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Authors: Krijgsveld, Karen L., Akershoek, Kirsten, Schenk, Femke, Dijk, Femke, and Dirksen, Sjoerd

Source: Ardea, 97(3) : 357-366

Published By: Netherlands Ornithologists' Union

URL: https://doi.org/10.5253/078.097.0311

Collision risk of birds with modern large wind turbines

Karen L. Krijgsveld[1,*], Kirsten Akershoek[2], Femke Schenk[2], Femke Dijk[3] & Sjoerd Dirksen[1]

Krijgsveld K.L., Akershoek K., Schenk F., Dijk F. & Dirksen S. 2009. Collision risk of birds with modern large wind turbines. Ardea 97(3): 357–366.

We studied collision rate of birds with modern, large 1.65 MW wind turbines in three wind farms in The Netherlands during three months in autumn and winter. Collision rate, after correction for retrieval and disappearance rate, was 0.08 birds per turbine per day on average (range 0.05–0.19). Collision risk, i.e. the number of victims relative to the flight intensity of birds at the wind farms, was 0.14% on average. For nocturnal migrants, risk was as low as 0.01%, while the risk was 0.16% for local birds flying at night. In absolute numbers, the overall collision risk was similar to the 0.06–0.28% found for earlier-generation lower turbines that have a smaller rotor surface. However, given the comparatively large rotor surface and altitude range of the modern turbines, the risk was c. threefold lower than for smaller turbines. A large fraction of collision victims were diurnally active and local birds that were foraging in the area, rather than nocturnal migrants. Flight intensities of this group should be taken into account as well as that of nocturnal migrants, when calculating collision rate.

Key words: wind energy, wind farm, collision risk, collision victims

[1]Bureau Waardenburg, Box 365, 4100 AJ Culemborg, The Netherlands;
[2]van Hall Institute, Box 1528, 8901 BV Leeuwarden, The Netherlands;
[3]Wageningen University and Research Centre, Environmental Sciences, Bornsesteeg 69, 6708 PD Wageningen, The Netherlands;
*corresponding author (k.l.krijgsveld@buwa.nl)

INTRODUCTION

With the increasing demand for renewable energy, increasing numbers of wind turbines appear on our horizons. Notwithstanding the benefits of wind energy, one of the down sides is that birds may collide with these turbines. Especially when a wind farm is placed at a location with a high intensity of flight movements of vulnerable bird species, the number of bird victims may be substantial (Thelander *et al.* 2003, Everaert & Stienen 2007). To prevent large reductions in bird numbers by future wind farms, or to evaluate the number of bird victims at existent wind farms, assessments are made of collision rates of birds with wind farms. To date, these assessments are largely based on a few studies on 300 kW turbines dating from the late 1980s and early 1990s (Musters *et al.* 1996, Winkelman 1992a,b). The collision rate, i.e. the number of collision victims in a wind farm, is a combination of the flight intensity and the collision risk of a bird flying through that wind farm. The more birds fly through a wind farm, the more birds will collide with a wind farm (e.g. Desholm *et al.* 2006, Band *et al.* 2007). The chance that a given bird flying through a wind farm will collide with a turbine, i.e. the collision risk, depends on an array of factors such as location and lay-out of the wind farm, landscape features, and behaviour and morphology of the species (e.g. Thelander *et al.* 2003, Dirksen *et al.* 2007, de Lucas *et al.* 2008).

Similarly, collision risk of birds with more modern types of wind turbines may deviate substantially from the collision risk with older types of turbines. The first generation turbines (prior to early 1990s) were low, had a small rotor diameter, and a high rotation speed in relation to more recent turbines of 1.5 MW and more. The increased rotor diameter leads to an increased surface over which birds risk collision. Due to the increased height in combination with the large rotor diameter, birds flying higher and in a broader range of altitudes are at risk. As birds often fly at species-specific altitudes, different bird species may be affected, with related different flight intensities (van den Bergh *et al.* 2002, Dirksen *et al.* 2007). Apart from birds moving sideways to avoid the turbines, birds may pass above or underneath the turbines. Whereas birds generally do not pass underneath rotors of lower turbines, passage underneath rotors of modern and higher turbines is observed more frequently, possibly because the rotors are positioned further away from the ground (own observations). Finally, large rotors rotate at lower speeds than small ones. This reduces the probability that a bird flying through the rotor disc will be hit (see Orloff & Flannery 1996), and may enhance the visibility of the turning blades to an approaching bird.

Actual collision risks of birds with modern large turbines have rarely been studied (e.g. Hötker *et al.* 2004, but see Everaert *et al.* 2002, Grünkorn *et al.* 2005). Instead, to estimate the effects of these turbines on birds, collision rates determined in studies on small turbines are used and upscaled to larger turbines (Desholm *et al.* 2006). Tucker (1996) demonstrated mathematically that, as collision risk is higher closer to the hub than at the rotor tip, collision risk does not increase linearly with the rotor surface area. Using Tucker's model, it can be calculated that collision risk should increase as (rotor diameter)$^{0.7}$. Thus, collision risks with modern turbines are often calculated based on collision risks with small turbines, in which a 'Tucker correction factor' of 0.7 may or may not be incorporated. This correction however does not incorporate factors such as altitude distribution of the birds, perception by birds of the slower turning turbines, or behavioural changes of birds towards the turbines. Band *et al.* (2007) have developed a promising model in which these aspects can be included, and this model is becoming a commonly used technique to estimate collision rates. The more precise we can determine flux and deflection around wind farms and around turbines, the better we can estimate collision rate with this model. Despite this development, actual collision risks with modern turbines remain largely unknown.

We studied collision rate of birds under modern large 1.65 MW wind turbines in three wind farms in The Netherlands for three months during autumn migration and in winter. The number of collision victims found was corrected for the probability of both finding a victim during searches and losing a victim through depredation, by establishing these probabilities in experimental tests. Collision risk was calculated based on the number of birds passing the wind farms, by quantifying nocturnal bird movements using radar.

METHODS

Wind farm locations and specifics

Three wind farms in The Netherlands were selected for this study. Two of these, Waterkaaptocht and Groettocht, are located in the Wieringermeerpolder in the province of Noord-Holland. The third, Jaap Rodenburg, is located southwest of Almere in the province of Flevoland (Fig. 1). All three were situated in flat, large scale open agricultural areas in man-made polders. The fields underneath and surrounding the turbines had been in use for growth of various crops, but had mostly been recently harvested or were barren at the time of the research.

Waterkaaptocht comprises 8 turbines placed in a single line oriented NW–SE at 18 m from a c. 4 m wide ditch. The line consists of 2 groups of 4 turbines each, with a distance of 300 m between turbines and of 1 km between groups. Groettocht is located c. 15 km to the southwest of Waterkaaptocht. The wind farm comprises 7 turbines in a single line oriented NW–SE, at 40 m from a c. 4 m wide ditch. Distance between turbines is 285 m. Jaap Rodenburg comprises 10 turbines placed in a cluster of three lines oriented NW–SE. Distances between rows are 320 and 350 m, distance between turbines within rows is 350 m.

Turbines in the Jaap Rodenburg wind farm were 11 m lower compared to the turbines in the other two wind farms, but were otherwise identical (Table 1).

Table 1. Characteristics of turbines at the three wind farms.

Wind farm	Power (MW)	Rotor diameter(m)	Hub height (m)	Tip height (m)	Rotation speed (rpm)
Waterkaaptocht	1.65	66	78	111	21.3
Groettocht	1.65	66	78	111	21.3
Jaap Rodenburg	1.65	66	67	100	21.3

Figure 1. Locations of the three wind farms in The Netherlands (A), and position of turbines in these wind farms. B Waterkaaptocht; C Groettocht; D Jaap Rodenburg. Black circles indicate turbines that were searched, white circles indicate turbines that were not searched.

Searching methods

The research was carried out in October, November and December of 2004. A total of 14 turbines was searched for victims (5 at Waterkaaptocht, 5 at Groettocht and 4 at Jaap Rodenburg. We included only turbines under which vegetation type and - height did not obstruct visibility of potential victims. Search frequency was once every three days initially, but this was increased to once every two days after depredation tests revealed that disappearance rates were too high to permit searching at a lower frequency. At this time, with a limited number of people to search, searches at Groettocht were discontinued.

A circular area with a radius of 100 m around each turbine was searched for dead birds. At Waterkaaptocht and Groettocht, lack of permission to search the opposite side of the irrigation ditch resulted in semicircular search areas, ending at the water's edge. Previous studies have shown that victims fall within a radius of 0.75 to 1.1 times the hub height of the turbine (Winkelman 1992a, Grünkorn *et al.* 2005), i.e. up to 88 m in this study. Therefore, the searched area was large enough to include all potential victims. The area was walked in parallel lines 4 to 6 m apart, depending on factors affecting visibility of the field.

Retrieval probability

The probability of finding victims during searches was determined in a series of tests running simultaneously with the searches for victims. Fresh (defrosted) bird carcasses were laid out at Waterkaaptocht and Jaap Rodenburg, underneath turbines where victims were searched. All birds were marked with a small tag hidden underneath the bird. Location of each bird was marked with a clothes peg also hidden underneath the bird. Carcasses were laid out by someone other than the observers who would search the area for victims, and observers were uninformed about date of testing, and quantity, species and location of carcasses. Carcasses were laid out late in the evening or early in the morning before searching. Carcasses were collected when they were found or, if not found, after the area had been searched. Retrieval probability was calculated as the number found divided by the number laid out.

A total of 39 birds were laid out on various dates at Waterkaaptocht and Jaap Rodenburg. As size and colour of birds are likely to affect retrieval probability, species of various colour and size were used. Colour was marked as conspicuous or inconspicuous with respect to the background of the field. Species were: 2 chicks of Brent Goose *Branta bernicla* (inconspicuous), 1 Wigeon *Anas penelope* (inconspicuous), 1 Oystercatcher *Haematopus ostralegus* (conspicuous), 1 Rock Dove *Columba livia* (inconspicuous), 1 Godwit *Limosa limosa* (inconspicuous), 17 adult, subadult and juvenile Black-headed Gulls and 1 one-day-old chick *Larus ridibundus* (conspicuous), 9 Japanese Quails *Coturnix c. japonica* (inconspicuous), 2 Red Knots *Calidris canutus* (inconspicuous), 1 Whinchat *Saxicola rubetra* (inconspicuous), and 3 Zebra Finches *Taeniopygia guttata* (inconspicuous after painting the bill black).

Disappearance rate

To determine disappearance rate of victims, fresh (defrosted) bird carcasses were laid out in all three wind farms. For this purpose, we used turbines other than those used for victim searches, to avoid predators and scavengers being attracted to the latter, which could lead to a subsequent increase in disappearance of collision victims. Carcasses were laid out semi-randomly, in all directions at distances between 1 and 105 m from the turbine. Each carcass was marked with a small tag hidden underneath the bird. Location of each carcass was marked with a small pin placed 10 m SW of the carcass. Presence and condition (eaten, moved) of carcasses was registered on three consecutive days after carcasses had been laid out. After that, remaining carcasses were checked irregularly once or twice up to day 9, after which all remaining birds were removed. From these data survival rate of carcasses was calculated, i.e. the probability that a carcass present on day t was still present at day t+1, day t+2, etc. For reasons of comparability, these calculations were made in a similar fashion as reported in Winkelman (1992a,b).

A total of 72 carcasses was laid out with 5 to 10 birds per turbine per test. In each wind farm, three tests were done on various dates in November and December. Species were: 2 chicks of Brent Goose, 1 Wigeon, 27 adult, subadult and juvenile Black-headed Gulls, 6 Rock Doves, 25 Japanese Quails, 2 Red Knots, 2 Dunlin *Calidris alpina*, 1 Nuthatch *Sitta europaea* and 6 Zebra Finches.

Victims

Of all birds found within 100 m from the turbine, the position in relation to the turbine was registered using a range finder and compass, and each bird found was photographed. A detailed description was made of condition and possible external injuries, and cause of death was determined as far as possible. Each find was identified to group or species level. For internal analysis of injuries and condition, bird remains were inspected by the Dutch veterinary laboratory CIDC-Lelystad.

Calculation of collision rate

To obtain an estimate of collision rate (N_C), the number of victims found (N_F) has to be corrected for the probability of a victim remaining at the location rather than disappearing through scavenging (P_D), the probability of finding a victim that is present (P_F), the fraction of the total area (100 m radius) underneath the turbine that was searched (F_S), and the fraction of days of the research period that victims were searched (F_d). Collision rate thus was calculated as follows (following Winkelman 1992a):

$$N_C = N_F / (P_D \times P_F \times F_S \times F_d)$$

As disappearance rate turned out to be high in the Groettocht and Jaap Rodenburg wind farms, the number of days in between searches was set to a maximum of two days in these farms (yielding a disappearance of 25% of victims at maximum). If the search interval was longer, days were not included as being searched. Victims found after periods longer than two days were included only when evidently fresh. The number of collisions was first calculated per wind farm. As the correction factor for disappearance rate changed with the interval between searches, a weighted mean per wind farm was used, taking this variation in search interval into consideration. Overall collision rate was calculated by averaging the collision rate of all three wind farms.

Quantification of flight movements

The number of birds passing the wind farms at night was estimated using a 12 kW X-band marine surveillance radar (Furuno FR1510). By tilting the radar vertically, bird echoes are detected in the vertical plane, and altitude of echoes as well as the number of echoes passing per unit of time per surface area can be registered. The radar beam was positioned perpendicular to the main flight direction (SW) of migrating birds. Measurements took place from the end of dusk until early dawn. During this period, all bird echoes (within a range of 0.25–0.5 nautical mile from the radar) were recorded manually in 10-min intervals, and altitude was classified (in 10 classes), as well as flight direction (in 3 classes), and distance from the radar (in 5 classes). Flux (i.e. flight intensity) was expressed as mean traffic rate (MTR, n birds/h/km), including bird echoes to an altitude of 140 m (i.e. turbine altitude). To calculate the flux through the wind farm, average MTR was multiplied by 13 (hours of darkness) and by the actual length of the wind farm. Because one echo may belong to either an individual bird or a bird flock, the calculated flux may underestimate actual flux.

Radar observations were conducted in all three wind farms on three nights each (Waterkaaptocht: 18 October, 17 November and 20 December; Groettocht: 20 October, 22 November and 22 December; Jaap Rodenburg: 26 October, 24 November, 17 December 2004).

During daylight, birds present in the wind farm area were recorded when the wind farm was visited for e.g. victim searches. Daylight flux was not quantified, however.

Statistics

Data were analysed statistically using Genstat version 7. Factors affecting retrieval probability were tested in a logistic regression model. Factors affecting disappearance rate were tested in a multiple linear regression model, after arcsine transformation of the dependent variable (i.e. fraction of carcasses still present).

RESULTS

Retrieval probability

At Waterkaaptocht, 9, 6 and 3 carcasses were laid out on three days, of which 9, 5 and 3, respectively, were retrieved during the first following search. In Jaap Rodenburg, 11 and 10 carcasses were laid out, of which 6 and 7, respectively, were retrieved. Thus, a fraction of 0.74 on average was retrieved (95%-confidence interval = 0.40–0.94; allowing for variance between tests and overdispersion of data). This average value was used to calculate the number of victims in all three wind farms. Whether the bird was conspicuous or not had no effect on retrieval probability. Larger birds however were more likely to be retrieved than smaller birds (logistic regression: $F_{1,36} = 2.1$, $P < 0.05$). The retrieval tests in the Jaap Rodenburg farm were carried out under conditions with poor visibility due to fog (visibility 0.1–0.5 km). This resulted in a significantly lower fraction retrieved in the Jaap Rodenburg farm than in the Waterkaaptocht farm, where visibility was more than 0.5 km on all three test days (logistic regression: $F_{1,36} = 2.5$, $P < 0.05$).

Disappearance rate

The fraction of carcasses still present decreased significantly with the number of days elapsed since laying out the carcasses (Fig. 2; $F_{1,32} = 13.9$, $P < 0.001$; difference in number of tests per day explains the apparent increase in fraction present). In addition, disappearance rate of carcasses varied significantly between the three wind farms, being highest at Jaap Rodenburg and lowest at Waterkaaptocht: fraction still present was significantly higher at both Waterkaaptocht ($P < 0.001$) and Groettocht ($P < 0.05$) than at Jaap Rodenburg. Wind farm and number of days elapsed together account for 69% of variance. Neither size or conspicuousness of carcasses, nor soil- or vegetation type, nor distance to the turbine affected the rate of disappearance. Fraction still present in each of the three wind farms was calculated using the following regressions: Jaap Rodenburg: 0.86–0.11 × number of days; Waterkaaptocht: 1.11–0.07 × number of days; Groettocht: 0.82–0.04 × number of days. Correlation in the last was not significant, but was used to achieve a correction factor for calculation of the number of collision victims.

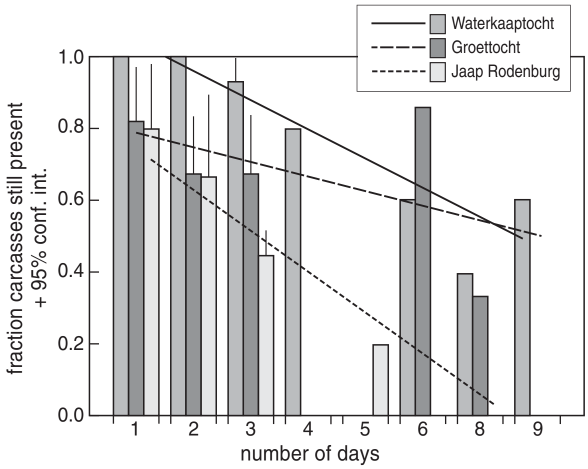

Figure 2. Disappearance rate of birds in the three wind farms, depicted as the fraction of carcasses still present in relation to the number of days that have passed since the carcasses were put out. Number of tests on which fraction was based, for Waterkaaptocht: 3,3,3,2,1,1,1; for Groettocht 3,3,3,1,1; for Jaap Rodenburg: 3,3,2,2,1.

Species present at the wind farms

West to southwest oriented migration was observed in October and to a lesser extent in November in all three wind farms, comprising mainly thrushes (predominantly Redwing *Turdus iliacus*) and some shorebirds. No redwings were found under turbines after radar observation nights, despite searching after three heavily clouded nights with strong winds and rain. Local bird movements were observed mostly around dusk and dawn. At Waterkaaptocht and Groettocht these were made mainly of gulls (to and from a night roost at the nearby Lake IJsselmeer), ducks, shorebirds (Golden Plover *Pluvialis apricaria* and Lapwing *Vanellus vanellus*) and Common Crow *Corvus corone*. At Jaap Rodenburg, hundreds of ducks, geese and Cormorants *Phalocrocorax carbo* passed the area, as well as thousands of Starlings *Sturnus vulgaris*. During nighttime, occasional observations revealed foraging Golden Plovers, Lapwings and one Dunlin. During daytime, mainly Skylarks *Alauda arvensis*, Lapwings, Golden Plovers, Common *Larus canus* and Black-headed Gulls, Common Crows, Greylag Geese *Anser anser* and White-fronted Geese *A. albifrons* were seen at Waterkaaptocht and Groettocht. At Waterkaaptocht, groups of Bewick's Swans *Cygnus columbianus* were occasionally seen. At Jaap Rodenburg, some ten to twenty raptors (mainly Buzzards *Buteo buteo* and Kestrels *Falco tinnunculus*, also a few Sparrowhawks *Accipiter nisus*) were seen during daytime throughout the observation period, as well as similar numbers of Common Crow and Grey Heron *Ardea cinerea*. In October and November, large flocks of Starlings (c. 20 000) were present in the fields around and underneath the turbines, as well as Skylarks (c. 250).

Remains encountered

In total, 14 bird remains were found underneath the wind farms, 6 of which were found at Waterkaaptocht, 5 at Groettocht and 3 at Jaap Rodenburg (Table 2). Three additional remains were found at Waterkaaptocht, but on closer inspection, based on diagnostic feeding marks and faeces patterns found at the site, these turned out to be prey remains of a Goshawk *Accipiter gentilis*. These were not included in further analyses. At Waterkaaptocht a Pheasant *Phasianus colchicus* was found at 50 m distance from a turbine. Although Pheasants usually fly low above the ground, and are therefore not likely to collide with a turbine, collision could not be excluded and the bird was included as victim.

Even after internal inspection of the birds, only one could be identified with certainty as being a collision victim. This Black-headed Gull was found with a wing ripped off, skull fracture, a broken bill and a torn liver. Two other birds were identified as probable victims. These were two Goldcrests *Regulus regulus* without apparent internal or external injuries, that may well have been caught in the turbulence behind the turbine (*cf.* Rodts 1999). The 11 other birds were found in various states of decomposition, from intact but decomposing birds to just some feathers and bones, all without direct evidence of collision. The Herring Gull had both legs broken in several places and died from starvation. This may be the result from collision with a turbine, but other causes cannot be excluded.

Birds were found at an average distance of 66 m from the turbines (range 25–107 m). Distance from the turbine at which the birds were found was not correlated to size or mass of the bird. Eight birds were found in the northern segment of the search area (NE-N-NW), five birds in the southern segment (SE-S-SW), one unknown.

Number of victims

To obtain the actual number of victims in each wind farm, the number of victims found was corrected for birds not found, for birds having disappeared as a result of scavenging animals, surface area searched and the total number of days searched (see methods). Assuming equal numbers of victims throughout the year, Waterkaaptocht would thus have 27 collision victims per turbine per year, Groettocht 39 and Jaap Rodenburg 20 (Table 3). The differences between the three wind farms were not significant. Averaged over the three wind farms, the number of victims was 28 birds per turbine per year (range 19–68; 95%-confidence interval) or 0.08 per turbine per day.

Bird flux and collision risk

Bird flux (number of flight movements per hour per km) through the wind farms was highest during the autumn migration period in October. In November and December, fluxes became increasingly less (Fig. 3). MTR at turbine height (0–140 m) was 251 echoes per hour per km (SD between nights 266) at Waterkaaptocht, 370 (SD 255) at Groettocht and 175 (SD 150) at Jaap Rodenburg. Migration was seen at altitudes of 50 m and up. The majority of birds in the lower air layers (up to 1000 m) flew above rotor height (Fig. 4).

Table 2. Possible collision victims by species found underneath turbines studied at the three wind farms, with indication of flight behaviour/activity.

Wind farm	Species	Migrant/local	Night/day
Waterkaaptocht	Black-headed gull *Larus ridibundus*, first year	local	diurnal
	2 Goldcrest *Regulus regulus*	migrant	nocturnal
	Oystercatcher *Haematopus ostralegus*	local	nocturnal
	Skylark *Alauda arvensis*	local	diurnal
	Pheasant *Phasianus colchicus*	local	diurnal
Groettocht	Herring gull *Larus argentatus*	local	diurnal
	Common gull *Larus canus*	local	diurnal
	Redwing *Turdus iliacus*	migrant	nocturnal
	2 unknown species	-	-
Jaap Rodenburg	Wood Pigeon *Columba palumbus*	local	diurnal
	Mallard *Anas platyrhynchos*	local	nocturnal
	1 unknown species	-	-

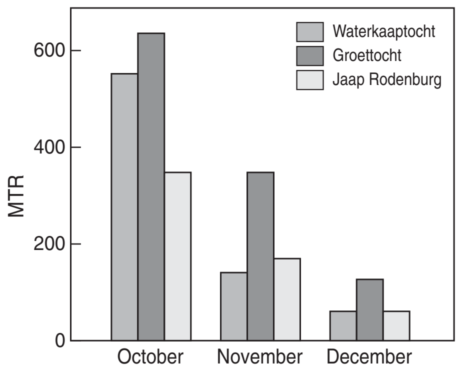

Figure 3. Number of birds passing each of the wind farm locations per month during hours of darkness. Data presented as mean traffic rate (MTR, number of bird echoes per km per hour) of altitudes up to 450 m, as measured by radar observations.

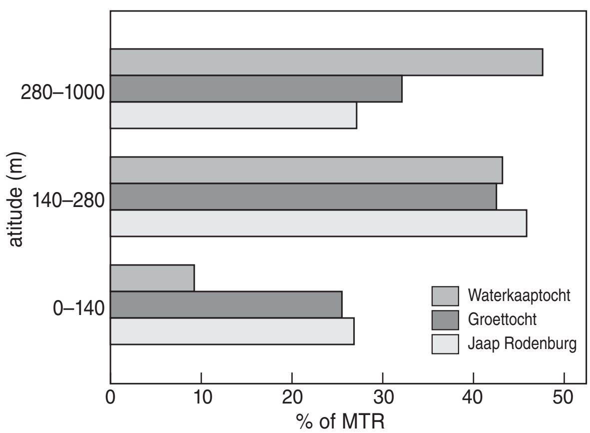

Figure 4. Altitude distribution of birds passing each of the wind farm locations during hours of darkness. Data are presented as percentage of total MTR at altitudes up to maximum rotor height (0–140 m) and above rotor height (135–280, 280–1000 m).

The collision risk of birds with turbines was calculated from the (corrected) number of victims and the flux of birds (flux up to 140 m altitude per 13 h of darkness (18:00–7:00) per total length of the farm). Based on the average of 0.08 victims per turbine per night (Table 3), collision risk was 0.14% on average. Of birds passing the wind farms at or below rotor height at night, as many as 84% were migrating birds (average flux in October minus that in December), whereas only 27% of victims identified to species level were migrating birds (three out of 11; two Goldcrests and one Redwing). Thus, taking into account the comparatively high flux of migrant birds and low number of victims under migratory species, the actual collision risk of migrating birds was only 0.01% and thus far lower than average. Collision risk of local birds flying in the dark period was 0.16% on average (calculated based on average flux in December).

DISCUSSION

Local and diurnally active birds are at risk

Birds found underneath turbines included comparatively few nocturnally migrating birds (27% of carcasses), and comparatively many local (55%) and diurnally active birds (73%). These findings are similar to results of several other studies (see review of Hötker *et al.* 2004). In a study in northern Germany at a site with considerable quantities of broadfront migration during autumn (Grünkorn *et al.* 2005), c. 85% of collision victims were local birds, and over half were diurnally active birds. Similarly, in several studies carried out in Belgium and the USA, the majority of victims were local and diurnally active birds such as gulls and raptors (Everaert *et al.* 2002, Thelander *et al.* 2003). This is surprising, because birds can see the turbines during

Table 3. Average number of victims per turbine per day and year, and collision risk. Values are based on number of days that turbines were searched for collision victims, and on bird flux through the wind farms. Maximum and minimum are calculated based on 95%-confidence intervals of retrieval probability and disappearance rate.

Wind farm	Turbine days	*n* victims	*n* victims/turbine/d	*n* victims/turbine/yr	Collision risk (%)
Waterkaaptocht	245	7	0.07	27	
Groettocht	42	2	0.11	39	
Jaap Rodenburg	68	2	0.05	20	
Average (max–min)			0.08 (0.19–0.05)	28 (68–19)	0.14

daylight hours and local birds are familiar with the presence of the towers, which has generally been thought to result in low collision risk during daylight hours and for local birds. An explanation may lie in the fact that local birds generally pass a wind farm several times while a migrant bird passes that farm just once. This could result in a higher number of victims among local birds, even when local birds per passage through the wind farm have a lower collision risk than migrant birds. In addition, birds concerned were mostly foraging birds, that may not pay attention to the turbines while foraging. Also differences in behaviour and morphology can affect collision risk. For example, a study of collision victims among larger bird species in a mountainous area in Spain revealed a comparatively high number of fatalities among Griffon Vultures *Gyps fulvus* (and other raptors), which was attributed to species-specific flight behaviour, bird morphology and topographic factors (de Lucas *et al.* 2008). Similarly, a large number of fatalities among White-tailed Eagles *Haliaeetus albicilla* has been reported in the literature (Hötker *et al.* 2004, Bevanger *et al.* 2008). On the other hand, very low collision rates were measured for Bewick's Swans and geese *Anser* spec. flying and foraging on a daily basis between turbines in wind farms in the Wieringermeer in The Netherlands (Fijn *et al.* 2007). Thus, species-specific behaviour near and in response to wind farms seemingly also affects collision risk of birds.

Despite occurrence of nights with heavy migration of thrushes, and unfavourable weather resulting in reduced flight altitudes and poor visibility, just one thrush was found as victim during the present study. Probably the majority of thrushes migrated at altitudes well above rotor height and therefore were not at risk of collision. Thrushes migrating at rotor height still constituted considerable numbers however, and the low number of collision victims among thrushes indicates that the birds were well capable of avoiding collision. These results suggest that besides calculating collision risks of nocturnally migrating birds, it is at least equally important to calculate collision risks of diurnally active local birds, based on the number of collision victims in combination with flight intensities of these birds in the wind farm area.

Collision rate

On average, 0.08 birds per turbine per day collided at the three wind farms. The collision rate of 0.08 probably overestimates the actual number of collision victims, because only one of the birds found could be positively identified as a collision victim, and two additional birds as very likely victims. In addition, although it could not be excluded as a collision victim, the probability of a low flying bird such as the Pheasant colliding with a turbine would seem to be very low. However, a pheasant colliding with a turbine base has been observed (own observations Bureau Waardenburg). As 25% of birds were not detected during retrieval tests, and up to 25% of carcasses disappeared within two days when put out in the field, collision rates cannot be calculated accurately without correction for these retrieval and disappearance probabilities. To interpret whether birds found underneath turbines are actual collision victims, it would be useful to study the number and condition of dead birds found in fields without turbines as well.

The observed collision rate is comparable with the number of birds colliding with much smaller turbines as reported by Winkelman (1992a) who found between 18 and 37 victims per turbine per year. At Kreekraksluizen however, a well-lit wind farm with low bird fluxes, only 4 victims were found on a yearly basis (Musters *et al.* 1996). In general, the number of victims per turbine per year as presented in various studies ranges between 0 and 125 (Winkelman 1989, Still et al 1996, Everaert *et al.* 2002, Thelander *et al.* 2003).

Collision risk

The high variation in the number of collision victims found at various wind farms illustrates the importance of including the number of birds that pass a location in collision estimates, and thus of comparing collision risk rather than number of victims. At locations where large numbers of birds fly through the wind farm area, more birds are likely to collide with turbines than in areas where only few birds do so (Thelander *et al.* 2003, Desholm *et al.* 2006, Band *et al.* 2007, Dirksen *et al.* 2007). Collision risk did not vary significantly between the three wind farms studied. As turbines at Jaap Rodenburg are clustered, in contrast to the other two wind farms where turbines are placed in a line, one might expect a deviant collision risk. The risk for a bird to collide with a turbine is not only dependent on turbine characteristics but also on the configuration of the wind farm as a whole (total rotor surface area as a fraction of total frontal area of the wind farm from the viewpoint of an approaching bird). This implies that wind farm configuration (e.g. cluster vs. line, or turbine density) should be taken into account when comparing wind farms or making predictions.

Winkelman (1992b) measured a collision risk between 0.09 (all birds) and 0.17% (birds flying at night), and Everaert *et al.* (2002) measured a collision risk of 0.08% (all birds), both at wind farms with smaller turbines than in the present study. Compared to these values, the collision risk of 0.01 to 0.16% found in the present study on larger turbines is low. In the study presented here, only nocturnal flux was used (and measured) to calculate collision risk, and not the diurnal flux. Because of this, the actual number of birds passing the wind farms will have been higher than the flux used to calculate collision risk. This means that actual collision risk will be lower than that presented here. In addition, migration was assumed to occur perpendicularly to the radar beam. On some nights, migration also occurred parallel to the radar beam to some extent. Due to the shape of the radar beam, flux (expressed as number of bird echoes per km per hour) of birds flying parallel to the beam will be underestimated. As a result, actual flux will also be slightly underestimated, and actual collision risk will be overestimated even more.

Without actual data on the collision rate at modern wind turbines and without an estimate of actual flux, the number of victims would have been estimated based on Winkelman's collision risk corrected for the non-linear increase with rotor surface area (Tucker-correction), and using an estimated flux of birds through the wind farms based on the study in Oosterbierum (Winkelman 1992b). This method would have resulted in an estimate of c. 100 victims per turbine per year. This is more than three times higher than the actual 28 victims found, and lies well outside the confidence interval. Such a correction for the increase in rotor surface area therefore results in an overestimate of the actual collision rate. We suggest that estimates of collision risks for older-generation turbines can be used for modern larger turbines without correction.

The results reported in this paper indicate that collision risk of birds with larger multi-MW wind turbines is similar to that with smaller earlier-generation turbines, and much lower than expected based on the large rotor surface and high altitude-range of modern turbines. This result may be due to several factors. The increased altitude of the turbines may allow more birds to pass underneath the rotor area, which hardly occurred at lower turbines (own observations). Local birds, which are generally flying at altitudes below 70–100 m (Dirksen *et al.* 1998, Dirksen *et al.* 2007), thus can pass mostly below rather than at rotor height. Additionally, the distance between turbines has increased compared to earlier-generation turbines (spacing in lines mostly 4–5 D, in clusters mostly 7–10 D, where D is rotor diameter). This may allow more birds to pass between turbines. Also the rotor speed is lower in larger turbines. Clearly, more studies of collision victims are needed before we can confidently predict the relationship between size and configuration of wind turbines and the risk for birds to collide with a turbine.

ACKNOWLEDGEMENTS

This study was carried out under permit of the Dutch Ministry of Agriculture, Nature and Food Quality by KA, FS and FD as part of their study at the Van Hall Institute and Wageningen University & Research Centre, and was supervised by Bureau Waardenburg. H. Schekkerman from Alterra Wageningen contributed substantially to planning and design during initial phases of the research. Several farmers in the study area have kindly provided indispensable logistic support. D. Knibbe lodged us at his farm for several months and put his land at our disposal for searching. T. Veenkamp, R. Bouthoorn & H. Heynen provided logistic support. H.J. Kouwenhoven of Nuon Energy Sourcing, M. Poot, H. Schekkerman and A. Spaans provided useful comments to improve this manuscript. We thank S. van Lieshout, M. Poot, H. Prinsen and P. Wiersma of Bureau Waardenburg for help during the nightly hours of radar work and for discussion on the subject. We thank Nuon Energy Sourcing for providing financial support to carry out this study, and for their ongoing commitment to include effects on birds in their wind farm placement decisions. This study was commissioned by Nuon Energy Sourcing for Bureau Waardenburg and Alterra.

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SAMENVATTING

Het aantal aanvaringen onder vogels met moderne, grote 1,65 MW windturbines is gedurende drie maanden in de herfst en winter onderzocht in een drietal windparken in Nederland. Het aantal slachtoffers was gemiddeld 0,08 vogels per turbine per dag (range 0,05–0,19), na correctie voor vindkans en verdwijnsnelheid van slachtoffers. Het aanvaringsrisico (het aantal slachtoffers in relatie tot het aantal vogels dat door het windmolenpark vliegt), was gemiddeld 0,14% en varieerde tussen 0,01% voor 's nachts trekkende vogels en 0,16% voor lokale, 's nachts actieve vogels. In absolute aantallen was het aanvaringsrisico vergelijkbaar met dat van de oudere generatie, lagere windturbines (0,06–0,28%) die een kleiner rotoroppervlakte hebben. Het risico was echter drie keer zo laag als verwacht op basis van de grotere rotoroppervlakte en de grotere hoogtespreiding van de moderne turbines. Een groot deel van de aanvaringsslachtoffers betrof dagactieve en lokale vogels die in het gebied foerageerden. De vliegintensiteit van deze groep vogels zou daarom tevens meegenomen moeten worden in berekeningen van aanvaringsslachtoffers, naast die van nachtelijke trekvogels.

Corresponding editor: Ken Kraaijeveld
Received 10 November 2008; accepted 15 September 2009

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Layout by Dick Visser, Haren, The Netherlands
Printed by Van Denderen, Groningen, The Netherlands, October 2009