, Switzerland. The system has been deployed offshore since 2016 at Fino 1 in the North Sea and more recently at Kincardine Offshore Wind Farm in the UK, however results gathered from offshore monitoring projects were unavailable for review (DTBird Team, 2021).

System functioning

Species group and bird behaviour can be noted from the video recordings. Birds between the sizes of 1.9 – 2.25m can be detected up to 320 – 380m away when four cameras are used, and up to 550 - 650m when eight cameras are used. Birds around the size of an Atlantic Puffin (0.47 – 0.63m) can be detected at about 80 – 100m away with four cameras and 130 – 180m with eight cameras (DTBird Team, 2017). Cameras cover the rotor swept area upwards and the approach zone towards the turbine with a view angle of 90°.

An example of spatial coverage thresholds is shown in Harvey et al., (2018) where a threshold of 240m from the camera was used before the object was classed as a detection. Once the bird flew within 170m from the camera, a warning signal was then emitted. If the bird stayed within the low risk zone (set at 170m) an additional signal was emitted. This would continue until the bird was no longer within the risk zone. Turbines were stopped if the bird then passed within 100m of the rotor.

The detection probability is dependent on the size of the bird and visibility conditions. Bird detectability is >80%, with onshore results indicating that the system recorded between 76-96% of all bird flights in the vicinity of the turbines during the day (May et al., 2012; DTBird Team, 2017). It is stated within Aschwanden et al., (2015) that the use of additional cameras on higher positions of the tower would increase the size of the surveyed area for birds smaller than Red Kites.

False positive rates seem to be heavily influenced by air traffic and insects, with the results obtained from the study carried out in Switzerland showing that only 30.5% of the targets detected by the camera were in fact birds (Aschwanden et al., 2015). However, it is detailed that the reason for this high false positive rate was due to the unexpected amount (>4 per day) of helicopters passing near the system, thus triggering the camera. Harvey et al., (2018) reported a false positive rate of 2.5% when reviewing the system at the Wind Energy Facility in California. The study carried out in Norway (May et al., 2012) showed a false positive rate of 1.2 per day (video sequences), which is in line with the proposed function from DTBird (< 2 false positives per day).

Hosting/logistical requirements

The DT-Bird system consists of between two to eight cameras per turbine (daylight and thermal capabilities), providing 360° coverage of the rotor swept area (dependent on the number of cameras used), two to eight speakers per turbine and the system is capable of recording relevant meteorological data (Figure 13) (Harvey et al., 2018). It is designed to detect birds at risk of colliding with the rotor blades and emit deterrent signals and/or stop the turbine in order to reduce instances of collision. The systems are attached onto the turbine tower.

The thresholds for each of the mitigation measures are set manually and can be adjusted accordingly to allow for sufficient time and space for a successful deterrence response to occur.

Figure 13 DT-Bird system, camera field of view and recorded detection (images taken from DT-Bird website)

Data collection

The system is not designed to detect direct collisions, however as video camera footage and audio is available, recordings could be viewed and collision events could be identified. DTBird data could be used to estimate micro-avoidance rates if the quality of the images showing the collision event were of good enough quality, allowing for the species to be identified. Empirical collision rates could be estimated for each turbine on which the system is deployed because video data immediately leading up to the collision and the collision events are registered.

Onshore results from the Haldenstein at Chur wind farm in Switzerland (Aschwanden et al., 2015) showed that there was a mean number of 0-3 animals/(km*h) during the day and 2-12 animals/(km*h) during the night exposed to collision risk. This was determined due to the number of times a deterrent signal (with recorded footage checked for bird sightings) was triggered. This meant that depending on the length of the day and the night, 13 (SD ±10) animals per day and 42 (SD ±30) animals per night, resulting in a total of about 2,300 animals, were exposed to a collision risk during the two month survey period.

Given the assumption that the period contained 50% of the animals of the migration season, the numbers were then doubled to get a value for the whole autumn migration season. Thus, it was estimated that about 4,600 animals were exposed to a collision risk during autumn migration season. This meant that an average of 25 birds per day (24h) in relation to six months (184 days) in the second half of the year were exposed to a collision risk.

Data processing and data analysis

Videos of every bird flight, environmental data, wind turbine operational parameters and DTBird actions (acoustic warning/deterrent or on-demand shut-down) are recorded and uploaded daily to an online Data Analysis Platform (DAP), accessible through the internet. For each detection event, the following information is recorded within the database:

- Date and hour

- Flight length (sec)
- Direction the turbine nacelle was facing (degrees)
- Wind speed (m/sec)
- Rotor status: was it spinning or not
- Illuminance level (lumens/m2)
- Warning initiation (start and end times of each deterrent: init.)
- Warning duration (sec)
- First detection camera: camera ID that first detected the object

For analysis, three-dimensional flight trajectories can be composed out of the locations of a target and for each flight trajectory, the closest point to the nacelle of the wind turbine is determined by dropping a perpendicular line connecting two localisations to the nacelle. In doing so, it is then possible to calculate the closest approaching distance of a bird before avoidance action is taken in respect to the wind turbine.

Recommendations

It is unclear how well this system functions within the offshore environment as results from the three offshore projects the system is currently deployed at, were unavailable for review due to confidentiality agreements. The results from onshore studies show promising results however (e.g., Aschwanden et al., 2015), and the multiple deployments around the world indicate a good level of confidence within the industry.

The DT-Bird system is designed to detect birds (and bats) approaching a turbine and to implement acoustic deterrents or shut down-on-demand to minimise collision risk. However, in the absence of the deterrent measures, the system has the capability to monitor collision rates and, potentially, flux data at the individual turbine scale. Multiple units would be needed to deploy at a wind farm scale to sample at multiple turbine locations. The system could be integrated with other systems that record flight trajectory (e.g., radar, or other radar-integrated systems) to obtain additional data about the birds' movements at the meso- and macro-scale beyond the rotor swept zone.

3.2.4. ATOM

Developer	Normandeau Associates, Environmental Consultants, USA
Contacted	Yes. First email sent 10 August 2021
Responded	Interview held with Julia Willmott, 19 November 2019. Questionnaire returned 21 December 2021. Detailed checked by Julia Willmott March 2022.

System design

The Acoustic Thermographic Offshore Monitoring (ATOM) system combines thermal imagery, ambient light imagery, vhf receiver, and acoustic technology with ultrasound sensors to allow for birds potentially affected by offshore turbines to be monitored. ATOM was originally designed to collect bird (and bat) activity data within the rotor swept zone and utilises two thermographic cameras, one ambient light camera, one vhf receiver, two acoustic microphones and two ultrasonic microphones to record data. The prototype of the system was described in Willmott et al., (2015).

ATOM has been tested at onshore wind farms (e.g., wind turbines at University of Delaware) and has been successfully deployed offshore at Frying Pan Shoals Light Tower off the US coast and at two operational offshore turbines offshore VA, USA. No further information on its capabilities at offshore wind farms is published, however it is stated that the system is offshore ready (personal communication, Willmott 19 November 2019).

System functioning

Depending on the quality of images, species recorded can be identified down to individual species level, with the acoustic data aiding with identification if the timestamps of both files overlap.

The camera can be installed on the turbine platform, a static buoy (which would require a power source via solar panels etc.) or on a substation, all of which would allow for the full rotor swept zone to be monitored. The system is bolted on either to the platform rails or a fabricated stand (Willmott pers. comm.).

Birds can be detected up to 180m, with acoustic data and VHF receiver data able to fill information gaps on small birds flying higher than 150m that might otherwise be missed by ambient light or thermographic technology due to the decay in detection over distance for smaller birds. It is stated that there are gaps within the field of view when the monopole blocks the view when only one system is deployed (Willmott and Forcey, 2014; Willmott et al., 2015).

ATOM utilises modified SwisTrack software to identify bird tracks, with the success rates of bird detections from within the video imagery ranging from below 15% to over 60% (Willmott et al., 2015). Success can vary depending on the number of video frames containing multiple birds. The SwisTrack software has difficulty discriminating between individual birds when multiple birds are flying within the camera's field of view.

Information on false positive/false negative rates is limited, however from the onshore testing, 34 video segments were recorded as false positives due to clouds (Willmott and Forcey, 2014). Information regarding offshore rates is currently unpublished, however personal communication with Willmott (19 November 2021) revealed that detection was very high and false positive rates did occur. This has since been checked and improved, although details on the improvements made to reduce instances of false positives is unpublished.

Hosting/logistical requirements

The system at the Frying Pan Shoals Light Tower (Figure 14) consisted of: a Verizon cellular modem and a Hughes satellite modem connected to different computers; two FLIR Tau 320 (Forware Looking Infrared) cameras and an integrated custom-built wiper system; two Bolide Technology Group BT-MP8087 acoustic microphones; one AR 125 ultrasonic microphone (Binary Acoustic Technology, Tucson); an integrated meteorological system recording visibility, temperature, wind speed and direction and humidity (Columbia Weather Systems MicroServer); and a power monitoring system (Power Control Hub) with built in satellite communication.

All sensor data received by the control computer is transferred to the storage system, with separate computers that comprised the central core of the ATOM system housed in custom-fabricated weatherproof containers. One houses the storage computer and storage drives, and the other is used for the remaining computer and the two thermographic cameras.

Data transfer, storage and analysis is then undertaken onshore and data is uploaded to the ATOM-dedicated Linux server from hard drives in the ATOM data storage system. Acoustic audio files are originally recorded as DAT files, which are then subsequently converted to CAF files for storage and eventually analysed as 16-bit PCM "wav" files.

Additionally, the cameras were installed with a wiper system to allow clear images to continuously be recorded and stereo thermal capabilities to give continuous records of flight height (Willmott, pers. comm.).

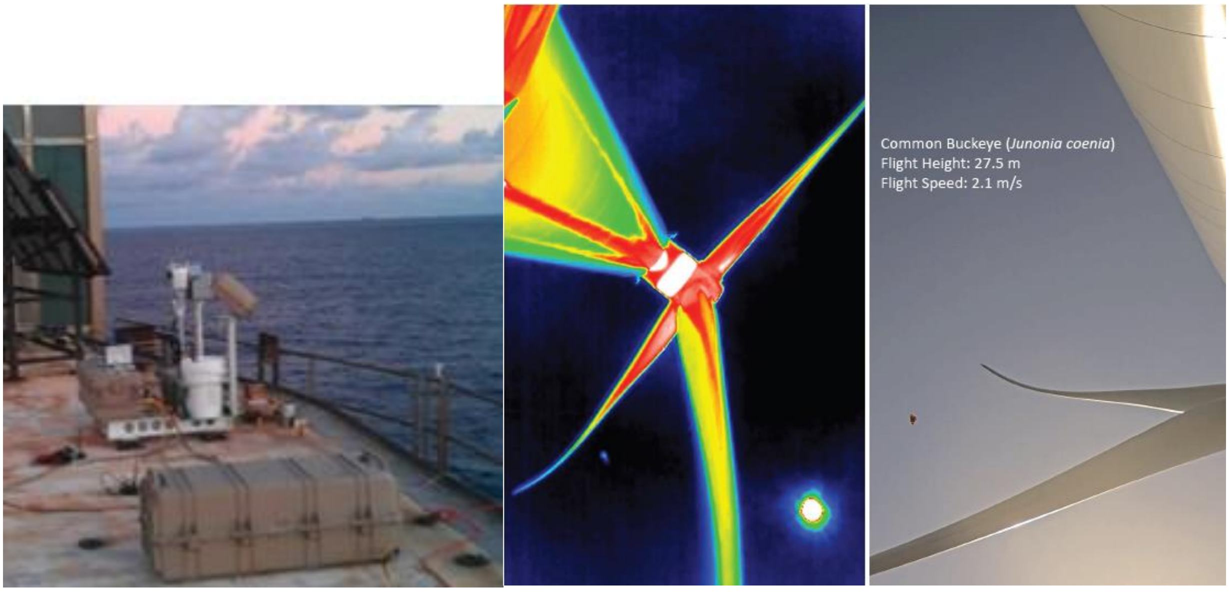

Figure 14 (Left) ATOM system deployed at the Frying Pan Shoals Light Tower (Image taken from Willmott and Forcey, 2014). Images on right provided by personal communication Willmott, 19 November, 2021

Data collection

The system is designed to survey birds and bats within the rotor swept area of a turbine, and therefore micro-avoidance behaviour can be recorded. Acoustic data also fill information gaps on small birds flying higher than 150m that might otherwise be missed by thermographic technology due to the decay in detection over distance for small birds.

Each thermographic record includes the month, timestamp, altitude, direction, and speed. The thermographic and acoustic data together can determine how many birds are in a flock along with the date, time, and season. The system is not designed to detect collision events, but collisions may be recorded by the camera.

Data processing and data analysis

The “Analyst Workbench” (AW) is the original software developed for the ATOM system, which provides the basic infrastructure and tools for analysts to visualise, analyse, and interpret the data for biological risk assessment. The basic AW structure is composed of two parts: (1) the analyst server, a Linux-based program that resides in an onshore in-house Linux server; and (2) the analyst client, a Windows-based desktop application that resides on each analyst’s (client) computer.

The thermographic data is processed through the modified automated target detection program SwisTrack, which produces video segments of potential targets. This filter is adjusted to eliminate tracking of all turbine blades and most clouds and insects using AI technology, and the parameters can be refined to reduce the number of false positives (i.e., moving clouds). However, from onshore testing it is evident that not all instances of clutter can be eradicated (Willmott and Forcey, 2014) and video segments containing potential bird detections need to be checked.

For the acoustic data, the Raven Pro Sound Analysis Software v.1.5 (Willmott and Forcey, 2014) can be used to process and analyse sound recordings, using two different Band Limited Energy Detectors to detect possible nocturnal flight calls in two discrete frequency ranges. A high range encompassing 6000–11000Hz is used to capture sparrows and warbler calls, with a lower range between 2250 and 3750Hz used to capture calls of thrushes, shorebirds, and other bird species.

Distance, velocity, and bearing of objects are estimated by triangulating the coordinates of the objects from each of two cameras. Near real-time data downloading has been developed for use when cellular connectivity is available. If data is not transmitted, it is stored on hard drives which are typically collected approximately every 3 months depending on weather.

Recommendations

The ATOM system is designed to detect and monitor the flux of birds (and bats) within its detection range, which when mounted on an operational turbine, covers the rotor swept zone and air space immediately surrounding it. The system is not designed with the aim of measuring collision rates but has capability to monitor collision events at the individual turbine scale and operates continuously, day and night. Multiple units would be needed to deploy at a wind farm scale to sample at multiple turbine locations. The system could be integrated with other systems that record flight trajectory (e.g., radar and outward directed cameras, or other radar-integrated systems) to obtain additional data about the birds' movements at the meso- and macro-scale beyond the rotor swept zone.

3.2.5. Wind Turbine Sensor Array

Developer	Oregon State University, USA
Contacted	Yes. First email sent 25 August 2021. Second email sent 5 September 2021.
Responded	Interview held with Roberto Albertani, Oregon state University, 30 November 2021. Questionnaire returned 23 December 2021. Details checked by Roberto Albertani March 2022.

System design

The Wind Turbine Sensor Array is an onboard, integrated multi-sensor system, incorporating on-blade vibration and visual sensing to provide detection of blade collision events, including taxonomic information and 3600 FOV camera and acoustic monitoring of airspace around the turbine. This system has been designed to detect collision events by monitoring vibration signals on the blades and automatically storing visual and acoustic data only when an event is detected to confirm an impact has occurred and for species identification. The system has been tested at onshore wind farms in New Mexico and Boulder, Colorado (Suryan and Polgaye, 2016; Hu et al., 2017; Albertani et al., 2018). Only one system (containing four components) has been installed at each site and the system has yet to be fully tested offshore.

The system can be deployed indefinitely, however it is not a commercially available product as of yet, with further testing relying on commercial partners for the final development of the system (personal communication, Albertani 23 December 2021). Maintenance requirements still need to be documented.

System functioning

The 3600 FOV camera and microphones (acoustic node) allow for species identification to take place by monitoring the airspace around the wind turbines. Additionally, automatic detection algorithms can be used (which utilise data from the optical node) and programmed to identify specific species (e.g., eagle; Albertani et al., 2018).

Test results of the vibrations node installed on blades showed that 14 out of 29 registered artificial impacts were detected, which corresponds to a 48.3% success rate (Hu et al., 2017). This testing event utilised a tennis ball with weight 57g (around a size of a small bird). It is envisaged that the success rate would increase if larger objects were to hit the blades. Further testing of the system with impacts from artificial projectiles with a minimum mass of 20g is subject to new funding for the project and no further analysis is currently available.

Testing indicated that it was possible for impacts to be successfully detected by sensors that were installed on blades other than the blade subjected to the impact. This is an indication that only one or two blades, out of the usual three blades of a rotor, could be instrumented with vibration sensors without decreasing the detection success rate significantly. However, it is required to have all three blades (the whole rotor) in the vision system's field of view for event confirmation and animal species recognition (Suryan and Polagye, 2016; Hu et al., 2017). Partial impact detection can also happen when a low-energy impact occurs, which results in a significantly low sensor signal-to-noise ratio that cannot easily be detected.

Hosting/logistical requirements

A blade impact detection unit (BID) is installed at the root of each blade to enable continuous and automatic collision data to be obtained (Albertani et al., 2018). Three primary sensors are integrated in each BID, including: 1) a micro camera, 2) an inertial measurement unit (IMU) and 3) a contact microphone (Figure 15). The camera, automatically triggered by the detected event, provides visual images in a window before and after an impact for event confirmation and taxonomic identification. All modules can continuously stream and save data to the central processing controller onboard (Albertani et al., 2018). The BID can also be reconfigured to perform other data gathering and analysis such as blade health, lightning strike or ice build-up monitoring.

The vibration nodes are easy to install, easy to maintain and have negligible aerodynamic effects on the blades. During onshore testing, they were attached using 3M double bonding tape. It is unclear how the devices would be attached offshore, as no offshore testing being carried out to date. All signals are digitised prior to wireless transmission (Clocker et al., 2021). The receiver station contains a paired wireless receiver and is placed inside the nacelle next to the central controller.

To record visual and acoustic data (impact sounds and animal calls) four UM250K ultrasonic microphones for 3600 coverage with sampling rate up to 250kHz for bat call detection are used and placed on top of the nacelle couples with a 3600 FOV camera.

Any node can be installed at any time on any turbine including retro-fitting of existing operational turbines (Albertani, pers. comm.)

Figure 15 The wind turbine sensor array unit installed at an onshore wind farm in Boulder, Colorado (images taken from Albertani et al., 2021a)

Data collection

Localised processing of data within the onboard system enables wireless transmission of only detected events instead of continuously streaming raw data, which reduces power consumption and storage needs. The unit can be integrated with Bluetooth Low Energy (BLE) and WiFi modules for investigation of appropriate node-node and node-nacelle communication links, and it may include a 3G uplink for cloud-based data logging (Albertani, pers. comm.).

With regards to monitoring avoidance behaviour, it is stated that meso-avoidance could be monitored due to providing 360 degree coverage around the turbine. It is unclear how well macro-avoidance could be monitored due to the short range at which the system currently operates. Further testing is required.

Information on impact before and after the event is recorded. Blade position is also documented and so micro-avoidance rates could be estimated. Additionally, when an impact is detected and validated with images, the blade position at impact will be available. This would allow the distance above ground that the impact has occurred to be known, and flight heights leading up to the collision could therefore be estimated (Albertani, pers. comm.).

Data processing and data analysis

Machine learning algorithms using a support vector machine and an AdaBoost classifier were implemented and tested as well as a custom, two-step classification approach using an anomaly detector, further improving the precision of the impact detection algorithm (Hu et al., 2017; Clocker et al., 2021). Hu et al., (2017) details that several improvements to the system could be made, improving the automatic real-time impact detection rate and coverage. These improvements are:

- Blade vibration sensors to have onboard data processing capabilities and transmit a packet of data only after the impact is detected;
- Sensor fusion be applied to improve detection success rate;
- Sensor wireless transmission should rely on more efficient and standard wireless protocols;
- An efficient and fast real-time signal filtering to decrease background noise and improve the detection success rate;
- More tests should be conducted with the specific objective of establishing the minimum number of vibration sensors on blades required for camera triggering; and
- Solar energy or rotational motion energy harvesting for sensor battery charging should be tested for increased autonomous and low-maintenance operations.

When estimating collision rates, it is stated that due to the count of blade impacts and images of the events being recorded, collision rates for specific species could be produced. However, the specifics of the statistical methods needed to do so is currently unknown (Albertani, pers. comm.).

Recommendations

The system is designed solely to monitor collision events and as such appears to be capable of measuring collision rates at the individual turbine level, subject to positioning of the camera sensors on each blade, as tested. Multiple units would be needed to deploy at a wind farm scale to sample at multiple turbine locations. The system could be integrated with other systems that record flight trajectory (e.g., radar and outward directed cameras, or other radar-integrated systems) to obtain additional data about the birds' movements at the meso- and macro-scale beyond the rotor swept zone. However, it is as yet untested in the offshore environment.

It is understood that following on from Hu et al., (2017), an extended and improved system is undergoing testing (Albertani et al., 2021b) although this appears also to be limited to onshore applications and the technology does not currently appear to be at a readiness level for offshore deployment. Personal communication with Albertani (23 December 2021) revealed that offshore deployment is the focus of current project work, with further testing reliant on the availability of grant funding.

3.2.6. IdentiFlight

Developer	IdentiFlight Team, Germany.
Contacted	Yes. First email sent 16 August 2021.
Responded	Received response (containing additional information) 25 August 2021. Developer did not respond to enquiry regarding interview and so no interview was held.

System design

IdentiFlight's technology combines high performance optical systems with the latest in machine vision and AI software. When installed as a network, IdentiFlight towers operate as an autonomous system with overlapping aerial coverage to provide highly detailed data. Proprietary software and neural network technologies process the images to determine 3D position, velocity, trajectory, and protected species of interest, all within seconds of detection (IdentiFlight Team, 2021).

This system has been effectively used at the Top of the World Windpower Facility in Wyoming, USA (McClure et al., 2018 and McClure et al., 2021) where four IdentiFlight systems are in operation. This system has yet to be tested offshore and so information on where the system would be installed is limited, though it is likely to be installed on either the turbine platform or on a separate structure such as substation or bespoke floating platform.

System functioning

The system can be programmed to detect specific species (e.g., eagles) and assess if they are at risk of collision based on the bird's specific risk profile (it utilises information on the bird's flight pattern, flight direction, flight height and speed). If the bird is deemed to be at risk of collision, mitigation measures are deployed to prevent collision from occurring (i.e., stopping the turbine or preventing the turbine from starting).

The IdentiFlight towers are typically spaced between 530m and 630m apart at onshore wind farms to allow for sufficient overlapping visual coverage. Study design requires each IdentiFlight system to be monitored by an individual and so for every installed system an observer is required.

Each IdentiFlight unit uses an algorithm to detect and classify objects within a 1,000m radius. The median distance from the nearest IdentiFlight tower at which birds were classified as non-eagles (due to their smaller size) was <600m. Onshore testing has shown that the IdentiFlight system successfully detected 96% of eagles flying through the wind farm in Wyoming (McClure et al., 2018).

Results from the onshore test produced a false negative rate (1 – sensitivity) of 0.06 and a false positive rate (1 – specificity) of 0.28. It was stated that observers were significantly better at identifying non-eagles compared to the IdentiFlight system (McClure et al., 2018). As the IdentiFlight system improves with time (through additional AI training), instances of false negative/positive are less likely to occur due to the expanded avian database.

Hosting/logistical requirements

The IdentiFlight system consists of a ring of eight fixed Wide Field of View (WFOV) cameras and a High Resolution Stereo Camera (HRSC) mounted on a Pan and Tilt Unit which constantly analyses the airspace (Figure 16). The system is installed independently from the turbine. The WFOV cameras detect moving objects in the environment and begin to track them. Once a moving object is detected, the HRSC is pointed at the object and estimates the line-of-sight distance to the object and takes photographs every 5 seconds (McClure et al., 2018).

One of the advantages of the IdentiFlight system is its ability to learn from the massive amounts of data that it collects daily from bird species around the world. By leveraging artificial intelligence technologies, such as machine learning and convolutional neural networks, the system continuously improves as the data set grows.

Figure 16 The IdentiFlight system (image taken from IdentiFlight website)

Data collection

The IdentiFlight system was designed to reduce collision fatalities at onshore wind farms (through detecting birds deemed to be at risk of collision and stopping the turbines as a mitigation measure) and so it does not directly measure collision rates or avoidance behaviour. However, it does gather information such as: species identification and confidence on a scale of 0.0 - 1.0 (1.0 being highest confidence); flight height; flight direction; and each individual bird's flight path.

The advantage of using stereo based cameras is that 3D flight tracks of each detected bird can be more accurately produced, and so birds close to turbine blades can continuously be monitored (unlike radar where turbine blades cause clutter and make it difficult for birds to be tracked within the RSZ).

Data processing and data analysis

All information recorded by the system can be viewed on the provided IdentiFlight dashboard. Information can be extracted from the dashboard to allow for additional analysis (within the computer software R for example) to take place.

Recommendations

Although designed as a mitigation measure to reduce collision fatalities, the information collected by the IdentiFlight system could be used to understand collision rates, as well as providing data on bird flight parameters (e.g., height, speed and trajectory) around turbines and meso and micro-avoidance behaviour.

This system has worked effectively onshore at helping reduce fatality rates (at the wind farm in Wyoming, mortality reduced by 82%; McClure et al., 2021). It is unclear how well this system would function offshore and so further testing in the offshore environment would be essential to further understand its technology readiness level.

3.2.7. Spoor AI

Developer	Spoor, Norway.
Contacted	Yes. First email was sent June 2021.
Responded	Interview with Lorea Coronado-Garcia, 26 August 2021. Questionnaire returned 2 September 2021. Details checked by Lorea Coronado-Garcia March 2022.

System design

Spoor is a Software-as-a-Service (SaaS) data platform that enables continuous monitoring of wildlife for offshore wind farms, pre and post construction. Before construction, the system can monitor bird behaviour, activity, bird count flux and flight path monitoring. After construction the system aims to obtain information on micro avoidance behaviour, flight path monitoring, collision risk, and empirical collision rates (personal communication Coronado-Garcia, 26 August 2021).

The Spoor AI system is currently installed at the Unitech Zefyros floating turbine test site off the coast of Norway (Coronado-Garcia, pers. comm.) and in the UK's North Sea. Additionally, it has been tested at four onshore sites. Results are currently unpublished.

System functioning

Individual species identification is not yet automated and requires video clips to be labelled manually. The development of AI automatic detection currently prioritises Northern European species (Coronado-Garcia, pers. comm.).

One camera can monitor a single turbine in its entirety. Typically, this would be above water and installed on the platform of a neighbouring turbine. Attachment is flexible. It is stated that if a pre-existing installed camera has the correct positioning (has a clear line of sight to the neighbouring turbine) and quality, they can be used with the Spoor AI system.

Multiple birds can be detected by the system, however there can be some complications when flight tracks overlap. Rain does not impact the detection software, though the presence of fog does impact the detection range.

From a sample size of nearly 10,000 bird tracks, Spoor has achieved a 77.2% precision. Continual improvement is expected with machine learning.

Hosting/logistical requirements

The hardware requirements are off-the-shelf camera and edge computer. The software uses computer vision and AI, and the system is scalable according to project needs. Spoor AI can be deployed to monitor the lifetime of the wind farm with annual maintenance and can operate during daylight and dusk periods. It is currently retrofitted at two operational turbines but has not been assessed thoroughly for implications on turbine under warranty.

Data collection

Bird flight paths are recorded and analysed for behaviour, with data on flight heights, flight speeds and trajectories obtained. It is intended that data collected can be used to estimate collision rates for specific species and also monitor pre-collision activity. Meso and micro-avoidance behaviour can be recorded by the system, however only micro-avoidance behaviour has been analysed during testing (Coronado-Garcia, pers. comm.).

Flux rates at bird activity level are currently tracked and species-level flux rates are detected and tracked by monitoring birds across multiple frames.

No further data has been published online.

Data processing and data analysis

Video data is recorded, then analysed and stored within either the cloud or local drive. Data can be stored as Json, CSV, TXT or XML (Coronado-Garcia, pers. comm.).

Recommendations

The camera system offers visual tracking of birds mainly in the micro-zone, although it reportedly could also track birds in the meso-zone. The system is capable of measuring collision rates at the individual turbine level, subject to appropriate positioning of the camera. Additional behavioural flight data (including flight height, direction and speed) can be obtained from the 3D track generated by the system. Multiple units would be needed to deploy at a wind farm scale to sample across a large multi-turbine facility. The system could be integrated with other systems that record flight trajectory beyond the meso/micro-zone (e.g., radar, or other radar-integrated systems) to obtain additional data about the birds' movements at the macro-scale. Integration with other sensors, such as acoustic sensors, may also offer improved identification. The system is being tested at two North Sea locations: the first location is at the METCentre area off the coast of Karmøy, Norway, at Unitech Zefyros. The second is installed at an offshore wind farm in the UK (details regarding the second wind farm commercially sensitive and cannot be provided at this time). Ongoing AI training is needed to improve the automation of species identification.

3.2.8. ACAMS

Developer	Biodiversity Research Institute (BRI, USA)
Contacted	Yes. First emailed 10 August 2021. Second email sent 13 September 2021.
Responded	Developer did not respond to either emails. Due to time constraints, no further attempts to arrange a call were made.

System design

The Aerofauna Collision Avoidance Monitoring System (ACAMS) uses two extreme high-resolution stereo optic cameras that are offset to create a three dimensional view of a wind turbine, the horizon and an area surrounding the turbine. Stereo-optic camera systems bring a higher level of precision to avian risk analysis as they are able to monitor bird movements close to turbines in three dimensions. Originally, the system included near-infrared technology that allowed for animal movements at night as well as during the day to be detected. However, it is recommended that thermal imaging technology instead of near-infrared is used in order to improve night-time detection (Adams et al., 2017). Using complex software algorithms, the technology can calculate the degree of randomness and make projections of avoidance behaviour.

Information regarding offshore results is unpublished (e.g., Mellor and Hawkins, 2013). See Adams et al. (2017) and Albertani et al. (2018) for onshore test results.

System functioning

Using the ACAMS system, small birds (with wingspan <400mm) can be identified to species level at distances of 20–44m. Medium birds (with wingspan 850–1,110mm) can be identified to species level at 12–88m, and larger non-eagle birds (with wingspan 1,270 –1,485mm) can identified to species level at 32–123m (Adams et al., 2017). Eagles with wingspans ranging from 2,036–2,446mm (Buehler, 2000; Imler and Kalmbach, 1955) can be identified to species level at 26–352m.

The furthest from a camera that an eagle can be detected with motion segmentation is estimated at around 500m using the fisheye wide-angle lenses, and eagle-sized targets could be identified to species level within 350m of the camera system. Bat-sized objects could not be detected more than 60m from the camera system.

During the onshore tests, the overall detection probability of eagles within 500m of the camera system was estimated to be 6% (95% credible interval: 1.2-13.2%). Detection/identification probability stayed near 100% for the first 40-50m then decreased thereafter. The overall detection/identification probability was estimated to be about 20% over the entire 500m range. The instantaneous detection probability approached zero around 400m, suggesting that detections were rare past 400m.

Non-eagle detectability was lower than that estimated for eagles. Overall probability of detecting a non-eagle in a 500m area around the camera was 1.5% (95% CI: 0.004–2.2%). Detection probability held near 100% up to 30–40m from the camera system then decreased rapidly and approached 0% detection near 150m (Adams et al., 2017).

Simulated testing showed the detection probability of the data containing eagles to be 67%, which suggested the ACAMS system was detecting and identifying about 9% of the total number of eagles that were within the 500m sampling area. Similar simulated testing for non-eagles showed that about 2.2% of birds within the sampling area were being detected and successfully identified.

Hosting/logistical requirements

The camera and associated control system would require deployment on a structure within visual range of the target area, which may be an adjacent turbine platform or nacelle, or another offshore platform. The system requires connection to the local power supply and can be monitored remotely via an internet connection. It is specified that the system requires frequent maintenance and it may also be necessary to exchange data drives to move data from offshore to onshore (Dirksen, 2017).

Figure 17 ACAMS installed offshore (image taken from Dirksen, 2017)

Data collection

Dirksen (2017) describes that pre-processing of data is carried out by control computers on the system, which also store data and enable transmission to a base station. Pre-processing involves screening of data for moving images which reduces the size of data required to be stored and transmitted.

The system could be useful in describing avoidance behaviour at the micro-avoidance scale (within immediate proximity of the turbine and with the full length of the turbine blades in view), but would not be effective at wider scales without system modifications (Adams et al., 2017). It is stated within Adams et al. (2017) that with the system's current capabilities, even micro-avoidance could be difficult to describe for turbines with long turbine blades. It is recommended that the system is used to sample the air space around the turbine and not used, as currently configured, for monitoring turbine interactions entirely.

Data processing and data analysis

Dirksen (2017) reports that camera images are stored every 5 minutes to provide contextual information (such as weather, visibility and turbine orientation). Post-processing includes calibrating the images for object distance estimates, marking avian object pairs between the two cameras, calculating 3D positions for each stereo pair, and manually identifying birds to species or species grouping.

To transfer data from the camera system to onshore file servers, a minimum bandwidth of 10Mbps (but optimally 50-100% above that) is required. This will allow for constant transfer of data to occur.

Recommendations

Several improvements to the system have been suggested, however no results incorporating these updates have yet to be produced. Suggested improvements are:

- further testing of all components of the system once installed;
- adding a pan-tilt camera to track and focus on the object of interest based on measured trajectory by the stereo camera system. This camera should have a lens with at least a 200mm focal length;
- use a rectilinear wide-angle lens; and

- software that uses advanced object recognition algorithms.

The twin camera system offers visual tracking of birds mainly in the micro-zone. Although not directly stated, the system would be capable of measuring collision rates at the individual turbine level, subject to appropriate positioning of the camera, and it may be possible to alternate the direction of the camera to focus on a sample of different turbines within range of the camera using a pan/tilt function. Additional behavioural flight data (including flight height, direction and speed) can be obtained from the 3D track generated by the system. Multiple units would be needed to deploy at a wind farm scale to sample across a large multi-turbine facility. The system could be integrated with other systems that record flight trajectory beyond the meso/micro-zone (e.g., radar and outward directed cameras, or other radar-integrated systems) to obtain additional data about the birds' movements at the meso- and macro-scale beyond the rotor swept zone. Integration with other sensors, such as acoustic sensors, may also offer improved identification. The system is being tested at an offshore facility and therefore is assumed to be close to readiness level for full deployment in the offshore environment.

3.2.9. B-finder

Developer	B-finder Team, EMPEKO, Poland.
Contacted	Yes. First emailed June 2021. Second email sent 11 August 2021. Third email sent 13 September 2021.
Responded	Developer did not respond to either emails. Due to time constraints, no further attempts to arrange a call were made.

System design

The basic principle of the B-finder system is to record falling animals after colliding with the turbine. The system is programmed to differentiate between birds in flight and those that are falling after a collision event. Data is collected and reported including photo and video evidence of the event, along with date, time and estimated location of the carcass. The system operates 24/7.

It has only been tested onshore, however it is stated that it is also designed for offshore use. The B-finder technology is patented in Australia, China, Poland, South Africa and Taiwan (Przybycin et al., 2019)

System functioning

Despite obtaining video imagery data, it can be difficult to determine individual species and collected images from the B-finder system can be unsuitable for species identification (Lagerveld et al., 2020).

The B-finder system in the basic configuration enables the detection of smallest bird species up to 50m from the wind tower (min. 95% efficiency), detection of all bigger bird species up to 100m from the wind tower (min 95% efficiency) and detection of all raptor species up to 100m from the wind tower (min 95% efficiency).

Out of six bird victims found during the onshore field tests, five were detected by the B-finder system. The other victim was missed due to the wide-angle cameras being inactive at that time. Wide-angle cameras are crucial for the detection of animals falling within short range from the tower, where gaps occur between the fields of view of the main camera. The victim was found at a distance of 1.5m from the tower. After this event, wide-angle cameras are now installed with the system in order to monitor the short-range space.

It is stated that it is possible to use only two levels of sensors, however installing three levels helps eliminate false signals.

Hosting/logistical requirements

Sensors are mounted at a minimum of two different heights on the wind turbine tower, with every level of sensors scanning 360° around the tower. When installed onshore, the system can predict the location of where the carcass will likely fall on the ground with precision of about 10m. It is unclear how well this function would work in the offshore environment.

A “positive hit” is an object that is detected by both, or all three, sensor rings within a predetermined time-frame (Figure 18).

For testing, the onshore turbines were equipped with three levels of sensors at 15, 30 and 45 meters above the ground. At every level, two types of sensors were installed:

- 12 thermal cameras: FOV 32°x26°; array format 640x480; and
- 4 thermal cameras: l FOV 93°x61°; array format 320x240.

Figure 18 B-finder system installed onshore (images taken from Przybycin et al., 2019).

Data collection

For each event, the B-finder system provides the following information:

- date and time of the collision (year, month, day, hour, minute);
- azimuth from the wind turbine tower to the carcass on the ground;
- approximate distance from the wind turbine tower to the carcass;
- screenshots from the sensors at the time of the event, included coloured trajectories of the falling object at every level of sensors;
- Video recording of the collision victim’s fall at every level of sensors;
- KML and GPX files with the location of the carcass on the ground.
- PDF file with the Field Inspection Report, including detailed data from the field control (e.g., species recognition, carcass description, carcass pictures). This report is available once the crew completes

the field control. The field control can and should be performed immediately because the collision alert is available directly after the collision. Note – this is presently for onshore projects only.

This system collects data relating to collision events, however in order for empirical collision rates to be estimated, additional technology would need to be used to allow for information to be gathered when a bird passes the turbine but does not collide with it.

Data processing and data analysis

All information relating to registered detection are uploaded and stored on the B-finder system user panel. The estimated time as well as the position of the carcass are displayed on a map for every event. Data can be extracted for further analysis within relevant software (e.g., the statistical software R).

Recommendations

B-Finder is designed primarily to detect collisions. Its function in the offshore environment would need to be integrated with other sensors to provide additional data on species identification and bird movement prior to the collision event.

The range of detection could be increased by adding additional cameras and changing optics, however this has yet to be tested. Other camera sensors could be installed with the B-finder turbine in view, collecting data on bird flight behaviour pre-collision. This system could be adapted to allow for empirical collision rates to be estimated, however this will require further testing as the level of modification needed to allow this information to be gathered is unknown as it was not designed for this purpose.

3.2.10. ID-Stat

Developer	ID Stat Team.
Contacted	Yes. First emailed 25 August 2021. Second email sent 13 September 2021.
Responded	Developer did not respond to either emails. Due to time constraints, no further attempts to arrange a call were made.

System design

The ID-Stat system uses acoustic microphone sensors at the base of each rotor blade to detect impact noise. Background noise is filtered out and detections of collisions (including the date and time of the event) are sent to a web based database which is accessed via the internet (Delprat and Alcuri, 2011).

It has been tested onshore at a turbine in Western France, however no updated information has since been made available.

3.2.11. MultiBird

Developer	BSH, Germany.
Contacted	Yes. First emailed 11 August. Second email sent 13 September 2021.
Responded	Developer did not respond to either emails. Due to time constraints, no further attempts to arrange a call were made.

System design

This system is currently in development (2019-2022) and so information on its function and capabilities is limited. The system will be a multi-sensor system, consisting of radars, video and thermal imaging cameras. Data on the behaviour of birds (evasion or targeted approach) and the resulting risk of collision, as well as flythrough rates, horizontal flight movements and vertical altitude changes, are said to be obtained when using this system.

The recording devices will be used for the first time in the German Exclusive Economic Zone (EESC) to research bird migration.

3.2.12. Bird Migration and Collision Monitoring System

Developer	wpd, Germany.
Contacted	Yes. First email sent June 2021.
Responded	Interview held with Dr. Susanne Schorcht, wpd offshore solutions GmbH, 13 October 2021. Questionnaire returned on Yunlin offshore wind farm, 3 November 2021. Questionnaire returned on Nordergründe wind farm by Freerk Nanninga, 26 November 2021. Details checked by Dr Susanne Schorcht March 2022.

System design

The system uses integrated radar, camera and acoustic sensors for bird calls and is designed to detect collisions and monitor meso and micro avoidance behaviour. The system also allows for data on flight height, flight direction, flux and migration rates (seasonal, day and night) to also be gathered. The bird migration and collision monitoring system will be installed at Yunlin offshore wind farm in Taiwan where it will be deployed for three operational years and operate 24/7 (personal communication Schorcht, 13 October 2021).

Additionally, there is a similar system installed at Nordergründe offshore wind farm in German waters, however there are fewer devices being used and the technical specifications of these devices are slightly different due to older devices being utilised. Results for this monitoring study are currently not published, however information has been provided following interview with wpd and included within this section.

System functioning

The system in OWF Yunlin consists of two horizontal and two vertical radars, several video and thermal cameras and four microphones on several turbines. The radar system has a horizontal radius of 10km and a vertical radius of 1.5km (Schorcht, pers. comm.). The camera system aims to monitor the entire turbine by using multiple cameras and species identification is possible via data collected by cameras and microphones. The system works regardless of time of day but adverse weather conditions (such as stormy weather and heavy rain) can impact data collection and in some cases when typhoons are present, operation of the system is typically halted.

At the Yunlin offshore wind farm, as there is no offshore transformer platform available, peripheral turbines were selected for all devices. The total distances between each of the turbines were;

- Between YUN03, YUN04 and YUN05 North around 700m;
- Between YUN70 and YUN71 South around 800m;
- From YUN70 and YUN71 to the next in the north ca. 2000m;
- YUN 47 East to next four turbines ca. 1200m and 1400m; and
- YUN 46 West to next four turbines ca. 980m and 1400m.

The wind farm consists of 80 turbines within $82km^2$, with each turbine having a rotor diameter of 167m and a swept area of $21,900m^2$. All systems will be placed on the main access platform (MAP; cameras and microphones will be installed on the handrail or railing, with radars fixed outside the MAP) of the foundation at a height of ca. 20m above MSL. Each radar will be mounted next to the railing on a foldable supporting mount facing outside the MAP.

The horizontal radar devices will be installed on peripheral northern and southern wind turbines with undisturbed opening angle of approximately 180° up to a maximum 270°. Four thermal cameras and four microphones for bird migration monitoring will face on peripheral turbines (all directions) transversal upright to investigate the bird migration through the air space outside the wind farm.

Three thermal/video cameras for bird collision monitoring will also be installed at an angle of 120° from each other on a wind turbine on the northern outside of the wind farm. All cameras will face the top of the wind turbine rotor swept area. Currently, there is no data on the specific detection rate/false detection rate of the observation system.

At OWF Nordergründe, one horizontal (Furuno FAR-2827/XN-24AF) and one vertical radar (Furuno FAR-2827/XN-24AF) device has been installed at the substation, with four thermal cameras (AXIS Q1932 E, 30 FPS) mounted offset by 90° to each other on the MAP of turbine no. NG02. Additionally, one video camera (MOBOTIX Allround Dual M15D) combined with thermal module (L43) has been installed on the rotor level of turbine no. NG02, with two microphones (Sennheiser MKH416), one on the MAP of turbine no. NG02, and one installed on the substation.

Hosting/logistical requirements

Camera and microphones are fixed with normal holders/clamps to the handrail of the platform, with all equipment components – holders, cabinets with control units, cabling, data transfer infrastructure – designed specifically by Wpd for the OWF at which it is deployed. All equipment, except the holders of the radars at the outer main access platform, will be fitted after the turbines are erected. There is no influence on warranty of the main components of the bird monitoring system (Schorcht, pers. comm.).

At Yunlin offshore wind farm, the horizontal and vertical radars aim to gather information on flight height, path and speed. Thermal cameras and microphones are able to collect data on flux and can allow species identification.

At the Nordergründe offshore wind farm, all systems are placed either on the turbine nacelle, turbine platform, MAP or on the substation (Figure 19). Most of the equipment has been fitted before the turbines were erected (personal communication, Nanninga, 26 November, 2021).

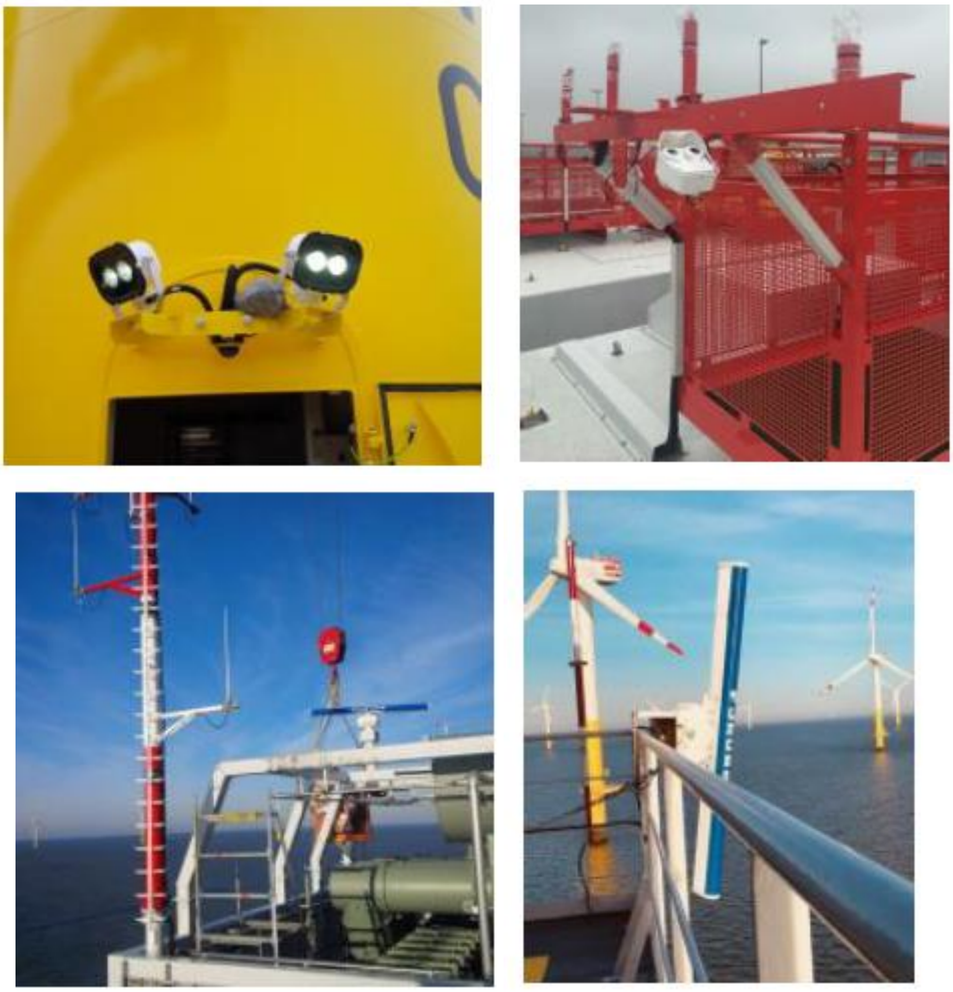

Figure 19 Bird Migration and Collision Monitoring System at Nordergründe. Top left: Microphone on platform of turbine; Top right: thermal and video camera system on the top of the nacelle looking on the rotor swept area from behind ; and Bottom left and bottom right: Horizontal radar (left) and vertical radar (right) on substation (images provided by personal communication, Nanninga, 26 November 2021)

Data collection

The study at OWF Yunlin and OWF Nordergründe does not aim to obtain data on macro avoidance behaviour, but it is mentioned that macro avoidance behavioural information could also be obtained and analysed by the use of additional radars, however without species identification (Schorcht, pers. comm.; Nanninga, pers. comm.). Radar tracks of birds within the wind farm would be available for analysis and would allow for meso avoidance behaviour to be understood.

The camera systems installed with the rotor swept zone within view allow for information on micro-avoidance behaviour to be obtained. The use of these cameras would also allow for species specific empirical collision rates for that individual turbine to be estimated.

Mean Traffic rates (MTRs) for the wind farm can also be calculated for the radar data.

Data processing and data analysis

The bird migration and collision monitoring system of OWF Nordergründe and OWF Yunlin utilises/will utilise hard disks for data storage as well as allowing for data to be transferred via fibre cables. The system is controlled via online infrastructure and stores raw data for a short time (offshore), with data processing occurring at a long term storage centre onshore. Currently, species identification is done manually by video analysts as well as by analysing the song calls by the use of an appropriate software (Nanninga, pers. comm.).

Observation data is extracted through the network by software originally developed by equipment suppliers, subcontractors or open source programs, and the data format differs depending on the observation system.

No information regarding the proposed statistical analysis methods was provided by the developer. It is anticipated that by using this system the following analyses can take place due to the relevant data being obtained:

- Bird migration behaviour and migration rates;
- Seasonal and day/night timing, flight altitude and horizontal spread during migration;
- Bird macro, but more meso and micro avoidance behaviour;
- composition of the species spectrum (if possible based on vessel observer surveys and with video camera and microphone data);
- Bird collision; and
- How daily weather events and/or conditions may correlate with the number and species composition.

Recommendations

To aid with collision detection, this system could be paired with collision impact detection technology as it is unclear how well this system can detect birds that might collide with turbines. It is evident that further study is required to understand the capabilities of this system, however, the presence of multiple cameras (seven in total) indicate that a substantial amount of species specific data on flight behaviour in the meso and micro zones at various points throughout the wind farm will be obtained.

3.2.13. Birdtrack®

Developer	Strix, Portugal.
Contacted	Yes. First email sent 5 August 2021.
Responded	Interview held with Miguel Repas Goncalves, 27 October 2021. Questionnaire returned 8 December 2021. Details checked by Miguel Repas Goncalves April 2022.

System design

Birdtrack® is a family of products (Birdtrack® radar and video systems and Birdtrack® Multispectral Collision Detection System (CDS)) that aims to evaluate and characterise bird movements and behaviour in the vicinity of turbines. The family of products includes Birdtrack® Dual 3D radar which is a dual radar system consisting of an X-band radar (9410MHz) and an S-Band radar (3050MHz) for 3D bird and bat detection and tracking, and can be linked to video cameras, and the CDS (which uses 5MP zoom cameras), which can be used to obtain information on collision events by monitoring the rotor swept area (personal communication Repas Goncalves, 27 October 2021).

The Birdtrack® system has been installed at several onshore wind farms (such as Barao Sao Joao and Raposeira Wind Farm in Portugal, and Gabal el Zayt Wind Farm in Egypt), with the system also currently installed offshore at WindFloat Atlantic, off the Portuguese coast. This system is also due to be installed at an offshore wind farm in the UK (details are confidential and cannot be disclosed at this time). The Birdtrack® products can offer continuous 24/7 bird and bat monitoring capabilities and can be linked to shut-down on demand procedures, with Birdtrack® lasting up to 20 years with an adequate maintenance plan.

System functioning

Information on offshore results are limited, with onshore monitoring relating to eagle species (Tome et al., 2017). The operational range of the radar system is typically up to 7-8km for good definition of seabird sized targets (Repas Goncalves, pers. comm.). The technology can successfully obtain data up to 12km for larger species.

If cameras are installed and linked to Birdtrack®, the operational ranges of cameras used at the meso scale are relatively large, between 1-2km (Repas Goncalves, pers. comm.) with species identification taking place up to 2km if the target is larger.

No information regarding false positive/missed detection or detectability rates is publicly available, however it was stated during interview that there was a high detection rate, with the amount of false positives/negatives dependent on the study site (Repas Goncalves, pers. comm.).

Hosting/logistical requirements

An Offshore IT Cabinet with server and rugged IT HW to process and store data are required. Remote access is required to monitor and optimise performance of the system as well as retrieve data for study. 10Mbit bidirectional is required. If video is added, bandwidth has to be upgraded depending on the number of camera sensors.

The S-band radar scans in horizontal surveillance mode and obtains precise bird and bat trajectories. The radars can accurately map trajectories of individual bats, birds or flocks, delivering flight speed and other parameters used for target identification (bird and bat species or groups of species). The X-band radar scans in vertical mode and obtains data on flight altitude, traffic flow and complementary data for target identification. The combination of the two radars provides 3D flight tracks.

The Birdtrack® system is typically installed on the turbine platform or any other platform depending on the study design.

The CDS utilises HiRes video cameras (5MP with image stabilisation) for species identification and behaviour studies, with the CDS having both night vision and daylight capabilities. The system is installed at the turbine and is attached to the handrails.

Data collection

The radar detects and tracks birds approaching the wind farm and with this data, the collision risk is assessed and turbines can be selectively shut down to reduce the risk of a strike. Information relating to flight height, flight speed, macro, meso and micro avoidance behaviour and direction for all tracked birds is obtained.

If the CDS is installed, it is stated that empirical collision rates could be estimated for the turbine it is installed at (Repas Goncalves, pers. comm.) and micro avoidance data could be obtained.

For onshore results (Tome et al., 2017) it was shown that nearly three quarters (72%) of the observed movements were registered at height classes involving high collision risk, and more than half (55.4%) of the total number of individuals flew over the wind farm area at high collision risk heights. Regarding the number of individuals, the largest proportion of birds were detected by the Birdtrack® system at the 200–500m height class (38.4% of the total number of individuals).

It was stated within the report that over the course of five years, no onshore bird collisions were recorded and concluded that the radar system was effective when the shutdown-on-demand procedure was applied.

Data processing and data analysis

The Birdtrack® family of products comes with a web-based data visualisation tool and database management system, which is a software application for storing data developed by Strix. The management system can incorporate advanced tracking algorithms to optimise automatic detection, tracking and classification of bird targets. The software includes modules for automatic data grabbing, calibration, ground and weather clutter filtering which renders very high detection efficiency and reduces significant errors in target classification.

Information stored within the database management system is georeferenced, with individual flight trajectories and associated parameters able to be exported for robust statistical analysis. Its bio analytics webtool includes data visualisation, and data management and validation tools.

Recommendations

Information on this system in the offshore environment is unpublished/confidential and so further information is required to assess how effective this system is at observing bird behaviour. Birdtrack® is used to predict the risk of a collision occurring and to implement shutdown on-demand, and so further information may reveal that it may be possible to adapt its use to calculate empirical collision rates and view micro-avoidance behaviour by integrating with the CDS.

3.2.14. Bird Protection System

Developer	Bioseco, Poland.
Contacted	Yes. First email sent 11 August 2021.
Responded	Interview held with Dawid Gradolewski and Adam Jaworski 25 August 2021. Questionnaire returned 30 August 2021. Details checked by Dawid Gradolewski March 2022.

System design

The Bioseco Bird Protection System (BPS) was originally designed to detect bird presence in the vicinity of a turbine and trigger mitigation measures to help reduce collision events at onshore wind farms (personal communication Gradolewski and Jaworski, 25 August 2021). It uses stereo-vision cameras to measure bird behaviour and includes three mitigation measures: lighting, acoustic signal and curtailment.

The BPS has only been deployed onshore currently (it has been installed on Vestas, Enercon, SiemensGamesa, Acciona Windpower and Alstom turbines in Spain, France, Germany and Poland), however it could be tested offshore (Gradolewski and Jaworski, pers. comm.).

System functioning

As the camera is equipped with stereo vision software, 3D bird tracks of the detected bird can be produced. Birds can be identified based on size and by manually reviewing video recordings. The system is currently being developed further to include AI functions to provide automated species identification (Gradolewski and Jaworski, pers. comm.).

The system currently only operates in daylight conditions, but once installed it can operate for the life-time of the turbine and provides a 360° view around the tower. As the camera has a 60° vertical view, it is not designed to view the rotor swept zone (Figure 20). However additional cameras could be added or angle of orientation altered to view the rotor swept zone for monitoring of collisions or flights in the micro-zone.

Usually 6-8 modules are used to cover the turbine being monitored, but it is possible for these cameras to be able to see other turbines within the wind farm (dependent on distance from the turbine the system is installed at and also visibility conditions - this is likely to vary for the offshore environment). However, the focus of the current system is collection of data at the turbine where the system is installed.

Efficient detection range is 500-700m, depending on size of bird and given distances between wind turbines offshore, and it is envisaged that one BPS can efficiently monitor the area of one turbine. The mitigation measure thresholds are programmed accordingly for each project. Generally, to stop the wind turbine safely, a bird needs to be detected from a distance up to 200-400m. This, however, depends on the species and their flying characteristics (Gradolewski et al., 2021).

The system can detect, at a minimum, 80% of all activity (this depends on the size of the bird and the distance from the camera). 4K cameras can detect red kites at 400-500m, white-tailed eagles at 600-700m and smaller birds would be closer (up to 150m). Larger birds such as large eagles could be detected and tracked up to 800m away from the system.

To test the false negative/positive rate, data collected by the system has been compared against long-term visual observations records. During a 67.5 hour observation survey, ornithologists identified 105 small, medium and large birds and during the same period, the system detected 96 birds (Gradolewski et al., 2021). Of these nine missed objects, all were observed at distance greater than 150m; however within the 100m range, all birds observed by ornithologists were also detected by the system (Gradolewski et al., 2021). At a distance between 100m and 200m, only one medium size bird was not detected by the system. The false negative rate has been brought down to within 1% or less for onshore wind farms (Gradolewski and Jaworski, pers. comm.).

Hosting/logistical requirements

The system is mounted onto the turbine base and installation is fairly simple as it uses magnets or steel clamps (Figure 20). For onshore deployment, it is installed on the turbine at 7-15m up from the ground, however for offshore installation, the placement of the modules would differ as the system needs to clearly see the horizon (Gradolewski and Jaworski, pers. comm.).

One system per one turbine is used for monitoring, with the system composed of between 6-8 detection modules depending on requirements. Each module has at least 2 ultra HD/4K cameras. The cameras do not have zoom capabilities (to help with accuracy and maintenance) and future developments of the system aim to equip the cameras with zoom lenses to aid with quality. Depending on number of modules, the system can have anything between 12 and 32 cameras. If the system aims to monitor beyond 500m with high detection efficiency, 32 4K cameras would have to be used (Gradolewski and Jaworski, pers. comm.).

Detection modules are connected by cables for power and data transmission, and are fed into the tower and to the server, where data is then processed and archived. Alternatively, a small power supply and data switch can be used, which would be connected to the fibre network, allowing data to be remotely sent to the substation. Internet connection is needed to access the data in the server from outside the wind farm with the BPS using a secure VPN.

Figure 20 (left) Monitoring area of the Bioseco Bird Protection System (middle) system installed on an onshore turbine (right) image showing area not monitored by the system (images taken from Kielanska et al., 2020; Gradolewski et al., 2021)

Data collection

The BPS system cannot be used to obtain data on macro-avoidance. As bird tracks are recorded, the density within the vicinity can be estimated and the system could be used to gather information on meso-avoidance behaviour. Heat maps can also be produced.

It does not monitor the micro-zone immediately around the rotors, but it is possible to add cameras looking upwards (towards the rotor area) and so, collision events could be detected. However, this has not been tested as of yet as it is not part of the original concept of the system (the system was designed to be used in wind farms where mortality was high or estimated to be high with the aim of reducing the risk of further collisions through curtailment).

With each detection, information on the flight altitude and flight path is gathered and flight speed could be estimated using the recorded coordinates. The direction of the bird's flight can also be viewed and flux rate could be measured based on the data collected (information is stored every time a bird is detected within range).

Environmental variables such as wind speed can be obtained from turbine SCADA and stored in the system for further analysis e.g., correlation of activity with wind speed.

Data processing and data analysis

Cameras sample 15 frames per second, and information (such as video clips and photos) are stored only when a detection has been made. All information could be stored, however this would result in huge amounts of data. The data is stored on a data server and accessed remotely via the internet.

The system is composed of five separate segments: Data Acquisition, Bird Detection, 3D Localisation, Bird Size Classification, and Collision Avoidance System. The Data Acquisition block represents the system hardware and its functionalities, which ensures the reproduction of the bird image onto an image plane. The Bird Detection algorithms allow real-time detection resulting from the object contour. The 3D Localisation algorithm is used for estimation of the detected object's distance and height from the turbine. The object's contour and its 3D localisation from the turbine are used for Bird Size Classification. In the final stage, the Collision Avoidance decision and method is undertaken (Gradolewski et al., 2021).

As the system was designed as a curtailment system, no statistical or in-depth analysis has currently taken place to estimate avoidance rates or collision rates using the data collected at this time.

Recommendations

The Bioseco system could be adjusted to the offshore environment ensuring similar functionalities to onshore. It is limited however by operation during daylight hours and would be ineffective in certain weather conditions with poor visibility (heavy rain and thick fog) (Gradolewski and Jaworski, pers. comm.). Although not yet tested, the system could be adapted to monitor for collision events and record bird behaviour in the micro-zone, similar to other upward facing camera systems designed for collision mitigation.

Supplementing the BPS system with radar data (or integrating the system with radar technology) and thermal cameras could provide reliable 24/h monitoring and could gather valuable data on bird activity and avoidance responses in the vicinity of turbines.

3.3. Fact table

Table 4 below summarises the monitoring technologies and systems discussed in section 3.1 and 3.2. For each technology and system mentioned, a short description of their strengths and weaknesses is provided and whether they are capable of obtaining data on collision and macro, meso and/or micro-avoidance behaviour. Where possible, costs of the monitoring technology/system have been specified, as well as whether the system has been deployed offshore yet and if so, whether that has been on fixed or floating turbines. Brief recommendations are included to state where and how the system could be improved based on the literature/ information obtained and outlined in section 3.1 and 3.2.

Table 4 Summary of technologies and systems for monitoring offshore bird behaviour (and collisions) in the vicinity of turbines

						Monitoring		Offshore Deployment	
Technology	**Cost**	**Strengths**	**Confidence**	**Limitations**	**Recommendations**	**Collision**	**Behaviour**	**Fixed**	**Floating**
Radar									
Merlin Avian Radar	Vary by project but a 2017 estimate valued the cost to be between £360,000 and £720,000 for the delivery and installation. One year warranty included.	Solid state S-band radar and has a good suppression for sea clutter (can work up to sea state 7) and can track birds in a wider range of weather conditions compared to other systems. The Merlin software also enables tracks to be identified easily. System can include Merlin detect and deter system.	This radar has been used effectively in offshore wind farm monitoring studies, with low false positive rates reported.	Species identification can only occur when paired with visual observational data (i.e., visual surveys or camera systems). Not all tracks identified on the Furuno radar are picked up by Merlin.	Pair with camera technology to view flight behaviour in micro-zone and facilitate species identification and reduce human observation costs.	No	Macro Meso Flux	Rodsand II Egmond aan Zee	Has not been tested but would be able to be deployed on floating structures.

						Monitoring		Offshore Deployment	
Technology	Cost	Strengths	Confidence	Limitations	Recommendations	Collision	Behaviour	Fixed	Floating
SCANTER 5000	No information available. Expensive compared to LAWR.	Produces echoes and tracks of higher resolution and of smaller size. Is less sensitive to sea clutter, rain and turbine movement. Up to 10 radar tracks can be followed at a time. Can measure flight altitude and speed for 3-D tracking.	SCANTER radar has been used effectively in offshore monitoring at Thanet offshore wind farm to monitor macro avoidance behaviour. This radar is less susceptible to clutter compared to other radars.	Birds flying less than 10m altitude within 45m cannot be detected. Maximum high detection efficiency up to 10km distance.	Pair with camera technology to view flight behaviour in micro-zone and facilitate species identification and reduce human observation costs.	No	Macro Meso Flux	Thanet	Has not been tested but would be able to be deployed on floating structures.
LAWR 25	No information available.	Can be connected to thermal camera technology to accurately analyse meso and micro avoidance behaviour.	This radar has been used in multiple offshore wind monitoring studies. Studies indicate it is a good option to use when monitoring	Sea clutter can occur when sea state is higher than Beaufort 2 resulting in limited or no radar detection. Birds flying less than 10m altitude within 85m of the radar cannot be	Pair with camera technology to view flight behaviour in micro-zone and facilitate species identification and reduce human observation costs.	No	Meso	Thanet Horns Rev 1 Horns Rev 2 Egmond aan Zee	Has not been tested but would be able to be deployed on floating structures.

						Monitoring		Offshore Deployment	
Technology	Cost	Strengths	Confidence	Limitations	Recommendations	Collision	Behaviour	Fixed	Floating
			meso avoidance behaviour.	detected. Maximum high detection efficiency of 3.5km distance limits macro-zone capability.					
3D Flex Robin Radar	No information available. Expensive compared to LAWR.	Identification of the presence and number of birds in time, including their location, size, direction, speed, altitude and trajectory up to 10km away, and is operational continuously day and night. The radar can jump from bird to bird as they come into range.	This radar has been deployed at several offshore wind farms and has produced high resolution 3D tracks both within and outside the wind farm.	There will be clutter issues caused by waves due to the radar being in horizontal mode. Robin Radar state they have made improvements on this. Small sized birds cannot be detected >6km.	Pair with camera technology to view flight behaviour in micro-zone and facilitate species identification and reduce human observation costs.	No	Macro Meso Flux	Luchterduinen Gemini Tahkoluoto	Has not been tested but would be able to be deployed on floating structures.
BirdScan MR1	On request About £10k per unit in 2015.	The system records flight altitude, wing flapping pattern and allows bird echoes to	BirdScan has not been used widely in monitoring	As the radar system is installed close (as close as 150m off the	Pair with camera technology to view flight behaviour in micro-zone and	No	Macro Meso Flux	Alpha Ventus	Has not been tested but would be able to be

						Monitoring		Offshore Deployment	
Technology	**Cost**	**Strengths**	**Confidence**	**Limitations**	**Recommendations**	**Collision**	**Behaviour**	**Fixed**	**Floating**
		be classified into their sub-groups. Flight trajectory and flight speed can also be obtained. The radar can detect small birds up to 1km and larger birds up to 2km depending on the setting of the scanning cone.	studies at offshore wind farms. Unclear how well the radar functions during the day at offshore wind farms due to the monitoring study at Alpha ventus only reporting its capabilities during nocturnal periods.	turbine) to the rotating blades, strong disturbances would make it hard to properly detect all birds. The radar becomes unusable during mass migration.	facilitate species identification, and reduce human observation costs.				deployed on floating structures.
Camera									
Video and Thermal Imagery	Dependent on camera and lens type used. Could be cheaper than VARS.	Using software flight tracks can be produced (images taken over time are matched together giving an overall	A combination of both video (daylight capabilities) and thermal cameras have increasingly been used in	High false positive rate if camera is not set to only record when a bird is in view. Limited in bad weather and if not integrated with	If paired with radar, macro and meso data could be recorded.	Yes Video camera footage may show instances of collision.	Micro	Thanet European Offshore wind Deployment Centre Nysted	Has not been tested but would be able to be deployed on floating structures.

						Monitoring		Offshore Deployment	
Technology	Cost	Strengths	Confidence	Limitations	Recommendations	Collision	Behaviour	Fixed	Floating
		picture of bird flight trajectory).	offshore monitoring studies at several wind farms.	thermal capabilities, only daytime data will be recorded.				Alpha Ventus	
VARS	Without offshore installation, about £18,000 for a single VARS with all components.	Can monitor birds during the day and at night. As the camera is aimed behind the rotor blades, it can measure the number of birds successfully crossing the rotor swept zone using motion detection. Birds entering this zone from behind can all be detected. Birds can mostly be assigned to species group.	Only appears to be used in monitoring studies at one offshore wind farm, however has produced high quality images indicating the camera functions well (91% of all species recorded could be assigned to individual species level).	VARS has a narrow field of view and short detection range.	If paired with radar, macro and meso data could be recorded. Additional cameras oriented away from turbine may offer views of meso-zone.	Yes Video camera footage may show instances of collision.	Micro	Alpha Ventus	Has not been tested but would be able to be deployed on floating structures.
Acoustic									

						Monitoring		Offshore Deployment	
Technology	Cost	Strengths	Confidence	Limitations	Recommendations	Collision	Behaviour	Fixed	Floating
Microphone	Audio moth devices can be fairly cheap, <£100.	Can pick up calls missed by observers and aid with species identification if camera quality is poor.	This technology is not used on its own and has only been used in two offshore monitoring studies.	Can be heavily impacted by background noise. Additionally, detection range can be limited (e.g., maximum range for some species is around 100m). Unclear what proportion of targets are successfully recorded.	Used to provide supplementary information for species identification. Would have to be paired with additional technology to monitor collisions or bird movements.	No	No	Egmond aan Zee Alpha Ventus	Has not been tested but would be able to be deployed on floating structures.
Impact Noise (micro-phone)	No information available.	Records collision events as it registers when an impact with the blades has occurred. Can be used to supplement other technologies to aid collision detection.	This technology has not been deployed as a standalone monitoring method – may be integrated within other systems – see e.g., ATOM, MultiBird.	Requires integration with other systems. Probability of detection may be relatively low.	Further testing/reporting is needed from integrated systems.	Yes If paired with additional technology, such as cameras, could derive collision rates.	No	See ATOM, MultiBird	Has not been tested but would be able to be deployed on floating structures.

						Monitoring		Offshore Deployment	
Technology	Cost	Strengths	Confidence	Limitations	Recommendations	Collision	Behaviour	Fixed	Floating
Impact Noise (piezo-electric paint)	No information available.	This technology can directly record collision events as it registers when an impact with the blades has occurred.	This technology has not been deployed offshore and only one study has been published detailing its capabilities.	It is unknown how well this would work for large-scale turbines. Further testing is required to conclude how effective this technology is in harsh environments.	Further testing is needed.	Yes If paired with additional technology, such as cameras, could derive species-specific collision rates.	No	Unknown (not tested)	Unknown (not tested)
Bio-logging									
Radio Tagging	Radio tags are cheaper than GPS tags.	Can be used on smaller species and allow for spatial and temporal movement information to be gathered. Tagging data can provide information on the origin of birds entering the wind farm	Radio tagging monitoring studies at Scroby sands have produced good results. However birds have only been tracked manually.	If radio substations are not used, birds need to be tracked manually and information obtained via hand-held devices. This can be difficult if species are fast fliers and limits	Used to provide supplementary information.	No	Macro Meso	Scroby Sands	Has not been tested but would be able to be deployed for floating structures.

						Monitoring		Offshore Deployment	
Technology	Cost	Strengths	Confidence	Limitations	Recommendations	Collision	Behaviour	Fixed	Floating
		and can identify foraging hotspots.	Unclear how effective antennas within wind farms would be at obtaining information.	the sample size achievable. Tagging can influence seabird behaviour.					
GPS	Costing is determined by the size of tag used. Is more expensive than radio tagging.	Tags have longer lifespans compared to radio tags and can track birds over greater distances. Solar panels can increase the lifespan of a GPS tag to several years. Tagging data can provide information on the origin of birds entering the wind farm and can identify foraging hotspots.	Has been used within several monitoring studies at offshore wind farms to obtain seabird behavioural information, generating information on flight avoidance behaviour at meso and macro scales.	Tag failure can occur due to battery depletion and some tags require the bird to be recaught in order to collect the data. Tagging can influence seabird behaviour.	Used to provide supplementary information on provenance of birds as well as information on avoidance behaviour.	No	Macro Meso	Amrumbank West Nordsee Ost Meerwind Sud/Ost Scroby Sands Greater Gabbard Galloper East Anglia One Thornton Bank Alpha Ventus DanTysk	Has not been tested specifically but would be able to be deployed for floating structures.

						Monitoring		Offshore Deployment	
Technology	**Cost**	**Strengths**	**Confidence**	**Limitations**	**Recommendations**	**Collision**	**Behaviour**	**Fixed**	**Floating**
Combined System									
MUSE	Accurate costs would need to be sought from manufacturer. Can cost between £500k - £1M depending on the quality of technology used.	The software used uses radars to trigger the camera to aim and record a video sequence of the bird(s) passing the field of view. This can allow flight altitude and speed to be known. The system can allow for AI-based species identification and nocturnal data capture to take place. As radar and camera track data are fully integrated the spatio-temporal resolution is high (10-20m/1-2 seconds). Can record birds up to 10km and flocks up to 25km.	This system has been deployed at multiple offshore wind farms and has obtained high quality data across all monitoring studies.	The system records a substantial number of videos, one camera can only follow one bird at the time.	Does not aim to record macro avoidance and so would need to be paired with additional technology to obtain information on these parameters.	Yes Video camera footage may show instances of collision. Setting may be adapted to generate empirical collision estimates.	Meso Micro	European Offshore Wind Deployment Centre Luchterduinen Block island USA Wikinger, Germany Sg. Brieuc, France Two sites in Taiwan Mannar, Sri Lanka (Older system deployed at Thanet)	Has not been tested but would be able to be deployed on floating structures.

						Monitoring		Offshore Deployment	
Technology	Cost	Strengths	Confidence	Limitations	Recommendations	Collision	Behaviour	Fixed	Floating
WT-Bird	For one wind turbine, between: £26k - £90k. Costs of installation are not included. Is not commercially available yet.	The sensors detect the collision events with few false positives. Rotor blades are always entirely in view. This can allow for species identification to take place. The software can be adjusted to account for various weather conditions, such as rain.	Has not been widely used in offshore monitoring studies. It is unclear how well this system functions within the offshore environment.	The sensors are limited in detection. The signal of a bird hit has to be detected by the sensor and filtered out from the background noise by algorithms. This can result in collisions of smaller birds going undetected.	Install additional monitoring technology to obtain data on the bird leading up to the collision.	Yes Could be used to obtain empirical collision rates.	Micro	Egmond aan Zee	Has not been tested but would be able to be deployed on floating structures.
DTBird	These systems are customised for every wind farm project. The cost takes into account wind turbine dimensions, target species, local weather, detection	DTBird is designed to detect birds in collision risk with wind turbines and to trigger actions to prevent collision. This can involve stopping the turbine and/or emitting signals to deter the bird(s).	Results regarding offshore monitoring are not publicly available.	In order to get from DTBird detection to collision rates, all videos stored from bird movements in the vicinity of the wind turbine will have to be manually checked for the fate of the bird involved.	Likely to be adaptable to provide information on collision rates and micro-avoidance behaviour and therefore may be paired with other technology.	Yes Could be used to obtain empirical collision rates.	Micro	Fino 1	Kincardine

						Monitoring		Offshore Deployment	
Technology	Cost	Strengths	Confidence	Limitations	Recommendations	Collision	Behaviour	Fixed	Floating
	model (day/night, number of cameras), number of DTBird units and location.			Smaller birds are detected proportionally at smaller distances and larger birds at longer distances. Species determination isn't always possible.					
ATOM	On request	The thermographic component of the ATOM system is designed to calculate, record and store flight altitude and direction data of all flying animals up to 180m over the day-night period and is capable of viewing the rotor swept zone of one turbine. It simultaneously captures acoustic data, providing some species-specific	Has not been fully tested yet at an offshore wind farm Testing onshore did record ample amount of data and no collisions were recorded in the test period. Developer has stated it is offshore ready.	ATOM has been extensively tested, but only on land and at sea at a light tower.	Could be integrated with radar technology to provide additional information of bird flight activity in meso and macro-zone. Not designed to specifically record collision impact events but collision can be viewed within data video clips.	Yes Video camera footage may show instances of collision.	Micro	Yes	Has not been tested but likely to be able to be deployed on floating structures.

						Monitoring		Offshore Deployment	
Technology	Cost	Strengths	Confidence	Limitations	Recommendations	Collision	Behaviour	Fixed	Floating
		identification of vocalising bird(s).							
Wind Turbine Sensor Array	No information available. Is not commercially available yet.	Can directly record collision events and allow for species identification to take place.	Has not been tested offshore yet. Further testing is dependent on future funding. Has not been tested against 'real' (bird) targets.	As cameras are looking directly at the blades, information leading up to the collision is not always obtained Coverage depends on where the camera is installed Detection probability is not 100% and may be relatively low.	Additional camera would allow meso-avoidance to be recorded if oriented away from turbine. Could be integrated with radar technology to provide additional information of bird flight activity in meso and macro-zone.	Yes Could be used to obtain empirical collision rates.	Micro	Unknown (Developer has stated offshore testing is planned).	Has not been tested but likely to be able to be deployed on floating structures if deployment at fixed structures is proven.
IdentiFlight	Information provided from manufacturer on request.	Comes with data dashboard where information can be easily accessed and viewed. Can be used to detect certain species of bird only and obtain tracking	It has yet to be tested offshore and so unclear if/how this system would work in the offshore environment.	This system has mainly been developed to detect eagles but has been recently updated to track other species.	Further testing offshore is required.	Yes Video camera footage may show instances of collision.	Meso Micro	Unknown (Developer has stated offshore testing is planned).	Unknown (not tested)

						Monitoring		Offshore Deployment	
Technology	**Cost**	**Strengths**	**Confidence**	**Limitations**	**Recommendations**	**Collision**	**Behaviour**	**Fixed**	**Floating**
		information on that species.							
ACAMS	No information available.	Uses stereo optic cameras and so can record data in areas close to turbine blades that could otherwise be impacted by radar (due to turbine clutter).	Information regarding offshore results is unpublished It was stated within Adams et al. (2017) that with the system's current capabilities, micro-avoidance could be difficult to describe for turbines with long turbine blades.	Appears to have limited detection capabilities currently Suggestions for improvement have been made however no updated information on how effective these improvements have been made available.	Further testing required. System alone cannot detect collision impacts, however collisions could be recorded within video clips. Install additional cameras to allow additional data to be collected.	Yes Video camera footage may show instances of collision.	Micro	Yes (details regarding the wind farm it is deployed at are unknown).	Unknown (not tested)
Spoor AI	Annual around £16k per turbine with analytics.	Uses AI technology for automatic detection of bird targets within video images. Species identification can	Results are currently unpublished and so it is unclear how well this	Bird detection precision approx 77.2%. False positive do occur, however developer	Meso and Macro avoidance can be recorded however this has yet to be analysed so cannot be	Yes Could be used to obtain empirical	Micro/Meso	Karmøy - Marine Energy Test Centre UK North Sea	Karmøy - Marine Energy Test Centre

						Monitoring		Offshore Deployment	
Technology	Cost	Strengths	Confidence	Limitations	Recommendations	Collision	Behaviour	Fixed	Floating
		occur but currently this requires manual input.	system works and the quality of data obtained when monitoring birds at offshore wind farms.	has stated AI is improving due to more data being recorded.	commented on at this time as unsure of accuracy of results.	collision rates.			
B-finder	Prices are tailored to the specification of the project. The price depends on the duration of deployment and the number of turbines equipped.	Provides 360° coverage around the turbine and can detect falling objects (e.g., birds that have collided with the turbine).	Has only been tested onshore, where it has produced promising results when detecting collision events. Developer has stated it is offshore ready.	As this system only detects when an object has collided with the turbine additional systems would need to be installed to aid with recording micro, meso and macro avoidance behaviour. Despite cameras being installed with the B-finder system, image quality can make it difficult to determine which species was	Install additional cameras to aid with species identification. Unsure how well this system operates offshore, however does state on the manufacturers website that it can be deployed offshore.	Yes If paired with additional technology, such as cameras could be used to derive species-specific collision rates.	No	Yes	Unknown (not tested)

						Monitoring		Offshore Deployment	
Technology	Cost	Strengths	Confidence	Limitations	Recommendations	Collision	Behaviour	Fixed	Floating
				subjected to the collision event.					
ID-Stat	No information available.	Can detect impacts from collision.	No published information was available for review. It is unclear how well this system works offshore as it appears to only have been tested onshore	Not much information is available on this technology and so is difficult to conclude if this would be effective offshore.	Further testing and information is required.	Yes However it is unknown due to lack of literature if empirical collision rates could be obtained.	No	Unknown (no information available)	Unknown (no information available)
Multibird	No information available.	Is a multi-sensor system that is capable of recording data during daylight and nocturnal periods integrating different sensors to provide a comprehensive monitoring system.	Is currently still in development. Offshore testing is scheduled.	Information available on this system is currently limited.	Further testing and information is required.	Yes However it is unknown due to lack of literature if empirical collision rates could be obtained.	Meso Micro Macro (unknown)	Unknown (no information available)	Unknown (no information available)
Bird Migration and Collision	Costs in relation to study at	Due to multiple cameras being used, this system potentially	Results for these two monitoring	It is unclear how well this system works and so	It is mentioned that macro avoidance behavioural	Yes	Micro	Yunlin	Has not been tested but would be able

						Monitoring		Offshore Deployment	
Technology	Cost	Strengths	Confidence	Limitations	Recommendations	Collision	Behaviour	Fixed	Floating
Monitoring System	Yunlin: In total ca. €3 Million incl. three year analysis and results.	offers comprehensive monitoring capabilities and can be used to derive empirical collision rates at the turbine it is installed at.	studies are currently not published and monitoring has only just begun/is underway.	further information is required (e.g., false positive/negative rates, detectability). The cameras are not linked to the radar technology.	information could be obtained if radars were installed to allow such information to be gathered. It is mentioned however that this would not allow species specific macro avoidance information to be obtained and additional cameras would need to be installed/observationa l surveys undertaken in order to obtain species specific information.	Could be used to obtain empirical collision rates.	Meso Flux	Nordergründe	to be deployed on floating structures.
BirdtrackÒ family of products (BirdTrack and CDS)	Cost based on project's characteristics .	The S-Band radar can map the trajectories of birds/flocks and obtain flight speed. The X-band radar scans in vertical mode and obtains flight altitude, traffic flow	Data is currently unpublished for offshore results and so unclear how well this system works No study utilising all	X-band radar can be susceptible to rain clutter.	Could be paired with additional impact detection technologies.	Yes Could be used to obtain empirical collision rates using the	(BirdtrackÒ) Macro Meso Flux (CDS)	Offshore wind farm in the UK (details regarding this wind farm are confidential).	WindFloat Atlantic

						Monitoring		Offshore Deployment	
Technology	Cost	Strengths	Confidence	Limitations	Recommendations	Collision	Behaviour	Fixed	Floating
		and complementary data for target identification. The system has ground and weather clutter filtering and as the system is built for site-specific characteristics, it allows for high detection efficiency and reduces errors in target classification. The use of the Collision Detection System would allow for collision events to be recorded and empirical collision rates to be estimated.	BirdtrackÒ products has currently been announced.			integrated CDS	Micro		
BPS	For onshore, depending on the version of the system £21k – £39k per system.	Uses stereo vision and multiple cameras to provide 360° coverage around a wind turbine. Does not directly record meso-	Has yet to be tested offshore, however has been used extensively at onshore wind	The current design as a deterrent system focusses cameras away from the micro-	If cameras are redeployed to view vertically upwards, coverage of the micro-zone is achievable and	Yes Could be used to obtain empirical	Meso Micro	Unknown (Developer has stated offshore	Unknown (not tested)

						Monitoring		Offshore Deployment	
Technology	Cost	Strengths	Confidence	Limitations	Recommendations	Collision	Behaviour	Fixed	Floating
	Costing includes the supply. For operation and maintenance costs, between £3.5k-£4.5k per year. Unsure of offshore costing.	avoidance behaviour however could be estimated from the video data collected in the space between turbines. Data is provided within a specific dashboard and so information can be easily accessed.	farms where a vast amount of data has been collected leading up to and after collision events.	zone but could be adapted. Was designed as a bird determinant system and so unclear the type of analysis that could be carried out to generate avoidance rates.	collision events could be detected. Could be paired with additional technologies such as radar to provide bird flight data within and outside the wind farm.	collision rates.		testing is in development).	

4. Conclusions

Our literature search has revealed a variety of studies utilising a number of technologies or combination of technologies to study bird behaviour around operating wind turbines in the onshore and offshore environments. However, there did not appear to be any recently completed or current studies focussing on the measurement of empirical collision rates for seabirds at offshore wind farms. Such information is critical for the industry to gain a better understanding of the collision risk that offshore wind farms pose to seabirds and to improve the models used to predict impacts at proposed developments at the single development and cumulative development scales. We identified 26 offshore monitoring studies within UK, Europe and global waters that are either completed, currently underway or planned utilising the multiple different technologies and systems that we have detailed in the literature review above. The majority of operational monitoring studies that use the technology/systems are designed to further the understanding of avoidance and flight behaviour at different scales (micro, meso and macro) or to implement mitigating actions to avoid or minimise the occurrence of collisions.

There are a number of existing monitoring systems that incorporate camera technology and have the capability to detect the occurrence of species-specific collisions, such as MultiBird, MUSE, ATOM, DT-Bird, the Strix Collision Detection System, the Bird Migration and Collision Monitoring system and updates to the WT-Bird system. The aim of the projects we have reviewed has not been focussed on the measurement of empirical collision rates but these have the potential to be adapted or designed in such a way to collect such information. It is clear however, that a further study that incorporates a combination of these technologies/systems is needed for comprehensive monitoring of species-specific collision rates and bird flight behaviour at different scales and in different conditions.

Not all technologies/systems that collect data on collision events can be used to derive empirical collision rates. In order to obtain empirical collision rates, instances of collisions must be detected over a given period of time and with a known degree of confidence (i.e., an understanding of false negative rate). It is necessary for a monitoring system to provide information on periods when no collisions occur but birds are detected within close proximity to the turbine blades in order to understand collision rates in the context of flux. It is also necessary to have the capability to identify species and as such, the incorporation of cameras is required to observe the birds at risk, while acoustic technology may also aid identification in low-light conditions.

Table 5 provides an overview of the capabilities of the reviewed technologies/ monitoring systems to measure collision rates and reactive flight behaviour at different spatial scales.

Table 5 Technologies/systems that have been used to monitor either collision, micro, meso, and/or macro-scale avoidance behaviour. Coloured cells indicate if the technology/system has the potential to observe each observation type; collision, micro, meso, macro

System	Collision	Micro	Meso	Macro
Video and Thermal Imagery				
VARS				
Impact noise (piezoelectric paint)				

System	Collision	Micro	Meso	Macro
MUSE				
WT-Bird				
DT-Bird				
ATOM				
Wind Turbine Sensor Array				
IdentiFlight				
ACAMS				
Spoor AI				
B-Finder				
ID-Stat				
Bird Migration and Collision Monitoring				
CDS				
MultiBird				
Merlin Avian Radar				
LAWR 25				
3D Flex Robin Radar				
BirdScan MR1				
Radio Tagging				
GPS				
BirdTrack®				

System	Collision	Micro	Meso	Macro
BPS				
SCANTER 5000				

Systems that detect collision events (e.g., DT-Bird, B-Finder, the Wind Turbine Sensor Array and the Bioseco Bird Protection System) are mainly tested onshore, and so offshore results are limited at this time and it is unclear how these systems would function within the offshore environment. Developers of these systems do state however that they could be capable of being deployed offshore, subject to ongoing and further testing and system modifications.

Not many technologies/systems have been tested at floating wind farms yet (testing of systems such as Spoor AI, BirdTrack and DT-Bird are currently underway) so it is currently unclear how these systems could be impacted by deployment at floating rather than fixed foundation turbines. Although it is anticipated that if they can be deployed offshore at fixed turbines, following some technical solutions (for example to reduce motion effects caused by swell and wind), these monitoring devices could be installed on floating platforms as well.

In addition, the amount of information gathered from monitoring technology/systems can be dependent on the species being monitored, as some cannot easily detect smaller birds (e.g., terns). Radars such as BirdScan is stated to become unusable during mass migration events, with detection of certain cameras limited depending on where it is installed (e.g., the Wind Turbine Sensor Array). The positioning of the installed monitoring technology/system needs careful consideration during the design of a future monitoring programme.

Despite each technology/system having its own limitations, the literature review includes possible recommendations on how each could be integrated with additional technologies/systems in order to enhance the quality of data across multiple spatial or temporal scales. The review reveals that a combined monitoring strategy that includes some type of radar device (allowing data on the meso and macro-scale as well as information on flux rates to be gathered), camera or visual observation (allowing birds within the meso and micro zone to be monitored and can allow species identification to take place) and impact detection technology (allowing for collision events to be recorded with some degree of certainty) could generate the best results. Additionally microphones may be used to aid with species identification and bio-logging devices could provide contextual information (i.e., the origin of the bird, relative amounts of time spent within and outside wind farms and seasonal changes in behaviours) and show how habitat use and behaviour towards the wind farm changes overtime.

Using the information provided within this literature review and the outcomes of the power analysis in Work Package 3, Work Package 4 then aims to identify an appropriate future seabird monitoring study. This will aim to address knowledge gaps surrounding seabird collision rates and reactive behaviour in the vicinity of offshore turbines through a strategic monitoring campaign. In light of the potential cumulative risk to seabirds from the expansion of offshore wind energy around the UK required to meet Net Zero targets, we consider that it is essential for the industry to gain a better understanding of the occurrence of seabird collisions at offshore wind turbines through the implementation of a future monitoring campaign.

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APPENDIX

Appendix 1: Interview questionnaire

Apx Table 1. Interview questions / questionnaire

Question	Response
Name of Monitoring Technology	
Project Contact	
Date of interview/response	
What is the objective of the monitoring system? - what is it trying to measure? (e.g., collisions, avoidance, behaviour, flux)	
Method of monitoring (e.g., is the system visual, acoustic, radar, GPS, combination)?	
Scale of deployment (number of devices deployed)? How many turbines (or other platforms) will the system be deployed at?	
Where is the equipment deployed? (e.g., attached to the blades of the turbine, attached to the base of the turbine, attached to platform etc.) And how is it fixed to the infrastructure? Are there limits on the location of where the equipment can be installed on the infrastructure?	
Is information on bird behaviour prior to collision or in the vicinity of the turbine collected and in what format? Other information collected (e.g., flight heights, flight speeds, flight path etc.)?	
Equipment (e.g., cabling and control cabinets) and turbine requirements for hosting, including whether this can be retro-fitted to operational turbines and any impact on wind turbine performance certificate/warranty?	

Question	Response
Duration / Frequency of deployment – how long can it be deployed? How often does it operate (e.g., 24-7 or periodic)	
Estimated costs (per unit)	
Diurnal / Nocturnal / Visibility – can it operate at night, or in poor weather conditions?	
Offshore capability – is it ready to be deployed in the offshore environment?	
Species identification - does it record to species level, or species groups? What species is it capable of recording?	
How has the data been (or is intended to be) used to estimate macro-avoidance rates?	
How has the data been (or is intended to be) used to estimate within-wind farm avoidance rates (meso-avoidance)? What do these avoidance rates describe in reality, behavioural avoidance (similar to that calculated in Skov et al. (2018)), model error or a combination of these?	
How has the data been (or is intended to be) used to describe and/or categorise bird behaviour immediately preceding collision/avoidance (micro-avoidance)? What other information was required to do this?	
Type and format of information recorded/stored and how that information is retrieved (i.e., information broadcasted to receiving station, information is stored in a hard drive onsite and then collected)	
How is data extracted and in what format?	
What analyses can be envisaged for the processed data?	

Question	Response
Monitoring capacity of each device (for example does each device monitor a whole turbine, several turbines, or any part of a single turbine/rotor-swept area)?	
What parts of the structure are visibly monitored beyond turbine blades/rotor-swept area (e.g., floating wind platforms)?	
What is the false positive/missed detections rate?	
Reliability at detecting birds in the vicinity of turbines (if not directly recording collisions); how has this been tested/validated?	
How has the data been (or is intended to be) used to directly estimate empirical collision rates per (surveyed) turbine? What other information was required to do this? How accurate were the estimates thought to be?	
How has the data been (or is intended to be) used to estimate CRM parameters (such as flight heights and flight speeds)? How accurate were these thought to be? How might this information most meaningfully be used to improve collision estimates or future predictions?	
How has the data been (or is intended to be) used to estimate flux rates through individual turbines and/or the wind farm as a whole? How was this done and what other information was required to do this?	
Are there existing case studies where it has been deployed? If so, are data published or available?	

Appendix 2: Literature search

Apx Table 2. Monitoring Reports and Scientific Papers reviewed during Literature Search.

Author / Date	Monitoring Report / Scientific Paper
Albertani et al., 2018	Eagle Detection, Identification and Deterrent, with Blade Collision Detection for wind Turbines
Aschwanden et al., 2015	Investigation on the effectivity of bat and bird detection at a wind turbine: Final report Bird Detection
Aschwanden et al., 2018	Bird collisions at wind turbines in a mountainous area related to bird movement intensities measured by radar
Becker, 2016	Optimising The Use Of Visual And Radar Observations For The Mitigation Of Wind Energy Related Impacts On Cape Vultures (Gyps Coprotheres) In The Eastern Cape Province
Blew et al., 2008	Investigations of the bird collision risk and the responses of harbour porpoises in the offshore wind farms Horns Rev, North Sea, and Nysted, Baltic Sea, in Denmark Part I: Birds
Borkenhagen et al., 2018	Estimating flight heights of seabirds using optical rangefinders and GPS data loggers: a methodological comparison
Christensen et al., 2003	Visual and radar observations of birds in relation to collision risk at the Horns Rev offshore wind farm
Collier et al., 2011 & 2012	A review of methods to monitor collisions or micro-avoidance of birds with offshore wind turbines. Part 1 & Part 2
Delprat and Alcuri, 2011	Innovative technology for assessing wildlife collisions with wind turbines. Conference on Wind energy and Wildlife impacts
Desholm, 2005	TADS investigations of avian collision risk at Nysted offshore wind farm, autumn 2004.
Desholm and Kahlert, 2005	Avian collision risk at an offshore wind farm
Dirksen, 2017	Review of methods and techniques for field validation of

Author / Date	Monitoring Report / Scientific Paper
	collision rates and avoidance amongst birds and bats at offshore wind turbines
Fijn et al., 2015	Bird movements at rotor heights measured continuously with vertical radar at a Dutch offshore wind farm
Grunkorn et al., 2016	Prognosis and assessment of bird collision risk at wind turbines in northern Germany
Guillemette et al., 1999	Asessing the impact of the Tuno Know Wind Park on Sea Ducks: The influence of food resources
Harwood et al., 2017	Unforeseen Responses of a Breeding Seabird to the Construction of an Offshore Wind Farm
Hill et al., 2014	Of birds, blades and barriers: Detecting and analysing mass migration events at Alpha Ventus
Hu et al., 2017	Wind turbine sensor array for monitoring avian and bat collisions
Japan Weather Association, 2020	Japan Weather Association joins Taiwan's "Ex-post Birds Survey Work on Offshore Wind Power Generation" with "Birds Migration and Collision Monitoring Technology" ~Japan's Birds Monitoring Technology adopted for infrastructure equipment overseas for the first time
Japan Weather Association, 2021	AI bird identification system has been developed. ～ Contributing to the coexistence of rare wild animals and wind power generation business with new technology
Jenkins et al., 2018	Combining radar and direct observation to estimate pelican collision risk at a proposed wind farm on the Cape west coast, South Africa
Jensen et al., 2016	Post-construction monitoring of bird migration
Kang and Kang, 2017	Development of wireless bird collision monitoring system using 0-3 piezoelectric composite sensor on wind turbine blades
Krijgsveld et al., 2005	Baseline studies North Sea wind farms:

Author / Date	Monitoring Report / Scientific Paper
	fluxes, flight paths and altitudes of flying birds 2003 - 2004
Krijgsveld et al., 2011	Effect studies Offshore Wind Farm Egmond aan Zee
Leopold et al., 2013	Responses of Local Birds to the Offshore Wind Farms PAWP and OWEZ off the Dutch mainland coast
Masden et al., 2009	Barriers to movement: impacts of wind farms on migrating birds
Masden et al., 2012	Assessing the impact of marine wind farms on birds through movement modelling
McClure et al., 2018	Automated monitoring for birds in flight: Proof of concept with eagles at a wind power facility: Duke Energy Renewable's Top of the World Windpower Project
Molis et al., 2019	Measuring bird and bat collision and avoidance
Niemi and Tanttu, 2019	Deep learning-based automatic bird identification system for offshore wind farms
Perrow et al., 2006	Radio telemetry as a tool for impact assessment of wind farms: the case of Little Terns Sterna albifrons at Scroby Sands, Norfolk, UK
Peschko et al., 2020	Telemetry reveals strong effects of offshore wind farms on behaviour and habitat use of common guillemots during the breeding season
Roel et al., 2012	Evaluation of the DT-Bird video-system at the Smola wind-power plant
Skov et al., 2012	Horns Rev 2 Offshore Wind Farm Bird Monitoring Program 2010-2012
Skov et al., 2016	Patterns of migrating soaring migrants indicate attraction to marine wind farms
Skov et al., 2018	ORJIP - Bird Collision Avoidance Study
Strix, 2011	RADAR Assisted Shutdown on Demand

Author / Date	Monitoring Report / Scientific Paper
Thaxter et al., 2015	Seabird - wind farm interactions during the breeding season vary within and between years: A case study of lesser black-backed gull in the UK
Tome et al., 2017	Radar Assisted Shutdown on Demand Ensures Zero Soaring Bird Mortality at a Wind Farm Located in a Migratory Flyway
Trinh et al., 2016	Bird Detection Near Wind Turbines From High-Resolution Video Using Lstm Networks
Verhoef et al., 2003	WT-bird: A novel bird impact detection system.
Willmott and Forcey, 2014	Acoustic Monitoring of Temporal and Spatial Abundance of Birds Near Outer Continental Shelf Structures. ATOM developed by Normandeau Associates
Willmott et al., 2015	Developing an automated risk management tool to minimise bird and bat mortality at wind facilities
Winkleman, 1992	The impact of the Sep wind park near Oosterbierum (Fr.), the Netherlands, on birds, 1: collision victims.

Appendix 3: Additional monitoring systems

This Appendix provides a summary of some additional monitoring systems that came to light at a late stages of the project, for which we were unable to carry out more detailed review.

1.1. Calidris Monitoring System

System functioning

It is unclear what devices this monitoring system includes, however it is stated on the developer's website that equipment for environmental protection monitoring, including monitoring collision and activity can be installed at onshore wind farms. It is mentioned that birds and bats can be monitored, however details on its deployment at operational wind farm sites is unclear. It appears to be installed at onshore wind farms in Portugal, Morocco, Romania and Tunisia. It is unknown if this system can be deployed offshore. The system is developed by the French company, Calidris.

1.2. 3DFlighTTRack Radar

System functioning

The 3DFlighTTtrack monitoring system is a high-definition, panoramic, 3D radar for advanced aerial detection, positioning and tracking of small flying objects (such as birds and bats) in the vicinity of turbines (Figure 21). The system was designed to detect, position, track and also predict routes of single birds or flocks in real-time in all weather conditions to enable deterrent signals to be emitted if birds were deemed to be at risk of collision. It utilises an innovative dual-antenna orientation technique and simultaneous angle-difference measurements. The system can detect and track in 3D single birds up to 3km and flocks of birds up to 10km and can be linked to cameras, allowing photographs of birds/objects to be taken and stored. Additionally, the system can be linked to weather sensors, enabling information on weather conditions such as wind, current and temperature to be recorded.

It is unclear where this system has been deployed, with information online indicating it has mainly been deployed onshore. This monitoring system has been developed by Diades Marine in France.

TECHNICAL CHARACTERISTICS

Maximum range	10 km (birds) / 30 km (vessels)
Operating bandwidth	X-Band 9.4 Ghz ± 30 Mhz
Peak power	2 x 25 kW ± 50 %
Power consumption	400 W
Power requirements	230 V
Dimensions	1200 x 1200 x 1100 mm
Weight	60 kg

Figure 21 Image of the 3DFlighTTrack Radar and table providing additional technical characteristics (images taken from Diades Marine website)

1.3. Fly'rsea

System functioning

This floating radar has been developed by the company Akrocean in France, allowing for year round, continuous monitoring of birds and bats at offshore wind farms (Figure 22). It provides advanced Real-Time 3D detection, positioning and tracking and has a maximum bird detection range of 10km. It is unclear if this monitoring system has been deployed in monitoring studies offshore to date, however the Windsea system, used for monitoring weather and oceanographic conditions has recently been deployed at the Thor offshore wind farm, off the coast of Denmark.

It is stated on the developer's website that data is stored on board and also transmitted to a dedicated server onshore via GPRS/Satellite.

Figure 22 Fly'rsea floating radar system (image taken from Akrocean website)

Appendix 4: Literature search & interviews

Please find Appendix 4 here, in a separate Microsoft Excel document.

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