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Enterprise Number:
NO 939 350 675 MVA

Project memo

Review of technology for bird detection and collision prevention

VERSION
1.0

DATE
2022-12-15

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CLIENTS
Northwind partners

CLIENTS' REFERENCE
Deliverable No. 14

PROJECT
Northwind – WP5

NUMBER OF PAGES AND ATTACHMENTS
15

SUMMARY

Wind energy has played a crucial role on the transition towards more sustainable ways of generating power. However, the collision of birds and bats with wind turbines is widely recognized as a negative environmental impact of wind farms. Collisions with either the static structure or the rotating blades of the wind turbines occur. This project memo provides a review of technology for bird detection and collision prevention, focusing on post-construction minimization measures. Initially, an overview of sensor technologies commonly used to detect birds in the vicinity of wind farms, namely radar and camera-based systems, is presented. Then, four minimization measures including experimental tests at different wind farms worldwide are described: habitat management and painting (categorized as passive measures), and turbine curtailment and deterrents (categorized as active measures, as they require information from an external source to trigger an action for collision avoidance). Advantages and disadvantages of the measures are discussed throughout the document.

SINTEF REPORT NUMBER
AN 22.12.42

CLASSIFICATION
Unrestricted

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Document History

VERSION	DATE	VERSION DESCRIPTION
1.0	2022-12-15	Original document

Contents

1 Introduction

1.1 Purpose

Wind energy developments have played a crucial role on the transition towards the replacement of fossil fuels by cleaner and more sustainable ways of generating power. However, the collision of birds with wind turbines is widely recognized as a negative environmental impact of wind power plants. The number of bird deaths due to collision with wind turbines varies greatly between sites around the world, with estimates ranging from zero to almost 40 deaths per turbine per year [1] (and references there in).

Many efforts have been made to measure and mitigate impacts from wind farms on wildlife, and the collision of birds with wind turbines has been the focus of a number of studies and reviews, see, e.g., [1–12]. Minimisation of impacts should typically be addressed following the *mitigation hierarchy*, which involves avoidance of high-risk sites during planning of wind farms, followed by minimization measures during operational phase, and compensation for unforeseen or unavoidable impacts [6, 7]. Mitigation measures to reduce bird mortality are particularly complicated due to the fact that birds are exposed to collisions with the static structure, as well as to collisions with the rotating turbine blades [6]. In addition, bird species have different sensory faculties and behavioural aspects. Currently, there is not a single solution that can be applied to all sites and species. The proposed measures are species-specific and tailored to the most collision-prone species at a certain location [6].

This project memo presents an overview of sensor technologies commonly used to detect birds in the vicinity of wind farms for mitigation purposes, and minimization measures that have been tested in the field. The focus is on *operational mitigation*, i.e. measures that aim to decrease the risk of bird collisions with wind turbines, post-construction of the wind farm. As indicated by the mitigation hierarchy, the initial planning for the wind farm is the most important stage of collision mitigation. However, even after good strategic planning, some risks of collision might persist. Minimization measures during the operational phase of the wind farm can contribute to further reduce these risks [1].

1.2 Methods

A scientific literature search was carried out in Scopus database using the following keywords:

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- bird AND collision AND wind AND turbine AND monitoring OR detection
- bird AND collision AND wind AND turbine AND mitigation OR prevention
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In addition, the search spanned Tethys literature database "Wind Energy Monitoring and Mitigation Technologies Tool" [13], a database that catalogs monitoring and mitigating technologies to assess and reduce potential wildlife impacts from wind energy development. More than 150 works were found in total but, after an initial sifting, around 50 works have been considered in this review. Since the focus of this report is on real-time bird detection and collision prevention methods during wind farm operation, studies targeted to e.g., mapping bird populations, understanding migration patterns, and technology for detecting the occurrence of collisions have been omitted here.

1.3 Scope

This document is organized into three main sections. Following the Introduction, Section 2 presents an overview of technology commonly used for monitoring birds in the vicinity of wind farms, namely radar and camera-based systems. Section 3 presents minimization measures, focusing on a few recent developments with in-situ experimental studies. The measures described are habitat management and painting (categorized as passive measures), as well as turbine curtailment and deterrents (categorized as active measures, as they require information for an external source to trigger an action for collision avoidance). The aim is to provide an overview of common practices, rather than presenting an exhaustive list of approaches.

2 Detection of birds in the vicinity of wind farms

This section presents an overview of technologies for monitoring birds in wind farms. It should be noted that visual observation by humans has also been used to detect the presence of birds in the vicinity of wind farms.

2.1 Radar

To detect moving or stationary targets, the basic working principle of a radar system is to transmit electromagnetic waves and study the echo signal reflected off the target. Radars operate at different frequency bands, and can also be designated by the wavelength, as summarized in Table 1. The operation range depends on the application requirements, as each frequency band has particular characteristics [14]. The most common radar systems proposed for monitoring bird movements operate in one of the band designations from L- to Ka-band. Overall, radars operating in the S-band or with higher frequency bands are able to detect not only birds but also echoes from insects, light rain, and ground objects, which require adequate distinction from the bird's echoes. While radars with lower frequency bands (L-band) are less sensitive to precipitation, they are not appropriate for detecting small birds [15].

The use of radar technology can vary from real-time detection to monitor bird migration. In [16], a radar system operating in a frequency-modulated continuous wave (FMCW) mode in the Ka-band from 33.4 GHz to 36.0 GHz was proposed for real-time detection of birds. The detection was based on calculating a Range-Doppler map through a signal processing strategy implemented in the radar receiver data. An experimental set up was installed at the tower of a 2 MW wind energy plant about 95 m above the ground, where flying birds and controllable drones were detected. Doppler analysis was also used by the FMCW radar demonstrator in the Ku-band in [17], where a signal analysis method was applied for surveillance and motion estimation of birds. Experimental tests were performed initially with a controllable target flying close to wind turbines, and subsequently with cormorants around Mosel river in Germany. The radar was able to observe both lateral and radial movements of very small targets.

Currently, available commercial solutions using radar technology for monitoring birds are commonly based on Doppler, tracking radar and surveillance radar [11]. The solutions can monitor the presence of birds within individual turbines and the wind farm (as well as beyond its perimeter), but monitoring the flight behaviour within the rotor swept area requires pairing with cameras. In addition, visual observation by cameras or humans is also required for obtaining specific information about the bird species. More details about some available commercial solutions using radar technology in offshore wind farms can be found in [11].

Table 1: Radar frequency bands.

Band designation	**Nominal frequency range** (GHz)	**Wavelength** (cm)
UHF	0.3 - 1	100 - 30
L	1 - 2	30 - 15
S	2 - 4	15-7.5
C	4 - 8	7.5 - 3.75
X	8 - 12	3.75 - 2.5
Ku	12 - 18	2.5 - 1.67
K	18 - 27	1.67 - 1.11
Ka	27 - 40	1.11 - 0.75
V	40 - 75	0.75 - 0.4
W	75 - 110	0.4 - 0.27
mm	110 - 300	0.27 - 0.1

2.2 Camera

Camera-based systems have also been used for detection of birds in the vicinity of wind farms. Daylight high-definition (HD) cameras and thermal imaging cameras for nocturnal monitoring activities are commonly used. Computer vision systems are developed for automatic detection, as the analysis of video images by humans tends to become ineffective when applying mitigation strategies in real-time. By using the camera image as input, a bird-detection software combines image processing methods with techniques of machine learning and deep learning for automating the tasks of the human visual system.

The identification and classification of bird species using camera-based systems is an ongoing topic of research. A number of works have been focusing on developing algorithms and tools able to interpret the images from daylight or thermal imaging cameras; not only for real-time detection purposes but also for quantifying birds and monitoring migration, see, e.g., [8, 18–25].

A number of solutions for detecting birds using camera technology are currently available in the market [26–28] or have been tested in experimental set-ups [18, 19]. The solutions are based on either mono or stereo-vision camera. Both methods are able to detect bird movement and allow species identification through the detection software, but monoscopic solutions are more cost-effective than stereoscopic. However, the latter can provide additional information about the bird position (e.g., in relation to the turbine) and size [18]. The maximum detection range is also higher for sensors based on stereoscopic vision; for instance, a detection range of 1500 meters can be obtained by a stereo solution, and 600 meters for a mono solution vision [18].

2.3 Radar-camera systems

Radars are able to detect birds over a wider range than cameras. Then, they are best suited for wide area monitoring [24]. However, depending on the frequency band of operation, small birds cannot be reliably detected by radar, and in any case, it is difficult to determine the birds species by using only radar data [11, 16, 24]. Camera-based systems are well suited for collecting data within the rotor swept area and 500 meters of the wind turbine as well as for identifying species. Therefore, multi-sensor systems extend the parameter coverage and allow different features of the target to be obtained [29].

The integration of technologies provides wider range of coverage, while allowing for automatic bird species identification when a computer vision system is included. The combination of radar and camera technology for such purposes has been demonstrated in [30, 31]. In [29], the authors have proposed the use of data fusion to integrate the data from infrared camera and marine radar. In this application, the sensors provided complementary information: while the radar provided the altitude of the bird (z-dimension), the infrared imaging sensor informed its location (x-y dimension). Then, a more accurate information about the bird flight was obtained than if only one of the sensors has been adopted.

3 Minimization measures to prevent collision

A comprehensive literature review on post-construction minimization measures to reduce bird collisions in wind farms has been presented in [1, 6], including an evaluation of the efficacy of the measures from an avian sensory, aerodynamic and cognitive perspective [6]. In this section, a few recent developments with in-situ experimental studies are summarized. The measures are categorized into passive, when they do not require external information from an human or sensor technology to reduce collision risk, and active measures, when actual information triggers an action for collision avoidance.

3.1 Passive measures

3.1.1 Habitat management

Habitat management measures include both on-site and off-site habitat alterations to reduce the risk of bird collision with wind turbines. On-site alterations aim to decrease the bird activity within the wind power plant,

Figure 1: Tilled soil. Image by `April Sorrow (UGA CAES/Extension)` licensed under `CC BY-NC 2.0`.

which can be done, e.g., by clear-cutting forests or reducing the attractiveness of the vegetation around the wind turbines either for the birds or their preys [6]. In contrast, off-site alterations aim to promote bird activity in areas outside the wind power plant. The measures include the creation of new areas for foraging habitat and breeding sites away from the wind farm [1, 6].

The effect of modifying the vegetation around wind turbines to make the area less attractive to *lesser kestrel* was verified in [32] for three wind farms in Spain. The procedure consisted of superficially tilling the soil (3-8 cm deep) in the base of wind turbines by using a plough, tiller or cultivator once a year for two years. To illustrate the tilling procedure, Figure 1 shows a freshly tilled soil for agriculture purposes. In [32], the tilling was done at the beginning of the bird breeding season to eliminate the natural vegetation, and consequently, to decrease the number of preys (insects). In total, the basis of 42% of 99 turbines in the wind farms had the soil tilled. The statistical analysis considered the number of dead kestrels found in tilled bases and in non-tilled bases as well as the mortality before and after the mitigation phase, which represented, respectively, eleven and two years of data. For the three wind farms, the results indicated an average reduction of 86% in the annual collision rates after the mitigation measure was applied. This reduction was attributed to the lack of prey around tilled bases, since the birds had to search for food in other areas away from the wind turbines [32].

As discussed in [6], the efficacy of on-site habitat alterations relies on the importance of the habitat for a certain specie. If the area is not dramatically modified, it may still be revisited. In any case, habitat alterations might affect other wildlife that were not previously affected by the wind farms. Additionaly, the creation of artificial breeding for raptors or building perching towers for offshore birds have been proposed as off-site habitat alterations. Still, the measures do not prevent the birds to move through the wind farms and utilise the area for foraging [6].

3.1.2 Painting

The rotational motion of turbines causes an effect known as motion smear (or motion blur) that can make the blades appear transparent to birds [33]. Based on laboratory tests, painting a single blade in black has been proposed as a suitable measure to reduce motion smear and risk of collisions [33]. In addition, ultraviolet (UV) coating has been also proposed to increase the visibility of blades, as some bird species are able to see in the ultraviolet spectrum [1]. However, there have been no clear conclusions about the efficacy of UV coating to prevent collisions [6].

Recent studies have tested the hypothesis that painting in black one of the turbine blades (Fig. 2) to reduce motion smear, and painting the tower to increase the contrast against the background, would reduce the collision risk of birds with wind turbines [34,35]. The measures are intended for different bird species: the former targets species that fly at the blade height, such as *soaring raptors* and birds with aerial display, while the latter targets species with poorly developed vision and flight maneuverability, and species typically flying relatively low heights, such as *galliformes* [35]. Both studies followed a before-after-control-impact (BACI) approach to test the painting effects in turbines at the Smøla wind power plant in Norway. In total, eight turbines were considered for testing the effects of painting one turbine blade in black, and 20 turbines were considered for the experiments with the tower. Figure 3 shows the experimental set-ups at the Smøla wind power plant [34, 35]. In each experiment, only half of the turbines were painted, while the other half were neighboring unpainted turbines defined as "control turbines" for ensuring similar spatial conditions in the comparisons.

Statistical analyse included the number of carcasses found before and after the painting and the number of searches with trained dogs. The experiment spanned over eleven years, where seven and a half years consisted of data before the treatment, and three and a half years of data after the treatment [34]. For the in-situ experiments with the blades, an annual fatality reduction of around 70% was observed mainly for raptors.

Even though the results were encouraging, the authors recommended to replicate or implement the measure in a larger number of turbines, given the limited number of turbine pairs in their experiment. The in-situ experiments with the tower indicated that the effect of painting was most pronounced in spring and autumn, as winter generally has poor light conditions and tower basis are hard to observe regardless of their appearance [35]. In this case, an annual fatality reduction of 48% was observed for *willow ptarmigans*.

Painting the turbines to increase visibility is a relatively simple and cost-effective measure. However, when possible, it is recommended to paint rotor blades before construction of the wind farm, as in-situ painting has high costs and requires specialized personnel [34]. Based on the results obtained in [34], wind farms in Spain [36] and Netherlands [37] have recently painted one blade of a number of turbines in black to test the minimization measure in their locations. At the same location in Spain, vinyl shapes resembling eyes were also applied at the tower bottom of a few turbines to increase their visibility [36].

A limitation of visual cues based on painting is that the measure becomes less effective in low light levels during poor weather conditions or at night. In addition, reducing the motion smear by painting the rotor blades is also less effective for species that constantly look down when flying [1]. In either way, it might be difficult for them to see the wind turbine ahead.

Figure 2: Wind turbine with rotor blade painted in black at the Smøla wind power plant, Norway. Image by May et al. 2020 [34] licensed under `CC BY 4.0`.

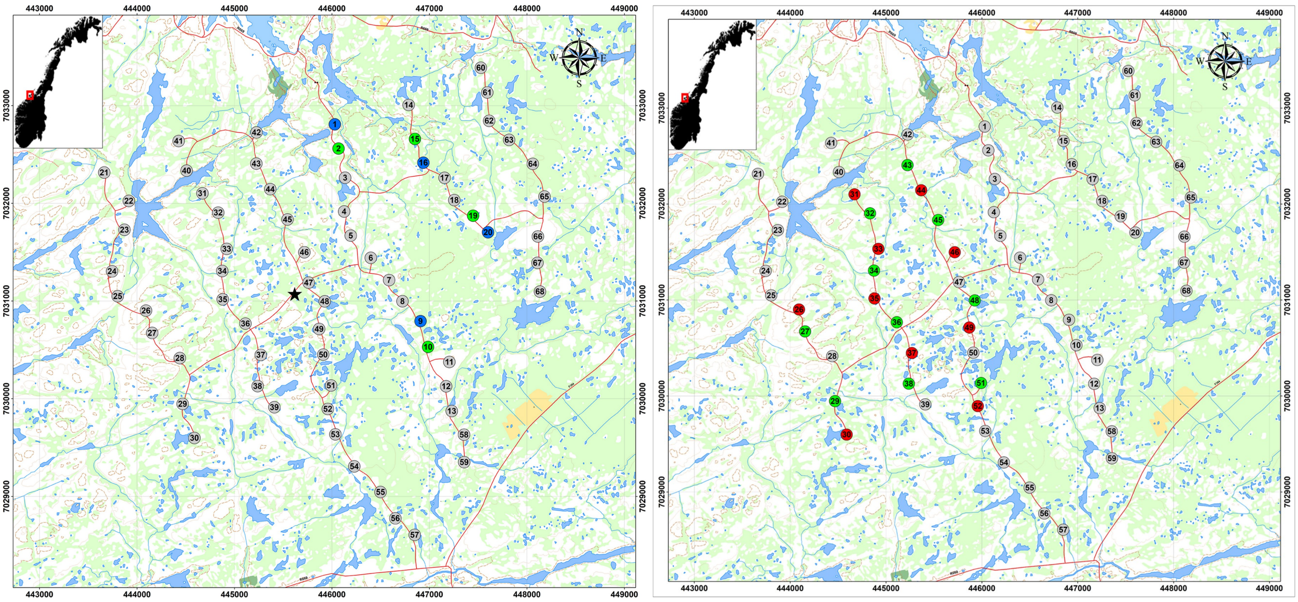

Figure 3: Experimental set-ups at the Smøla wind power plant. Left: Four turbines with painted rotor blades (blue) and neighboring turbines (green). Right: Ten turbines with painted tower bases (red) and ten neighboring turbines (green). Figures from May et al. (2020) [34] and Stokke et al. (2020) [35], respectively. Both figures are licensed under `CC BY 4.0`.

3.2 Active measures

3.2.1 Turbine curtailment

Curtailment and temporary shutdown of wind turbines have been proposed as minimization measures for birds flying at the blade height. Naturally, such measures can only be effective for birds colliding with rotor blades and not with the turbine structure. Shutdown or curtailment can be performed whenever a bird is detected in a high collision risk area or within a perimeter of the wind farm, which can be referred as "informed curtailment". Additionally, temporary shutdown can be done during migration seasons or certain weather conditions [1]. Shutting down during specific seasons or due to the weather relies on collision risk models, and not necessarily on actual risks of collision. Since this leads to large periods of shutdown and high reduction in the annual energy generation, this measure has not been well received by wind energy companies [1]. In addition, this approach tends to be ineffective for reducing the mortality amongst many bird species, as shown in [38]. However, informed curtailment can be effective for some soaring raptors [39–41]. Human observers, radar and/or camera-based systems have been used to determine the shutdown or curtailment time of specific turbines [26, 39–47].

The effectiveness of selective shutdown of wind turbines was tested in 269 turbines of wind farms in the southern of Spain, Cadiz area [39, 41]. A selective stopping protocol became mandatory in 2008 due to the high collision rates of *griffon vultures* with wind turbines in the location - an average of 61 death of vultures per year were observed within the wind farms before implementation of the measure. In the first two years of the application protocol, a reduction of mortality of about 50% was obtained for the vultures [39]. After 13 years of application of the same protocol, a reduction of about 93% in the mortality rate was observed when compared with the rate before the measure was applied (2006-2007). By considering all soaring birds, the reduction was about 65% [41]. The analysis considered before-after number of collisions, statistical methods, and annual counts of soaring birds, griffon vultures, passerines and bats. The protocol targeted soaring birds, specially vultures, while passarines and bats were considered for comparison purposes only. The wind turbines were shutdown whenever a dangerous situation was detected by trained observers (illustrated by Figure 4). A typical dangerous situation was defined, for instance, as griffon vultures with flight trajectories in potential risk of collision with the blades, or when flocks of medium to large sized birds were flying within or near the wind farms. In these cases, the turbines involved in the potential risk were switched off within three minutes after the observers contacted the local wind farm control office. On average, the turbines were out of operation for 108 minutes. By considering the number of times the turbines stopped during the last three years of the protocol (6700 times), it was estimated that 0.51% less energy was generated by the wind farms due to the stops. As discussed by the authors, vultures are large diurnal raptors, and most of accidents with these birds happen during daylight, from two hours after sunrise to two hours before sunset. Then, it is expected that the turbines can operate normally at night, minimizing the energy generation decrease by the wind farms.

Informed curtailment was also verified through BACI experimental studies in wind farms in Wyoming, Western United States [40]. Curtailment consisted of feathering the turbine blades to dramatically reduce the speed of rotation. In this case, a computer vision system consisting of a HD stereo camera and classification algorithm [26, 42] was used to identify *eagles*. The statistical analysis included the number of carcasses found before-after in the treatment site and in a reference site with similar characteristics (a wind farm with 66 turbines located 15 km from the treatment site). In the treatment site, 47 automated curtailment units were dispersed throughout 110 wind turbines, while in the reference site no curtailment was applied. The before period ranged over about four years, while the after period lasted around one and a half years for the reference site. The periods varied for the treatment site, as the installation of the automated curtailment units occurred at different stages. A reduction of 63% in the number of

Figure 4: Observation of birds by an ornithologist. Image licensed under CC0.

fatalities was observed in the treatment site after the automated curtailment has been implemented. Before the automated curtailment, human observers were responsible for ordering curtailments at the treatment site. Thus, the effectiveness of automated curtailment was in addition to an existing minimization measure [40]. An estimation of the reduction in annual energy generation due to curtailments was not presented in the study.

Informed curtailment is able to reduce the risk of collisions of soaring birds with rotor blades. However, the measure requires an efficient monitoring system to limit the number of turbine shutdowns, or curtailment, and reductions in the annual energy generation. When the curtailment is automatized, the results are further improved [40], but at the same time, the number of false positives might increase with an automated system, which also leads to unnecessary number of shutdowns. The automatic curtailment of wind turbines relies on the detection and identification of birds using camera-based systems, which is an ongoing topic of research, as previously discussed in Section 2.2.

3.2.1.1 Active control of wind turbine An alternative option to curtailment, or shutdown, is to design an active control system able to make small adjustments to the rotor speed (in real-time), so that the birds can fly through the rotor swept area without being hit by the blades. The concept proposed in [48, 49] is based on detecting the presence of birds with camera computer vision systems, and performing a probabilistic estimate of their flight path. Then, the rotational speed of the wind turbines is modified by a small amount to minimize the probability of collision without significant loss of power production. This concept, referred to SKARV[1], is illustrated in Figure 5 (on the left). Once the blades are ideally oriented with respect to the most likely flight path, there is a high probability of avoiding collision, even if the bird should conduct evasive manoeuvres. The SKARV system can be interfaced with an existing wind turbine control system, as modern wind turbines already have advanced control systems and operate with a variable and controllable rotational speed. A possible control architecture is shown in Figure 5 (on the right). The theoretical performance of the system was characterized in [49].

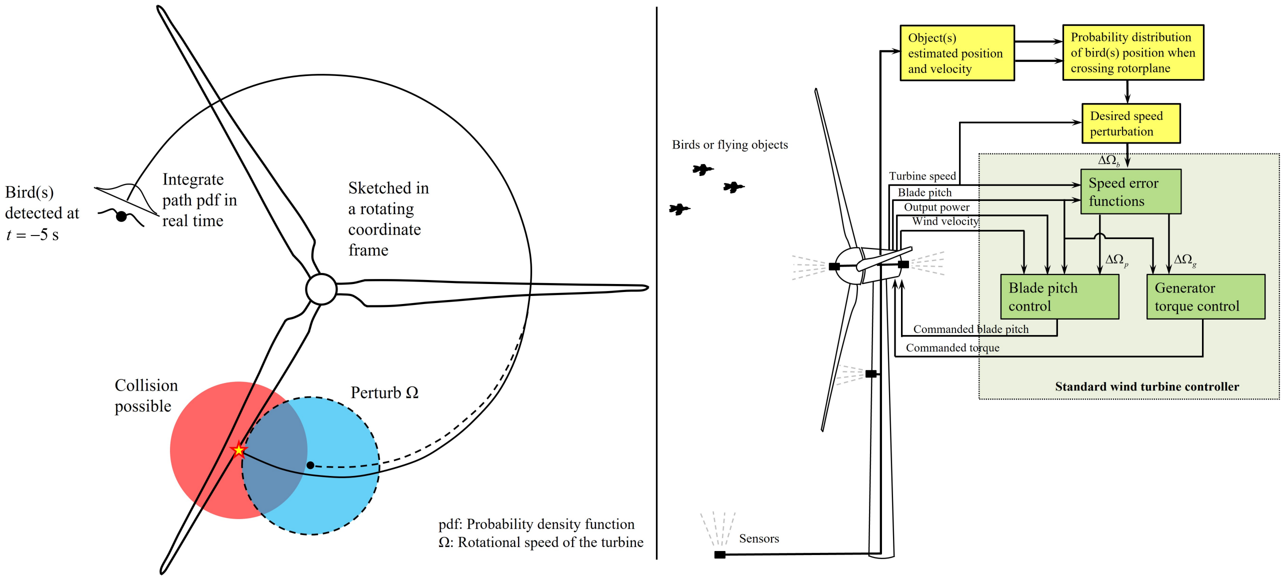

Figure 5: SKARV's concept – Illustration of how turbine speed control minimises probability for collision. The coloured areas indicate where the bird will be with high probability when crossing the rotor plane. A possible collision (red circle) is avoided by reducing the turbine speed so that the bird instead crosses the rotor plane between the blades (blue circle). Right: An example of control architecture that could interface with an existing wind turbine control system. The placement and number of sensors are only indicative [48, 49].

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[1] In Norwegian "Slippe fugleKollisjoner med Aktiv Regulering av Vindturbiner"

3.2.2 Deterrents

Some measures for minimizing the collisions are based on sensory cues, such as auditory, visual and acoustic deterrents, that are activated to scare or frighten birds and prevent them from coming closer to the wind turbines. Long-term use of auditory harassment has been proven to become ineffective with time as birds tend to habituate to the stimuli [2] (as cited in [1]), but the effectiveness can be improved by varying firing frequency and direction [6]. Preliminary tests at a wind farm in Spain indicated that *griffon vultures* can react to long range acoustic device (LRAD) sounds [50]. The efficacy of different LRAD sounds in dispersing birds depend on their distances from the device, their altitudes, as well as the number of birds in a flock [50].

In wind farms, deterrents have been commonly combined with the detection of birds in real-time by camera-based systems [18, 51–54]. A number of technical reports have evaluated commercial technologies aimed at detection and deterrence of raptors at different locations [51–54]. The most recent study [54] included species-level identification, probabilistic methods, unmanned aerial vehicles, and seven detection and deterrent systems installed on selected turbines in an operational wind farm in California, USA. The deterrence module operation was based on emitting an initial audible warning signal when a flying object was detected (bird or inanimate object), and a stronger dissuasion signal, when the object crossed a closer distance threshold, to scare the bird away from the signal noise and wind turbine. The study was performed over a nine-month period to quantify the effectiveness of the measure to reduce collision risk for *golden eagles* and other large raptors. It was estimated that the installed systems potentially reduced golden eagle collision risk by 33–53% for the studied case.

Overall, the activation of warning and deterrents signals to discourage birds to fly close to wind turbines has great potential to reduce the risk of collisions. However, this measure is also subject to a large number of false positives, as indicated by [52, 54]. In addition, warning and deterrent signals may disturb nearby residents and non-target wildlife [54], and may cause unpredictable effects on the bird's flight trajectory; thus, caution is advised when the deterrent is applied at a short distance from wind turbines [1].

4 Concluding remarks

Visual observations by humans, radar, camera-based systems or a combination of both technologies have been used for bird detection in the vicinity of wind farms. The integration of radar and camera technologies allows for automatic bird species identification when a computer vision system is included with the camera. Additionally, the integration also provides wider range of coverage, since radars are able to detect birds over a wider range than cameras. The operating frequency band of the radar is an important characteristic to be considered. Radars at low frequency bands (1-2 GHz) are less sensitive to precipitation, but not appropriate for detecting small birds, while higher frequency bands can detect not only birds but also echoes from insects and light rain. Thus, adequate distinction from the bird echoes is required. Camera-based systems have considered daylight HD cameras and thermal imaging cameras for nocturnal monitoring activities, with either monoscopic or stereoscopic solutions. Both solutions are able to detect bird movement and allow species identification through the detection software, but monoscopic cameras are more cost-effective.

A number of post-construction minimization measures has been proposed to reduce bird collisions with wind turbines. There is not a single solution suitable to all locations and species; proposed measures are species-specific and tailored to the most collision-prone species at a given location [6]. To verify the effectiveness of a measure, a suitable experimental study, such as before-after control-impact experiments, should be performed. Otherwise the results become difficult to interpret if the number of fatalities before the measure implementation is not known [38]. Overall, there is a limited number of published works that estimate the effectiveness of minimization measures in-situ. This project memo summarized the experimental results of two passive measures (habitat management and painting) and two active measures (turbine curtailment and deterrents). Such measures were performed at different wind farms worldwide, and showed great potential to reduce the risk of collisions between targeted species and wind turbines. The efficacy of the methods were calculated in terms of bird fatality reduction, but other factors such as power production reduction, disturbance to non-target wildlife and implementation costs are also considered in the development of minimization measures.

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