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Remote techniques for counting and estimating the number of bird–wind turbine collisions at sea: a review

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Since the early 1990s, marine wind farms have become a reality, with at least 13 000 offshore wind turbines currently proposed in European waters. There are public concerns that these man-made structures will have a significant negative impact on the many bird populations migrating and wintering at sea. We assess the degree of usefulness and the limitations of different remote technologies for studying bird behaviour in relation to bird–turbine collisions at offshore wind farms. Radar is one of the more powerful tools available to describe the movement of birds in three-dimensional space. Although radar cannot measure bird–turbine collisions directly, it offers the opportunity to quantify input data for collision models. Thermal Animal Detection System (TADS) is an infra red-based technology developed as a means of gathering highly specific information about actual collision rates, and also for parameterizing predictive collision models. TADS can provide information on avoidance behaviour of birds in close proximity to turbine rotor-blades, flock size and flight altitude. This review also assesses the potential of other (some as yet undeveloped) techniques for collecting information on bird flight and behaviour, both pre- and post-construction of the offshore wind farms. These include the use of ordinary video surveillance equipment, microphone systems, laser range finder, ceilometers and pressure sensors.

BIRDS AND OFFSHORE WIND FARMS

Migratory bird species enjoy a high public profile and are protected by international and national legislation designed to protect shared natural resources. Hence, migrant birds figure prominently in the environmental impact assessment (EIA) process associated with most wind farm development projects. The coastal and offshore waters of Europe are of global importance for several species of resident and migratory birds. The hazards posed to birds by the construction of offshore wind farms can be summarized under three broad headings:

(1) Displacement and flight avoidance responses (birds are displaced from an ideal feeding distribution by the presence of turbines, or avoid flying near to them on migration);

(2) Habitat loss/modification (physical habitat loss under foundations, or the creation of novel feeding and resting opportunities that actively attract birds to the turbines); and

(3) Collision risk (the probabilities of individuals of different species being struck by turbines).

Of these, collision risk will have the most direct impact at the population level, because it elevates the normal mortality rate of species (Johnson *et al.* 2002). This review will mainly focus on the risk of collisions. However, this does not imply that the other effects are trivial, especially when the cumulative effects of, for example, habitat loss are considered in the light of the construction of many offshore wind farms along the length of a migratory bird species' corridor (Fox *et al.* 2006).

DEFINING THE ROLE OF REMOTE TECHNOLOGIES

To support an adequate assessment of the risk presented by each hazard, and subsequently to monitor the actual effects or impacts of each hazard, EIAs need to predict the effect of each hazard and measure the potential effects each may have at the individual site

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level. These assessments are extremely time consuming or near impossible to achieve through direct human observation and increasingly, rely upon remote techniques to observe bird behaviour in a way which can provide robust objective data for modelling. For example, it is difficult for a human observer to physically watch and map the trajectories of migrating birds as they cross an area of open sea prior to the construction of a wind farm and make comparisons with post-construction observations in assessing the barrier effect (birds changing their flight path due to an obstacle) of the development. Such work requires the use of remote techniques, such as radar (Lack & Varley 1945, Eastwood 1967, Cooper 1996, Bruderer 1997a, Bruderer 1997b, Gauthreaux & Belser 2003), to accurately plot migration trajectories prior to and post-construction. Furthermore, counting the number of avian collisions directly or through carcass collection, as has been conducted at land-based wind turbines, will be constrained to a very high degree by the often harsh conditions in remote offshore areas. Such studies again require the use of remote video techniques, e.g. the Thermal Animal Detection System (www.praetek.dk; Desholm 2003b, Desholm 2005) which is an infra red-based technology developed as a means of gathering highly specific information about actual collision rates, but also for parameterization of input data for collision models.

The remote techniques need to be able to record multiple observations in order to assign probabilities under a range of parameters relating to prevailing environmental conditions and the birds involved. These remote techniques require a platform for mounting and preferably a stable platform. The most appropriate areas suitable for the application of remote technologies to collect data for the EIA process associated with offshore wind farms would seem to be the following:

(1) to provide a broad pre-construction phase description of the movements of birds within a study area, for the purposes of: (a) collision risk assessment and (b) as a base line for post-construction comparisons of flight pattern;

(2) to quantify probability models estimating the number of colliding birds; and

(3) to provide validation of (2) by measuring actual collision rates of birds hitting the turbine superstructure, or being killed in the vortices encountered in the wake of the turbines.

Researchers are already applying these remote techniques to the gathering of data to support pre- and post-construction studies of offshore wind farms in Denmark (Kahlert *et al*. 2000, 2002, 2004, Desholm *et al*. 2003, Christensen *et al*. 2004), the Netherlands (Sjörd Dirksen *pers. comm.*), Germany (Dierschke 2004, Hötker *et al*. 2004), and Sweden (Pettersson 2005). This experience, although limited, offers promise of comparable utility in other European waters. This review paper will assess the degree of usefulness and the limitations of different existing remote technologies for studying bird behaviour in relation to wind farms and provide recommendations for further methodological development to increase utility.

RADAR SYSTEMS

Hardware

The various commercially available types of radar can be classified in different ways. Firstly, the radar operating frequency can be subdivided into frequency bands, with the most frequently used radars in ornithological studies being the X-band (3 cm; 8–12.5GHz), S-band (10 cm; 2–4GHz) and L-band (23 cm; 1–2GHz). Second, the peak power output differs with regard to the strength of the radar signal (most commonly ranging between 10 kW and 200 kW), which determines the operational range for a given target size. Finally, classification based on mode of operation, most commonly grouped as (a) surveillance radar (b) doppler radar, and (c) tracking radar.

Surveillance radar systems

Surveillance radars are most often used for surveillance of ships (know as ship radar or marine radar); aircraft (airport surveillance radar); or precipitation (meteorological radar or weather surveillance radar [WSR]). These are characterized by a scanning antenna often shaped as a 'T-bar' or as a parabolic disc (conical or pencil beam). Surveillance radars can be used to map the trajectories of moving targets and the echo trail feature makes each echo visible for a given amount of time. Low-powered surveillance radars can detect individual birds (size of ducks) within a range of a few kilometres and flocks of birds up to 10 kilometres. These antennas can be mounted on a tripod, observation tower, or vehicle. High-powered surveillance radars can detect birds within a range of 100–240 km (Gauthreaux & Belser 2003) and are applied as stationary air route surveillance radars, airport surveillance radars, WSRs (Koistinen

2000) or military surveillance radars. Some of the high-power L-band radars are equipped with a Moving Target Indicator (MTI) that prevents stationary or slow moving echoes from being displayed on the monitor (in radar terms, Plan Position Indicator, or PPI).

Surveillance radars can also be configured to use a fixed beam collecting data along a predefined line of interest. Often these systems are modified marine surveillance radars where the 'T-bar' antenna has been substituted with a fixed parabolic disc. Whilst increasing detection range and providing data on flight altitude, the disadvantage of narrowing beam widths is that spatial coverage is reduced and, hence, the ability to obtain data over a wide area is reduced.

Doppler radar systems

These systems are used in a variety of applications from large scale WSRs to small portable low-powered traffic speed control doppler radars (Evans & Drickamer 1994). The identifying characteristic of these systems is their ability to detect small differences in target position between consecutive pulses of radiation, and generate information on the velocity of the target.

The new-generation weather doppler-radar (WSR-88D) used for weather forecasting throughout the US (159 individual radars) produce pictures showing the base-reflectivity (density of targets), base-velocity (radial velocity), and vertical wind profile (movement of small particles). The WSR-88D operate in the S-band with a peak power output of 750 kW and a scanning pencil beam from a large parabolic disc (diameter of *c*. 9 m), detecting birds at distances of up to 200 kilometres (Diehl *et al*. 2003).

Tracking radar systems

Tracking systems are made mainly for military applications and can only track a single target at a time (Fortin *et al*. 1999). They often have a high peak power output and are of relatively large size. The radar beam is of the narrow pencil type and operates often in the X-band. Most often the air space has to be scanned manually by the operator before locking the radar on to the target, however pre-programmed automatic scanning for targets can also be applied, after which the radar locks onto the target and follows it. The returned signal can be used to describe the three-dimensional movements of the target and provide data on ground speed, heading and modulations of reflectivity. Tracking radars are capable of analysing wing beat signatures (Renevey 1981). It requires the radar to dwell at a single bird for at least the period of a series of wing beats. However, if a flock of birds is illuminated with an incoherent radar, the amplitude fluctuation of the individual birds will destroy the echo signature for potential wing beat frequency analysis. A coherent tracking radar can measure the doppler spectra of individual birds and, in principle, can still provide useful wing beat information for a flock of birds. This is a new measurement technique for bird signature analysis which, as far as the authors are aware, has not yet been practically implemented. As with surveillance radars, the tracking radar can also be operated in a fixed beam mode where data are collected at predefined lines of interest.

RADAR STUDIES IN WIND FARMS

So far only X-band and S-band surveillance radars have been used in ornithological research in relation to wind power production facilities. Surveillance radars are designed for scanning 360° of azimuth to monitor spatially moving targets. However, in order to collect data on flight altitude, systems have been modified to incorporate vertical scanning modes or substituted the scanning 'T-bar' antenna with a fixed parabolic disc.

In Denmark, four bird studies have been conducted using marine surveillance radars. Pedersen & Poulsen (1991) used a 10 kW (Furuno FR-1500; www.furuno.com) surveillance radar with a scanning 'T-bar' antenna to study bird migration routes around an inland wind turbine. They showed that the birds changed direction by 1–30 degrees when passing the turbine, irrespective of whether the turbine was operational or not.

Tulp *et al*. (1999) used a 10 kW X-band ship radar (Furuno FR2125) to study the avoidance behaviour of wintering Common Eiders *Somateria mollissima* to an offshore wind farm comprising 10 turbines. In this study, a marked effect was noticed up to a distance of 1500 meters, with reduced flight activity in the vicinity of the wind farm.

At the Nysted offshore wind farm (Kahlert *et al*. 2000, 2002, 2004, Desholm *et al*. 2003) a before-and-after study is currently in operation, using a 25 kW Furuno FR2125 ship radar. This radar study concerns migrating birds, especially waterbirds. Owing to the relatively long distance between the radar observation tower and the wind farm area, it was difficult to map migration trajectories of landbirds, although larger bodied water birds were easier

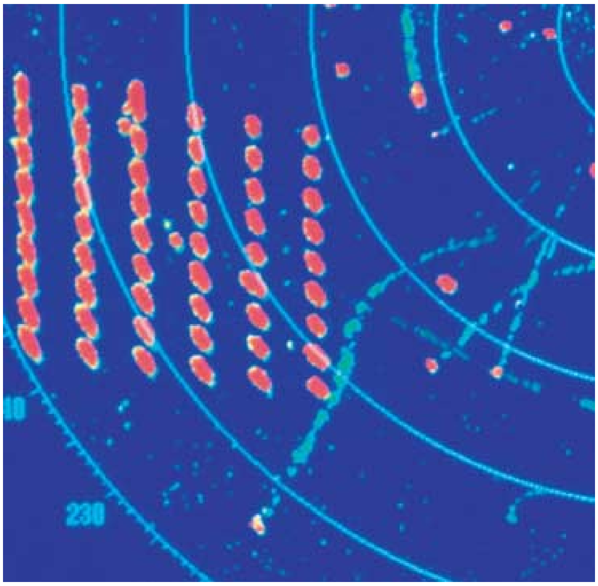

Figure 1. Photo showing the echoes of migrating waterbirds (red echoes with green tails) in the vicinity of the wind turbines (red echoes without tails) at the Nysted offshore wind farm, Denmark.

to track. Profound avoidance behaviour was recorded in a large proportion of the waterbirds in the vicinity of the wind farm (Fig. 1). Those entering the wind farm showed a high tendency to fly in the corridors between individual turbines (Desholm & Kahlert 2005).

At the Danish Horns Reef offshore wind farm in the North Sea, the same radar as that at the Nysted study has been used (Christensen *et al*. 2004), supplemented by a Furuno 10 kW ship radar. The difference in peak power output resulted in a marked difference in performance: the 25 kW radar detected flocks of birds much more easily and at longer range than the smaller 10 kW radar. In this study, avoidance behaviour by wintering and moulting Common Scoters *Melanitta nigra* and by migrating waterbirds was observed.

In the Netherlands, Winkelman (1989) used radar to monitor the nocturnal migration volume at a small land-based wind farm. Recently, a radar study in the Dutch part of the North Sea has been initiated (Sjoerd Dirksen *pers. comm.*). In 2003, Bureau Waardenburg contracted DeTect Inc. (Florida, USA) to install a custom-engineered environmental radar system 'Merlin' on Meetpost Noordwijk: a government owned research platform, situated 10 km off the Netherlands shoreline. The project is set up as a baseline study for the impact assessment for the Dutch Near Shore Wind farm (NSW). The NSW project is a 36 turbine wind farm to be erected 12–18 km off the Dutch coast at Egmond. 'Merlin' consists of a vertically operated X-band and a horizontally operated S-band radar, connected to computers running algorithms on the raw radar data. The system allows for automatic registration of signals of flying birds into a database. Simultaneous measurements by radar and by field observers provide a detailed picture of species and flight patterns. Results of the fieldwork are expected to be published in summer 2005.

In the US, a similar type of system called the Mobile Avian Radar System (MARS) has been used in the environmental impact assessment of the proposed Cape Cod wind farm in the Nantucket Sound (Geo-Marine Inc. 2004). The report of the work specifically mentioned that the X-band radar was particularly sensitive to rain which can provide signals that appear similar to bird echoes, making automatic detection of birds in rain unreliable.

Tracking radars have not so far been used in a wind farm context. To some extent, this can be explained by the way this system locks onto targets. Locking a tracking radar onto a migrating bird/flock approaching a wind farm would provide a good trace of the movement, until such time as the bird(s) passed in front of a moving turbine. The radar would then lock onto the first turbine passed by the bird, since the rotating blades reflect a much stronger pulse of energy than small flying birds. Thus, the risk of adopting such an approach is that only the approach part of the flight trajectory would be mapped, leaving the researcher with no information on the flight pattern of birds in the immediate vicinity of the wind farm – the main objective of the study.

Design of radar studies

The radar needs to be sited in such a way that the observer can view the approach of birds towards the wind farm (which may differ between seasons) to see the volume and direction of movements.

Platform deployment methods

Marine surveillance radars can be used to collect data on both the spatial and vertical distribution of migrating birds if the equipment can be mounted in both vertical and horizontal operating modes. This has to be considered when designing the study, involving either a flexible switching mounting device or preferably two independent radars.

Placing the radar on land will inevitably necessitate the use of long operational ranges if the bird trajectories within true offshore wind farms are to be studied. The advantages of working onshore are: stability; ease of deployment; readily available power supply; use of mobile laboratory; low cost; rapid repair and maintenance; and flexibility to choose height to minimize radar clutter.

Using a ship or fishing vessel as a radar platform will have the one major advantage of the very flexible positional possibility. However, the instability of any but a large (> 40 m) ship at sea will often make radar observations using horizontally mounted surveillance radar of birds more or less impossible due to sea clutter. The use of jack-up barges or oil-rigs as stable radar platforms will always be limited by their availability or high costs of hire. The normal procedure associated with the construction of an offshore wind farm is the erection of a meteorological mast several years in advance of the turbines. These masts will almost certainly have limited space for the radar and a human operator but often will be located conveniently close to the site of the future wind farm. One possibility would be to mount the antenna on the mast and the PPI, power generator and operator on a ship at anchor. Perhaps more preferable would be an adequate platform on the mast for both the radar and its operators.

Data handling

Bird flight trajectories (in all three dimensions) can be stored in a geographical information system (GIS) platform (Fig. 2) which makes further analysis very efficient (Desholm 2003a, Christensen *et al*. 2004, Kahlert *et al*. 2004).

Observed flight speed can be used to group the echoes into different groups of birds (Bruderer & Boldt 2001, Larkin & Thompson 1980, Larkin 1991), since small birds tend to fly slower than larger birds. Radars produce estimates of ground speed which need to be converted to air speed. By accounting for the tail wind component, air speed can be calculated from ground speed, and thus, be used to discriminate between different groups of bird species (e.g. water birds and passerines). Species recognition based on either simultaneous visual observations or on recorded air speed has to be noted in the GIS database of flight trajectories. To our knowledge, the two present studies from Denmark (Kahlert *et al*. 2000, 2002, 2004, Desholm *et al*. 2003, Christensen *et al*. 2004) and the study by Tulp *et al*. (1999) have been the only ones to fully integrate visual observations, radar and GIS to analyse data on avian migrants at offshore wind farms.

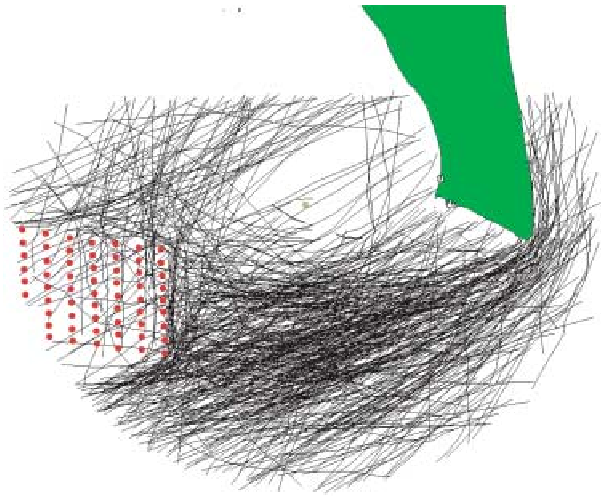

Figure 2. Radar registrations from the Nysted offshore wind farm applied on a GIS-platform. Red dots indicate individual wind turbines, green area the land, green dot the siting of the radar, and black lines migrating waterbird flocks determined visually at the Nysted offshore wind farm. Adopted from Kahlert *et al.* 2004.

Environmental factors are known to modify migration patterns at a given site (Zehnder *et al*. 2001, Alerstam 1990, Baranes *et al*. 2003). In a 'before and after study' these effects needs to be taken into account as covariables, so the possible effects of weather can be excluded as explanatory variables for any sudden change in migration pattern after the erection of a wind farm. Furthermore, if the influence of weather is known to be significant, a range of probability models, describing the probability of entering the wind farm for a given bird flock, should be produced in order to account for the changing risk of collision due to natural variability.

INFRA RED CAMERA SYSTEMS

Early generation hardware

Image intensifier devices (e.g. first, second and third generation night scopes and night vision goggles) are dependent on detecting and amplifying small amounts of ambient light present.

The earlier generations of true infra red cameras were dependent upon an external infra red source to light up a scene (active detectors) and illuminate the object of interest. In a wind farm context, Winkelman (1992) used two such infra red cameras to measure bird migration intensity between wind turbines.

A collision detection system is at present being developed based on microphones for impact detection and active infra red camera for species identification (Verhoef *et al.* 2004).

New generation hardware

The new generation equipment is generally categorized as forward-looking infra red thermal imagers (FLIR). These are true thermal imaging devices (passive detectors) that create pictures based on the heat energy (infra red spectrum of wavelengths between 2 and 15 μm) emitted by objects within the viewed scene rather than from small amounts of reflected light. As the heat radiation passes through the atmosphere, it is subject to a degree of attenuation due to particulate matter, water vapour and the mixture of gases in the air.

The radiation finally reaches the detector within the thermal camera via a lens, typically made of germanium (as IR-radiation is fully absorbed by conventional glass). The camera lens focuses the heat radiation onto elements called infra red detectors that transform the received radiation into an electrical signal. This is then amplified and transmitted to an array of light-emitting diodes that create a visible image, i.e. the thermal image (Hill & Clayton 1985). The long wave cameras (8–13 μm) are less susceptible to absorption by the atmosphere than the short wave (2–5 μm) applications (Desholm 2003b). The ability of a thermal imager to detect a given object is constrained by the optical resolution and the focal length of the lens used (Boonstra *et al.* 1995). Critical to object definition is the thermal resolution, which is defined as the minimum thermal differential between two objects (in this case, the heat signature of the body of a flying bird compared to its background environment).

Thermal imagers have been used extensively in industry (e.g. to detect electrical defective circuit boards and other electrical problems), and in physiological studies using thermography to detect heat differentials in the body (Klir & Heath 1992).

Thermal imagers offer several ways to identify observed birds to species or group level. Although plumage colouration is not distinguishable on a thermal image (birds appear white against a dark background; Fig. 3), body shape, wing beat frequency, flock formation, 'jizz' (often indefinable combinations of species characteristics) and flight pattern can all contribute to species identification by experienced observers. In the study by Desholm (2003b), the thermal imager was calibrated in order to relate a given body length – measured as the number of pixels at the monitor – to a real life body length at a given distance.

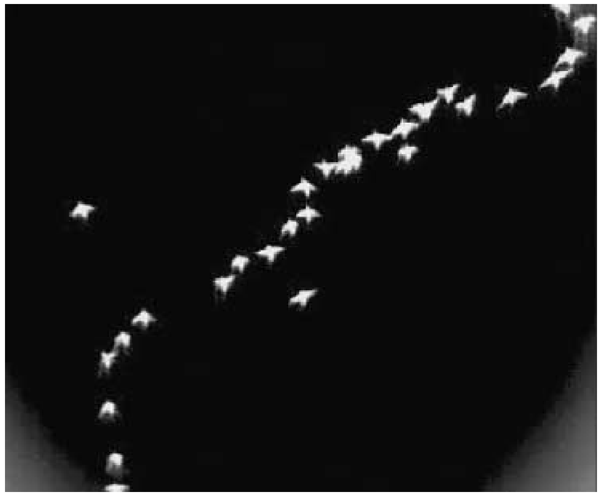

Figure 3. Thermal image recorded by TADS and showing a flock of Common Eiders passing the field of view at a distance of *c.* 70 meters.

In southern Sweden, the passerine migration pattern was studied using thermal imaging equipment with a relatively large telephoto lens of 1.45° (Zehnder & Karlsson 2001, Zehnder *et al.* 2001). A 'video peak store' was applied which superimposed several hours of recordings, so that birds passing the field of view appeared as individual lines of dots. This equipment could detect small passerine birds at a distance of up to 3 km. The same thermal imaging device has been used in conjunction with radar to calibrate the moon watching method (see below; Liechti *et al.* 1995).

Infra red studies in relation to wind farms

In a wind farm context, only two studies have been published so far using thermal imagers. The first study was conducted in Holland (Winkelman 1992) where a thermal camera was used to detect avian collisions at a land-based wind farm. The second study is still ongoing in Denmark and involves the development and use of Thermal Animal Detection System (TADS) for collision monitoring and collision model parameterization at an offshore wind farm (Desholm 2005a, 2005b). In the Dutch study by Winkelman (1992) in the 1980s, one thermal camera was used for detecting collisions between land-based turbines and migrating birds. A bird the size of a duck could be detected out to a distance of 50–250 m, 600 m, and 3 km for 15°, 5° and 3°

Figure 4. Photo showing the TADS mounted in the vertical mode on one of the wind turbines at the Nysted offshore wind farm, Denmark.

lens, respectively. In total, 65 birds were observed trying to cross the area swept by the rotor-blades of which 15 collided. Collisions did not always result in death and, in four cases, birds recovered after colliding and continued their flight. In six of the 14 nocturnal accidents, the birds were swept down by the wake behind the rotor and not by the rotor-blades themselves.

During the last 3 years, the TADS has been developed in Denmark for automatic detection of avian collisions at offshore wind farms (Desholm 2003b, 2005). The TADS could cover *c.* 30% of the area swept by the 42 m long turbine blades and detect individual waterbirds and passerines at distances of up to *c.* 150 m and 30 m, respectively. Thermal sensor software triggers the downloading of video sequences onto the hard disk, only when at least one pixel in the field of view exceeds an operator-defined threshold temperature level. This ensured a minimum number of recording events, so that mostly sequences of birds passing the field of view were recorded, avoiding arduous viewing of many hours of empty video sequences.

TADS has been used at the Nysted offshore wind farm in Denmark for measuring the number of collisions between waterbirds and wind turbines (Fig. 4). The collision monitoring programme has so far been running for one spring (Desholm 2005a) and one autumn (Desholm 2005b) migration period. To date, no collisions have been registered, which reflects the general avoidance behaviour of waterbirds towards the wind farm as a whole, and to the individual turbines as shown by radar studies of flight trajectories (Desholm & Kahlert 2005). Both TADS and radar data from that study support this conclusion, as does the study by Hansen (1954). It must be stressed here that only one thermal camera has been applied in this relatively short study of only 3 months and that collisions could have occurred at some of the other 71 turbines within the wind farm.

Design of thermal monitoring studies

When designing a thermal imaging monitoring programme, it is advisable to bench- and field test the equipment well in advance of initiating the study. Getting to know the effects of changing camera settings on the image appearing on the monitor is crucial, especially with regard to achieving sufficient contrast between bird and background (e.g. water surface or the clear background of a full clouded sky). Secondly, the trade-off between focal length (i.e. strength of the telephoto lens) and area of the field of view at a given distance should be taken into account when deciding the distance between thermal detector and monitoring area, and lens size. The consequence of a reduced monitored area (when using telephoto lenses), will be a reduced amount of accumulated data, if the number of monitoring devices or time spent on monitoring is not increased accordingly.

Collision monitoring

When dealing with the direct measurement of bird collisions, a monitoring programme must be the subject of careful design. The aim of such a programme will be to compile enough information to form the basis for a sound statistical analysis. Thus, the appropriate temporal scope and hardware volume of such investigations will be dependent on the actual number of collisions and on the spatial and temporal distribution of these at the wind farm. If several collisions occur daily at all the turbines, a single camera would be sufficient for a data collection protocol. However, if the annual collision rate amounts to 1–5 birds per annum within a 80 turbine wind farm, many more devices will be needed in order to provide reasonable precision on collision risk estimates. This means that low collision risk necessitates a large-scale monitoring programme (both in terms of number of devices and monitoring time).

The process of running a collision-monitoring scheme consists of operating the camera system over a given period. The degree to which the system is capable of running automatically will, to a high degree, determine the investment of man-hours needed. In the absence of automation, the operator will need to operate the camera and subsequently visually process all the recordings. Processing recordings can be made more efficient in two ways. Firstly, by fast-forward viewing of the recordings. Second, by the use of a video peak store to superimpose several hours of recordings onto a single frame (Zehnder & Karlsson 2001, Zehnder *et al.* 2001). If the image of the bird is represented by a very few pixels, the risk of missing an event during rapid visual viewing of the recordings increases significantly. Similarly, using the video peak store method, there is a risk that birds passing close to the camera will not be visible on the superimposed picture, because the time taken for the bird to pass out of the field of view will be less than the time interval between two consecutive frames. To date, TADS is the only system that merely records images when birds are either passing or colliding with the turbine blades (Desholm 2003b, 2005). However, the limited field of view is a drawback in terms of assessment, particularly when the cost of the appliance is taken into account. When running an avian collision detection programme, it is advisable to log all activities in a logbook. This ensures that data relating to monitoring efficiency, number of bird flocks passing per unit time, the influence of time of day and of the natural viability induced by weather on the collision risk can be analysed after the field season.

Collision monitoring can be either designed as a high intensity programme using a large number of thermal cameras for measuring the low daily collision frequency, or as a low intensity programme with only one or two thermal cameras for detecting periods with a high number of collision casualties under rare and unusual situations. Such mass mortality events have been reported in studies of illuminated land-based super-structures (Lensink *et al.* 1999, Nilsson & Green 2002) and of offshore platforms (Müller 1981). High death rate events may occur at offshore wind farms under conditions where a relatively uncommon combination of factors result in high collision events (e.g. high migration volume and a sudden decrease in visibility).

Collision model parameters

If the direct measurement of avian collisions turns out not to be feasible (economically, technically or for other reasons), an indirect approach of modelling the avian risk of collision can be applied. This approach necessitates the construction of statistical models that can forecast the number of potential future collisions that may occur at a given wind farm site. For this modelling work, radar data describing the three dimensional avoidance response and migration trajectories will be essential. However, the infra red monitoring device can also contribute with important data to these models, especially by providing estimates for the following parameters:

(1) near turbine blade avoidance behaviour;
(2) flight altitude;
(3) flock size (especially at night); and
(4) species recognition (especially at night).

Other techniques

Visual observation

During daylight, long-range spotting scopes (e.g. × 30 magnification) can be used to identify avian migrants to species, to a distance of at least 5 km for larger birds such as ducks and geese (Kahlert *et al.* 2000, 2002). This detection distance depends on the height above sea level at which the observer is sitting and the weather specific visibility. The fact that this method cannot be used in darkness and in periods with dense fog is its predominant shortcoming, since these are the very periods when one would expect the highest number of collisions to occur. For this reason, visual observations alone can never be the only mode of assessment. However, this ‘low-tech’ method can supplement the more sophisticated approaches using radar with very important specific data on migration volume, flock size and species identification (least during the daylight). Thermal cameras can provide these data during both day and night, but are constrained by a restricted data volume resulting from the smaller field of view and relatively fixed viewing direction. Light sensitive recordings suffer similar limitations as spotting scopes with regard to poor visibility. Nevertheless, a video camera can be operated remotely and can therefore potentially collect offshore data for long periods. The drawback of this system is the many hours of recordings, which have to be visually viewed, although this could be done remotely at the office and may be be simplified by the use of automatic pattern recognition software if developed in the future.

Avian acoustic monitoring

Detecting bird sounds using microphones in the vicinity of turbines offers sources of information to tackle two different issues. Firstly, monitoring of bird calls for species recognition (Larkin *et al.* 2002) and second, monitoring the sound of birds colliding with wind turbines as a means of measuring collision rate. The technique of acoustic monitoring by sensitive microphones of avian night flight calls is a way of producing a list of bird species migrating over a given site at night. Dierschke (1989) reported that very few species were calling intensively over the North Sea, and hence, that the acoustic monitoring was highly biased towards a few species. Additionally, this method will be biased towards species migrating at low altitudes which is likely to differ between areas. The relative volume (detection rate) at the species level can be obtained (Farnsworth *et al.* 2004), but such data will always be biased towards species using contact calls during nocturnal migration and towards birds migrating at lower altitudes. From studies in the US, some 200 species are known to give calls during night migration, of which roughly 150 are sufficiently distinctive to identify with certainty (Evans 1998). The remaining species can then be lumped into a number of similar-call species groups. The acoustic data on tapes can either be processed by ear or analysed by sound analysis software (Evans 1998).

At the time of this review, the ECN (Energieonderzoek Centrum Nederland) in the Netherlands is developing a bird–turbine collision detection system based on microphones linked to a video camera (Verhoef *et al.* 2004). The system aims to detect the acoustic signal created by birds hitting the turbine structures. The microphones are placed on the inner side of the turbine tower and the acoustic data are continuously analysed by sound analysis software. The system is not operational at present and some major problems remain unsolved. For example, the background noise of larger turbines far exceeds original expectation, and hence, the signal from avian collisions cannot be separated from background mechanical sounds. Furthermore, there are several shortcomings associated with the camera, because the quality of the night time images have been insufficient for species recognition, necessitating excessively long exposure times (Verhoef *et al.* 2004)

Acoustic monitoring could be used in combination with radar or TADS in order to determine the species detected by these other methods.

Laser range finder

A laser range finder can be used to measure the distance and vertical angle to an object and thereby estimate the height. Furthermore, the horizontal angle also can be obtained in some devices which, in combination with the distance to the object and the geographical position of the observer, can give a three-dimensional position of the object (Pettersson 2005). Several consecutive positions of an object, e.g. a migrating bird flock, can be used to describe the migration trajectory of the bird. The drawback of this method is that it can be operated only in daylight, the spatial resolution is relatively restricted, and it is also hard to hit a small and fast moving object. However, it offers an alternative to radar measurements of flight trajectories at short distances from the observer and during daylight periods.

Ceilometers

Ceilometer surveys involve direct visual observation of night-migrating birds using a high-powered light beam directed upward from a study site (Able & Gauthreaux 1975, Bruderer *et al.* 1999, Williams *et al.* 2001). Birds will appear as white streaks as they pass through the beam and must be viewed through a spotting scope or binoculars. In general, this method enables birds as small as thrushes to be detected and counted up to a distance of up to 400 m from the observer. Data can be collected on total number of birds passing the beam and can be used to estimate an overall passage rate for the site. Furthermore, the approximate heading of the migrating birds can be assessed. At wind farms, this method can be used to describe the species or groups of species composition during night-time migration. One of the biggest drawbacks is the necessary night-time siting of a human observer on an offshore platform.

Moonwatching

Moonwatching is a similar technique to the ceilometer where the light beam is exchanged by the full or nearly full moon (Liechti *et al.* 1995). Otherwise this technique follows the procedures used in ceilometer surveys. Moon-watching can be a useful adjunct to ceilometer-based studies, since ceilometer beams are difficult to see on bright moonlit nights.

Carcass collection

The practice of collecting dead and injured collided birds at offshore wind farms is believed to be untried and is judged to be unrealistic due to the currents moving corpses away from the collision site and due to an unknown scavenger rate. Construction of floating bunds and/or nets to retain corpses is expensive and impractical and would not overcome problems associated with predator scavenging over longer sampling periods.

FURTHER METHODOLOGICAL DEVELOPMENT

The wind industry is in its initial stage of exploiting the European waters, and hence, only few studies on wind farms have so far been conducted in offshore areas. As a consequence, only a limited amount of experience has been acquired regarding the use of radar and thermal imaging technologies in this specific context. Some promising methods are still to be developed and some of the existing technologies could benefit from a further development or bird-turbine specific adjustments.

So far only horizontal surveillance radar have been used in effect-studies of offshore wind farms (Kahlert *et al.* 2000, 2002, 2004, Desholm *et al.* 2003, Christensen *et al.* 2004), so even though the combined set-up of both a vertical and horizontal radar are being used in offshore areas, the results are not yet published.

It could be of great value to perform terrestrial validation tests of the TADS, so that the collision measures from this remote technology could be verified by carcass collection on the ground. The amount of data generated from TADS monitoring is still very limited, and hence, further collection of data could enhance our understanding of this passive infra red technique and its future application possibilities.

Another possibility could be the development of a low cost sensor-system for detecting the impact from bird-turbine collisions for large-scale implementation, i.e. at every turbine in a wind farm. It could be either a further development of the WT-bird microphone system (www.ecn.nl; Verhoef *et al.* 2004) or could be based upon a system using the piezo-electric technology that can detect acoustic vibrations in materials (e.g. vibration waves arising from the impact of birds hitting the rotor-blades, nacelle or tower construction). This approach necessitates collation of information on background vibration of turbines in order to detect vibrations from colliding birds.

COLLISION MODELLING

When constructing collision prediction models we have to discern between models for EIA studies (pre-construction) and models for effect studies (pre- and post-construction) since only the latter offer the opportunity to include avian avoidance response to wind turbines. This is because data on species-specific avoidance manoeuvring is very scarce. Consequently, such data need to be collected at the study site of interest before proper estimates of the number of collisions (including avoidance behaviour) can be estimated through quantitative predictive modelling (Chamberlain *et al.* 2006). Nevertheless, it is recommended to build non-evasive-type models as part of the EIA studies as a first crude assessment of the potential risk of collision for any proposed wind farm.

Framework for a collision model

Risk of collision is defined as the proportion of birds/flocks exposing themselves to collision by crossing a collision conflict window. The risk of collision (r_i) is assessed at four levels of conflict windows: Level 1 relates to the study area, level 2 the wind farm, level 3 the horizontal reach of rotor-blades, and level 4 the vertical reach of rotor-blade (Fig. 5). The value of r_i can be measured directly for each level post-construction as the transition probability distribution, or be estimated pre-construction by multiplying the pre-construction proportion of birds/flocks (p_i) passing the level specific conflict window with the assumed (published estimates) proportion of birds (a_i) not showing any evasive manoeuvres at the given level. After level 4, a factor describing the by-chance-probability (c) of not colliding with the rotor-blades must be incorporated to account for those birds safely passing the area swept by the rotor-blades by chance (Fig. 5; Tucker 1996, Band *et al.* 2005). An overall risk of collision (R) can be obtained by multiplying the four probability risk values:

$$R = r_1 \times r^2 \times r_3 \times (r_4 \times (1-c)) \quad [1]$$

The simple deterministic way of estimating the overall number of collisions at the wind farm ($n_{collision}$) would be to multiply R with n_1 using mean values for transition probabilities and for the *c*-value. The more profound way of estimating $n_{collision}$ would be by simulating the migration event from n_1 through $n_{collision}$ in accordance to the collision prediction model by resampling transition probabilities from field data-based probability distributions and applying the re-crossing loop (flocks passing more than one row of turbines; Fig. 5).

This model can be applied for different scenarios such as:

(1) day and night;
(2) head-, tail-, and cross-wind (especially r_3 and c may be affected by wind direction (Liechti & Bruderer 1998, Tucker 1996)); and
(3) rotor-blades, foundation and turbine tower.

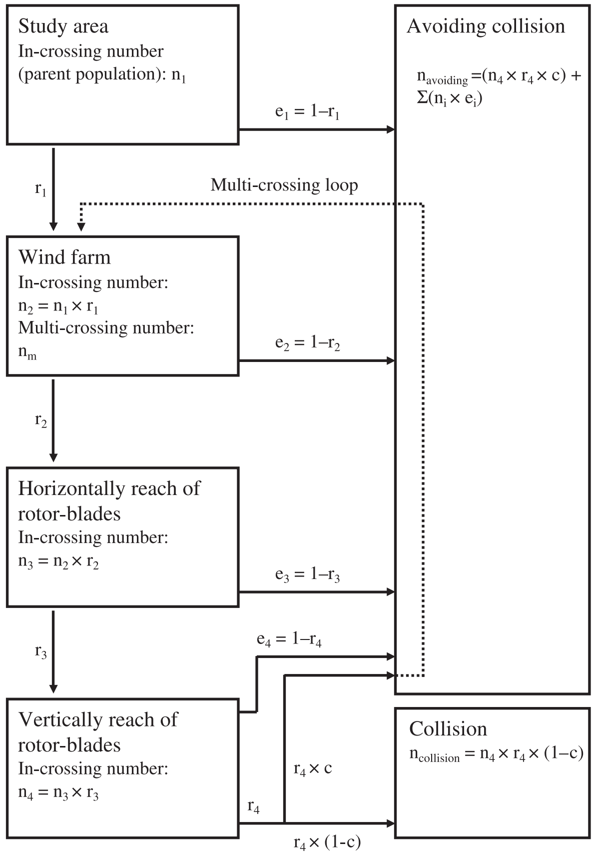

Figure 5. Schematic presentation of the collision prediction model where the boxes to the left represent the four scale-specific conflict windows and the boxes to the right the non-colliding and colliding segments of the migrants. The six values of n_i denote the number of birds/flocks which enter each box and can be calculated in accordance to the equations presented in the boxes. The migration volume in the study area is represented by n_1. The r_i-values represent the transition rates of birds exposing themselves to a conflict window and the e_i-values represent the transition rates of birds performing an evasive behaviour and thereby avoid colliding with the rotor-blades of the wind turbines. The n_m-value denotes the number of turbine rows passed, $n_{avoiding}$ the number birds avoiding a collision, $n_{collision}$ the number birds colliding with the rotor-blades of the turbines, and c the theoretic non-evasive probability of passing the area swept by the rotors by-chance.

Finally, the results from these partial models can be combined in an overall estimate of number of collisions at the wind farm under study. Parameterization of the collision prediction model can be done by applying radar, TADS and visual observations in the data collection protocol as follows for each of the four spatial levels (Fig. 5):

Level 1. n_1 represents the overall number of birds/flocks passing the study area during a migration event (i.e. spring or autumn migration season);

Level 2. For this part of the analysis radar data defining the probability distribution/proportion of migrants passing the wind farm is needed (r_1);

Level 3. Radar data defining the distance to the nearest turbine is needed for those flocks that pass through the wind farm. From the compiled frequency distribution of distance to nearest turbine, the proportion (r_2) of the migrating flocks that pass within the horizontal risk distance (equal to the length of the rotor-blades) of the turbines can be calculated for day and night. Desholm & Kahlert (2005) has recently recorded such diurnal difference in mean distance to turbines for waterbirds; and

Level 4. In order to estimate the proportion (r_4) of birds flying within the vertical reach of rotor-blades, a height distribution is needed. Depending on the level of information on migration altitudes the height distribution can be based either on theoretic values or preferably on directly measured altitude data collected at the study site. Altitude data on migrating birds can be collected by operating surveillance radar vertically or by applying the height data collection protocol by TADS (Desholm 2005b).

At this stage, n_4 (number of birds/flocks passing the area swept by the rotor-blades) is estimated and the final transitions to birds colliding with ($r_4 \times (1–c)$) and avoiding the rotor-blades ($e_4 + (r_4 \times c)$) must be executed. For inclusion of the near rotor-blade avoidance rate (e_4), which must be collected during both day and night, infra red detection systems (e.g. TADS) should be applied. So far, only Winkelman (1992) has reported avoidance behaviour using a thermal camera. Finally, an avoiding-by-chance factor (c) must be implemented after level 4 for those birds crossing the rotor-swept area safely, without performing any avoidance actions. Procedures for calculation of 'c' can be found in Tucker (1996) and Band *et al.* (2005) and can be directly incorporated in the collision prediction model.

The end product of the collision prediction model will be the predicted number of birds colliding with the turbines:

$$n_{collision} = n_4 \times r_4 \times (1–c) \quad [2]$$

and the predicted number of birds that avoid (either by chance or by evasive actions) colliding with the turbines:

$$n_{avoiding} = (n_4 \times r_4 \times c) + \Sigma(n_i \times e_i) \quad [3]$$

where n_1 (overall number of birds passing the study area) equals the sum of $n_{collision}$ and $n_{avoiding}$.

CONCLUSIONS

It must be emphasized that, due to the immature state of the offshore wind power generation and the relating environmental studies, both pre- and post-construction studies are of the utmost importance. Only by post-construction collection of data on avoidance response, can future pre-construction EIAs properly assess and predict the future impact from proposed wind farms.

Radars

It is concluded that, at present, the low-powered marine surveillance radars or modified avian research laboratory radars are the most appropriate radars for use in bird studies relating to a single wind farm. Economically, these relatively low cost systems are more feasible than both the tracking and doppler weather radars, if these are to be used specifically for a wind farm EIA. At present, all radars used by ornithological researchers have been constructed for detection of objects other than birds, and hence, their performance within this field is likely to be sub-optimal. Plans exist for developing a dedicated bird radar targeted exclusively at detecting flying birds and aimed at data collection on three-dimensional trajectories and wing beat frequency at relatively long range (Desholm *et al.* 2005).

It must be stressed here that in the near future strategic and larger-scale studies will most probably be initiated in Europe and the US, aimed at gathering information on the general migration patterns in different regions, enabling a more strategic, scientific planning process for the future siting of large offshore wind farms. The high-powered tracking and doppler radars might prove to be the best option for such generic studies.

Infra red camera systems

In general, it can be concluded that the thermal imaging products available can provide data on nocturnal bird behaviour that is difficult to obtain in any other way. For fast processing of data three options exist so far:
(1) fast viewing of recordings;
(2) trigger software that excludes the non-bird observations (Desholm 2003b, 2005b); and
(3) video peak store which superimposes several hours of recordings on to a single frame (Zehnder & Karlsson 2001, Zehnder *et al.* 2001).

The operational distance is much less than for ordinary video equipment due to the relatively low optical resolution in thermal imaging devices, but can in part be overcome by the use of large telephoto lenses. However, the trade-off between operational distance and the size of the field of view at a given distance should be considered, since the area monitored by the infra red device will affect the amount of data (number of birds passing the field of view) that can be collected by one thermal camera within a given amount of time.

Only one type of hardware arrangement (the TADS) has so far been used as a remotely controlled system for monitoring the collision frequency in offshore areas. However, since this kind of remote controlled software is comprised of standard components for any operational system, there are no constraints on its use besides the necessity for an optic fibre linkage between land and wind farm. TADS is the only system adapted for offshore use under harsh and corrosive (especially salt) conditions. No severe problems have been encountered with regard to its offshore use and the fact that the prototype of TADS has been operating continuously under these extreme conditions for more than 2 years clearly shows that these possible constraints can be easily resolved.

Before designing a thermal imaging programme it is important to consider several aspects of the study. Firstly, the physical structures available as potential mounting platforms (turbines and transformer platform, weather measurement towers) must be considered, since these and (especially) the distance between them can constrain the data collection because of the limited resolution of such thermal imaging devices. Second, it is necessary to consider the species of interest (or at least the size of the key focal species) and whether single individuals or flocks of birds form the focus of the study. If small birds are the main target and single individuals need to be detected (if collisions are to be measured directly) a telephoto lens is needed, and thus, the field of view will be highly restricted. A small field of view will necessitate greater replication (i.e. more TADS devices) if reliable collision estimates are to be produced. A low migration volume will also require a larger number of devices in order to increase the sample size of the data set.

Impacts on the population level

This review deals exclusively with the local effects from single wind farms, but more interesting in a biological and ecological perspective is the impact on the population level of the bird species involved.

A fly-way population of a specific species may not be impacted by 80 2 MW turbines erected at a single site, but if we are dealing with a long-distance migratory bird species, they might have passed several other utility structures along their migratory corridor. Thus, from a conservation management perspective, all the potential local effects must be assessed in combination. Such population level assessments cannot be expected to be dealt with at every single wind farm, but must be handled at a more strategic level, perhaps co-ordinated by governmental institutions. If negative effects are occurring at the site level, governments must provide best practice guidance for local EIAs, with the purpose of more strategic population assessments in mind. However, since avian migrants, by their very nature, cross national boundaries, a forum like the EU might be a suitable level for developing such strategic guidelines.

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