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Mitigation measures for preventing collision of birds with wind turbines

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Abstract. Bird collisions with wind turbines is one of the major environmental impacts of wind energy. To decrease the number of avian fatalities in wind farms, several studies have been done to understand, evaluate and apply measures that reduce the risks of collisions. Overall, mitigation measures during the operational phase of wind farms are based on either active or passive procedures, depending on the need (or not) for an external source to trigger an action for preventing a possible collision. The aim of this work is firstly to provide an overview of mitigation measures that have been demonstrated in-situ, including the overall procedures of the tests, results, as well as advantages and disadvantages of the measures. Subsequently, a new patented control concept to avoid collisions (SKARV) is described. Four measures that have been tested at wind farms in Spain, Norway, and USA are summarized: habitat management and painting (passive measures), turbine curtailment and deterrents (active measures). Estimations from these tests indicate an average reduction of 33%-86% in annual bird fatality for specific targeted species. The SKARV concept is not yet tested, but may be a benign alternative.

1. Introduction

The replacement of fossil fuel-based generation to wind power is seen as fundamental to meet the current targets for reducing greenhouse gas emissions. However, the expansion of wind farms (WFs) increases the concerns about the impacts on bird populations, which can undermine future plans for wind power generation. Habitat loss, barriers for migration and feeding areas as well as fatalities due to collisions with wind turbines are some of the widely discussed effects of wind farms on bird life [1, 2]. In this regard, many efforts have been made to understand and measure the impacts of wind energy on bird population [3–13], i.e. to measure how the reproduction, mortality, and survival of a population are affected [14]. In addition, mitigation measures to reduce the collision of birds with wind turbines has also been the focus of a number of studies [11, 13, 15].

The number of bird deaths due to collision with wind turbines varies greatly among wind farms around the world, with estimates ranging from zero to almost 40 deaths per turbine per year [11](and references therein). The birds are exposed to collisions with the static structure and the rotating blades of wind turbines. A number of factors contribute to the collisions, e.g., wind turbine design and layout of the wind farm, flight maneuverability, vision acuity and behavioural factors of bird species, as well as weather and light conditions [2, 15, 16].

To minimise the impacts, it is common to consider the mitigation hierarchy that avoids high-risk sites during the planning phase of new wind farms and applies minimization measures and compensation for unforeseen or unavoidable impacts [15, 17]. A number of post-construction minimization measures have been proposed to reduce bird collisions with wind turbines, as indicated by several reviews on the topic [11, 12, 15]. Minimization measures are particularly challenging since bird species have different sensory faculties, flight maneuverability, and behavioral aspects [15,18]. 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 [15].

Even though many measures have been proposed, only a few published works describing their effectiveness in-situ are available in the scientific literature. The first aim of this paper[1] to outline mitigation measures that have been demonstrated at wind farms, while indicating procedures of the tests and results, as well as main advantages and disadvantages of the measures. Thus, this work provides an overview of common practices, rather than presenting an exhaustive list of approaches. The measures described here are categorized into passive, when not requiring external information from an human observer or sensor technology to reduce the collision risks, and active, when requiring actual information to trigger an action for collision avoidance. In addition to tests performed in-situ, post-construction measures to reduce bird mortality related to wind power generation have also been tested outside wind farms, see, e.g. [20, 21]. Furthermore, new measures are under development. The second aim of this work is to describe the new patented control concept SKARV[2], an example of active measure.

2. Passive measures

Passive measures aim to reduce the risks of bird collisions with wind turbines without the need for a monitoring surveillance system or an human observer triggering an active response to prevent the collision. The measures may consist of alterations to habitat, and design or visual modifications of wind turbines, such as painting or lighting.

2.1. Habitat management

Habitat management measures consist of on-site or off-site habitat alterations to reduce the risk of bird collision with wind turbines. The aim of on-site alterations is to decrease the bird activity within the wind farm. This 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 [15]. In contrast, off-site alterations aim to promote bird activity in areas outside the wind farm. The measures include the creation of new areas for foraging habitat and breeding sites away from the wind farm [11, 15].

The effect of modifying the vegetation around wind turbines to make the area less attractive to lesser kestrel (Falco naumanni) was verified in [22] for three wind farms in Spain. The procedure consisted of superficially tilling the soil (3-8 cm deep) at 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 [22], 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 surrounding of 41 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, ten and two years of data. For the three wind farms, the results indicated reductions of 75%, 82.8% and 100% in the annual collision rates, representing a total average reduction of 86% after the mitigation measure was applied. This 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 [22].

[1] This paper is partly based on [19].

[2] SKARV is the Norwegian name for the Great Cormorant and acronym for (in Norwegian) "Slippe fugleKollisjoner med Aktiv Regulering av Vindturbiner".

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

2.2. 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 [21]. 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 [21].

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 [23, 24]. The measures were intended for different bird species: the former targeted species that fly at the blade height, such as soaring raptors and birds with aerial display, while the latter targeted species with poorly developed vision and flight maneuverability, and species typically flying relatively low heights, such as galliformes [24]. 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. 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.

Figure 2. Wind turbine with rotor blade painted in black at the Smøla wind power plant, Norway. Image by May et al. 2020 [23] licensed under `CC BY 4.0`.

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 [23]. For the in-situ experiments with the blades, a reduction of around 70%

in annual collision rates 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 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 [24]. In this case, a reduction of around 48% in annual collision rates was observed for willow ptarmigans (Lagopus lagopus).

Based on the results obtained in [23], wind farms in Spain [25] and the Netherlands [26] have recently painted one blade in black for a number of turbines to test the 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 [25].

3. Active measures

Active measures rely on the detection of birds prior performing an action to avoid a possible collision. Visual observations by humans, radar, camera-based systems or a combination of technologies have been proposed for detecting birds in the vicinity of wind farms [27–31].

3.1. Turbine curtailment

Curtailment and temporary shutdown of wind turbines are minimization measures for birds flying at the rotor swept 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 [11]. 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 [11]. In addition, this approach tends to be effective for some soaring raptors, but not for many other bird species [32]. In contrast, informed curtailment considers human observers, radar and/or camera-based systems to determine the shutdown or curtailment time of specific turbines [33–42].

The effectiveness of selective shutdown of wind turbines was applied in wind farms in the southern of Spain, Cadiz area [33,35]. In total, 269 turbines were selectively stopped during the procedure. A selective stopping protocol became mandatory in 2008 due to the high collision rates of griffon vultures (Gyps fulvus) 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 [33]. 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% [35].

In order to estimate the mortality rate, the analysis in [35] 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 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 [34]. Curtailment consisted of feathering the turbine blades to dramatically reduce the speed of rotation. In this case, a computer vision system consisting of a high-defintion stereo camera and classification algorithm [36,42] 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 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 [34]. An estimation of the reduction in annual energy generation due to curtailments was not presented in the study.

3.2. Deterrents

Some measures for minimizing the collisions are based on sensory cues, such as auditory, visual and acoustic deterrents, 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 [43] (as cited in [11]), but the effectiveness can be improved by varying firing frequency and direction [15]. Preliminary tests at a wind farm in Spain indicated that griffon vultures can react to long range acoustic device (LRAD) sounds [44]. The efficacy of different LRAD sounds in dispersing birds depend on their distance from the device, their altitudes, as well as the number of birds in a flock [44].

Deterrents in wind farms have been commonly combined with real-time detection of birds by camera-based systems [45–49]. A number of technical reports have evaluated commercial technologies aimed at detection and deterrence of raptors at different locations [45–48]. The most recent study [48] 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 periods to quantify the effectiveness of the measure in reducing collision risk for golden eagles (Aquila chrysaetos) and other large raptors. It was estimated that the installed systems potentially reduced golden eagle collision risk by 33–53% for the studied case.

Another study in Canada used a predator owl model deterrent paired with an audio recording of predator and alarm calls to deter birds from a wind farm in Nova Scotia [50]. However, the results were inconclusive.

3.3. Turbine speed control

A new active concept, nicknamed SKARV, to avoid collision between birds and wind turbines is described in the patent [51]. The concept consists of making small adjustments to the rotor

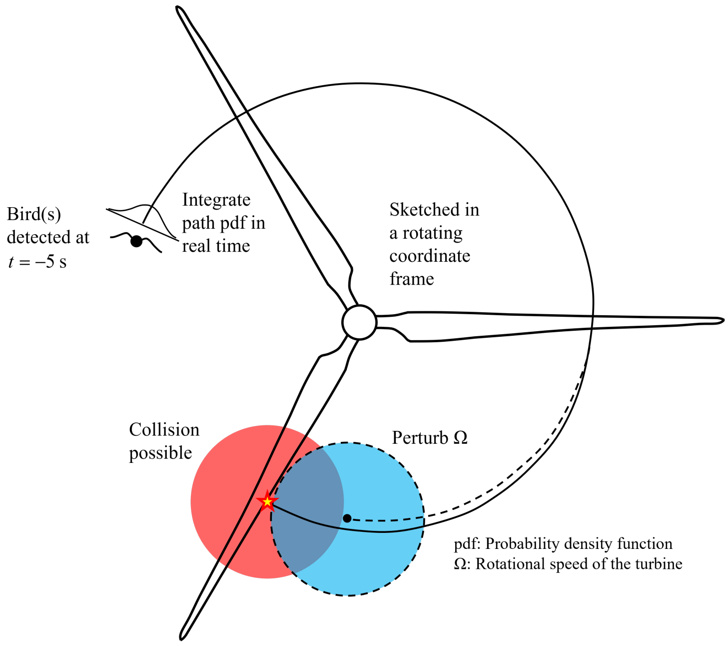

Figure 3. SKARV's concept - Illustration of how turbine speed control minimises probability for collision. The coloured areas indicate where the bird will be with high probability when crossing the rotor plane. A possible collision (red circle) is avoided by reducing the turbine speed so that the bird instead crosses the rotor plane between the blades (blue circle).

speed so that birds can fly through the rotor swept area without being hit by the blades. This requires a system to detect and track birds in proximity to a wind turbine. The detection and tracking can be based on radar, LIDAR or camera; for example, the Spoor system [52] applies off-the-shelf cameras in combination with artificial intelligence algorithms to detect, classify, and trace the presence of birds around wind turbines. Based on the observations, possibly coupled with machine learning, a continuous estimate of the flight path of the bird can be made. If the flight path is estimated to be towards the turbine rotor plane, the control system will slightly adjust the rotational speed of the turbine to minimize risk of collision between the bird and rotor blades, as illustrated in Figure 3.

The SKARV concept can be applied to modern variable speed wind turbines. In such a case, the concept would be implemented in a software that estimates in real-time the bird's probabilistic flight path and the desired rotor speed adjustment to minimize risk of collision. This requires the use of a bird-tracking system that follows the bird path. The rotor speed adjustment would be an input signal to the built-in standard wind turbine control system that governs the rotational speed of the turbine through blade-pitching and generator torque-adjustment. The speed adjustment would be only a small perturbation to the actual rotor speed, either an increase or decrease. Notice this is rather different from curtailment, where the speed of the wind turbine is significantly reduced.

In SKARV, the adjustment of the rotational speed of the turbine to avoid a possible bird collision should not lead to any noticeable loss of generation, as only small adjustments to the rotor speed should be made. However, in case the flight path cannot be estimated with any reasonable certainty, for example in the case of birds with highly irregular flight paths, turbine shutdown can be an option. The same would be the case if a flock of birds would be approaching.

Table 1. Summary of mitigation measures demonstrated in wind farms.

Measure	On-site habitat alteration	Painting (one blade)	Painting (tower)	Turbine shutdown	Sound activation
Type	Passive	Passive	Passive	Active	Active
Targeted species	lesser kestrel	raptors	galliformes/ willow ptarmigans	soaring birds/ griffon vultures eagles	raptors/ golden eagles
WF location	Cuenca (ES)	Smøla (NO)	Smøla (NO)	Cadiz (ES) Wyoming (US)	California (US)
Analysis of results consider	Before-after deaths	Before-after deaths	Before-after deaths	Before-after deaths	Measured bird activity
Duration of the measure	2 years	3.5 years	3.5 years	13 years 1.5 years	9 months
Reported effectiveness	86%	70%	48%	65%	33-53%
Shortcomings	Birds are displaced. Impacts in other wildlife.	Less effective in low light. Visual impact.	Less effective in low light. Visual impact.	Loss in power production and revenue.	Impacts in other wildlife. Disturbance to nearby residents.

4. Discussion

Table 1 summarizes the demonstrated mitigation measures described in this paper. The on-site habitat alteration has the highest reported effectiveness, but resulting in displacement of birds and negatively impacting the environment. The painting of a turbine blade is reported to be the second most effective measure, while turbine shutdown is reported to be third most effective measure. All the mitigation measures have some shortcomings that need to be balanced against their effectiveness in reducing bird mortality.

As discussed in [15], the efficacy of on-site habitat alterations relies on the importance of the habitat for a certain species. If the area is not dramatically modified, it may still be revisited. In any case, habitat alterations might affect other wildlife that was not previously affected by the wind farms. Additionally, 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 [15].

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 [23]. 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 downwards when flying [11]. In either way, the birds might not see the wind turbine ahead.

Informed curtailment is also effective in reducing 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 to limit the loss in annual energy generation. When the curtailment is automatized, the results are further improved [34], 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.

Overall, the activation of warning and deterrents signals to discourage birds to fly close to wind turbines also 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 [46, 48]. In addition, warning and deterrent signals may disturb nearby residents and non-targeted wildlife [48], 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 [11].

The new control concept SKARV is a promising solution to reduce the risk of collisions between birds and wind turbine blades without disturbing other wildlife and causing any measurable loss of production. However, its effectiveness is still not demonstrated, and there are a number of challenges that must be addressed prior full development of the technology, for example:

- Targeting bird species and different flight patterns: Ideally, functional mitigation measures should be tailored to as many bird species as possible. However, this is a challenging problem as birds present different behavior and morphology [15]. Thus, it is important to understand which/how many species can benefit from a collision avoidance control scheme, and to verify how the control should adapt to different flight patterns.
- Detecting and tracking birds approaching the rotor: To implement an active avoidance strategy, approaching birds must be detected and their path tracked. This must be done with equipment that comes at a reasonable cost on a per-turbine basis. Bird detection and tracking systems are available, e.g. the system of Spoor uses off-the-shelf cameras [52], but it is still an open question whether these systems provide sufficient accuracy and reliability for the approach and if modifications will be required for the integration.
- Preventing bird strikes: The idea relies on the ability to predict the birds' flight paths far enough ahead of time, so that a small correction to the rotational speed provides an effective reduction in the probability of collision. A practical control algorithm that implements the collision-avoidance strategy must be developed. The main challenge is to develop a real-time algorithm that provides a sufficiently accurate and reliable estimate of the flight path a few seconds ahead of a potential collision. The turbine speed control would then ensure that the blades will be as far away as possible from the bird when passing the rotor area.
- Keeping dynamic loads on structures low: The dynamic response of the turbine places constraints on the type of control actions that are feasible. Abrupt acceleration and deceleration of the rotor implies large fluctuating forces in the pitch actuators and turbine structures. Thus, the earlier that the control action is initiated, the more benign will be the consequences for fatigue of turbine components. Preliminary analysis using a 10 MW turbine model indicates that a 10 second lead-time would give no significant consequence on fatigue, while 5 seconds may be the shortest lead-time that can be accepted.

It will not be trivial to accomplish both control objectives of collision avoidance and keeping dynamic loads low. Where the best trade-off lies must be established through the development of the control system. In addition, it is acknowledged that certain species (especially small birds) fly in patterns that cannot be predicted a few seconds in advance. In this case, to prevent collisions, the turbine might need to be shut down as soon as the bird is detected. The active control aspect of SKARV is most likely applicable for species which fly in regular patterns.

5. Conclusion

A number of post-construction minimization measures have been proposed to reduce bird collisions with wind turbines. There is not a single solution suitable to all locations and species; the proposed measures are species-specific and tailored to the most collision-prone species at a given location [15]. 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 implementation of the measure is not known [32]. Alternatively, the current bird activity within the wind farm should be included in the analysis, as done in [48].

Overall, there is a limited number of scientific works that estimate the effectiveness of minimization measures in-situ, i.e. within the wind farm. This paper 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 loss in power production, disturbance to non-targeted wildlife and implementation costs are also considered in the development of mitigation measures.

The SKARV concept is an innovative control system to reduce the risk of collisions between birds and wind turbine blades, without disturbances to other wildlife and significant loss in power production. The hypothesis is that the concept can be effective for birds with relative regular flight patterns, whereas turbine shutdown can be applied as a back-up in the case of bats or birds with highly irregular flight paths. The SKARV concept has, however, not been demonstrated yet, and a number of challenges must be addressed before any conclusions can be drawn upon its effectiveness.

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