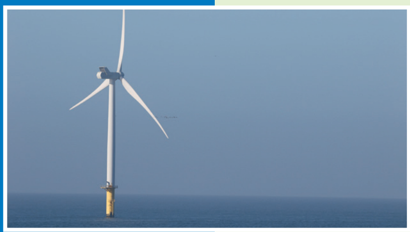
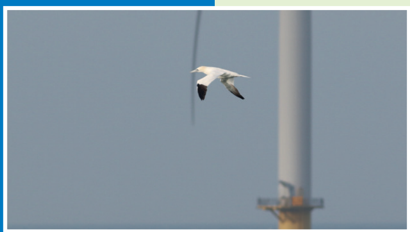
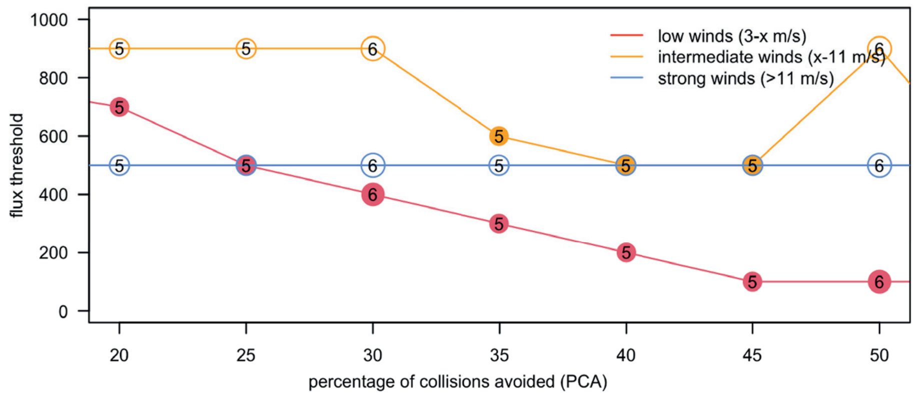
Potential curtailment regimes for offshore wind farms: exploring the relation between wind speed, bird migration intensity and power yield

Spatial variation in migration intensity and optimization of curtailment threshold







Rob S.A. van Bemmelen[1,]
Johannes de Groeve[2]
Astrid Potiek[1]

[1] Bureau Waardenburg, Culemborg
[2] Universiteit van Amsterdam

Bureau Waardenburg
Ecologie & Landschap

Bureau Waardenburg
Ecology & Landscape

Potential curtailment regimes for offshore wind farms: exploring the relation between wind speed, bird migration intensity and power yield

Spatial variation in migration intensity and optimization of curtailment threshold

Commissioned by: Rijkswaterstaat Zee en Delta

21 okt 2022
report nr 22-171

Potential curtailment regimes for offshore wind farms: exploring the relation between wind speed, power yield and bird migration intensity

Spatial variation in migration intensity and optimization of curtailment threshold

Rob S.A. van Bemmelen[1], Johannes de Groeve[2], Astrid Potiek[1]
[1] Bureau Waardenburg, Culemborg; [2] Universiteit van Amsterdam

Status: final report

Report nr:	22-171
Project nr:	20-0394
Date of publication:	21 okt 2022
Photo credits cover page:	D. Beuker, J. Leemans
Project manager:	dr. A. Potiek
Second reader:	dr. A. Gyimesi
Name & address client:	**RWS Water, Verkeer en Leefomgeving** Postbus 2232 3500 GE Utrecht
Reference client:	Bestelnummer: 4500329634, Zaaknummer 31177366
	Signed for publication: Team Manager Bureau Waardenburg bv R.C. Fijn, *MSc.*
Signature:	

Please cite as: Van Bemmelen, R.S.A., J. de Groeve, A. Potiek 2022. Potential curtailment regimes for offshore wind farms: exploring the relation between wind speed, power yield and bird migration intensity. Spatial variation in migration intensity and optimization of curtailment threshold. Bureau Waardenburg Report 22-171. Bureau Waardenburg, Culemborg.

Keywords: offshore wind farms, bird migration, curtailment, wind speed, power loss, radar

Bureau Waardenburg
Ecology & Landscape

Bureau Waardenburg, Varkensmarkt 9, 4101 CK Culemborg, the Netherlands
0031 (0) 345 512 710, info@buwa.nl, www.buwa.nl

Table of contents

Summary

Bird collisions with offshore wind turbines can be avoided by curtailment of wind turbines, a so-called curtailment procedure. A curtailment can save the lives of many birds during periods of high bird migration intensity. Rijkswaterstaat is implementing a curtailment procedure for offshore windfarms on the Dutch NCP on behalf of the Ministry of Economic Affairs and Climate Policy. The curtailment procedure is based on a prediction model for mass-bird migration, which is developed by the University of Amsterdam. Part of this implementation is the decision on the height of the threshold for a curtailment.

To get a better insight on an appropriate threshold, Rijkswaterstaat asked Bureau Waardenburg to study the variation in nocturnal migration activity between locations and seasons using radar data collected at two offshore wind farms in the Dutch North Sea: Luchterduinen (LUD) and Borssele (BSA). Migration intensity clearly differed between the locations. Moreover, moments of peak migration did not necessarily coincide.

In addition, we studied the relation between wind speed, bird migration intensity and the power generated by wind turbines, to illustrate how curtailment regimes could be optimized to reduce the number of potential bird collisions and at the same time the power loss due to curtailments. Our exploration of the relation between wind speed category, bird migration intensity and power generation by offshore wind turbines shows how power loss and the percentage of avoided bird collisions are related to threshold combinations at different wind speeds. Generally, curtailments during low wind speeds yield the largest gain in the percentage of avoided bird collisions and the lowest loss in power yield. Hence, thresholds per wind category may be preferred to a single, overall threshold for curtailment, as curtailment during hours with low wind speed will lead to a lower loss of energy yield.

1 Introduction

The expansion of offshore wind farms in the Dutch North Sea poses a potential risk for migratory birds. Migrating birds pass over the North Sea in vast numbers, with estimates running into the hundreds of million birds (Hüppop *et al.* 2006). The vast majority of migrants are passerines and other terrestrial species, that mostly migrate at night (Krijgsveld *et al.* 2011). Migration intensity shows marked peaks as a function of season and weather, with the largest peaks occurring in autumn and when birds have weak tailwinds (Bradarić *et al.* 2020).

One of the most promising mitigation measures to reduce the number of bird collisions includes the temporary curtailment of turbines during periods of high migration intensity of birds. Curtailment of turbines will come at the costs of decreased energy generation. Given the peaked occurrence of bird migration across the North Sea, curtailment of offshore wind turbines during nights with high migration intensity would be the most effective to avoid collisions. Note that the extent of curtailments (i.e. number of hours or percentage of flux during curtailment) is a policy decision, based on the trade-off between avoiding bird collisions and generating wind power. Based on the most recent knowledge at the time (Krijgsveld *et al.* 2015), the Dutch ministry of Economic Affairs and Climate (EZK) proposed curtailment rules to avoid high numbers of bird collisions based on a simple threshold at a migration intensity of 500 birds/km/h, which translated to 3.8% of the total flux over the year. Note that this 3.8% is based on nocturnal as well as daytime hours, and is based on the entire year, not only migratory periods.

Rijkswaterstaat is implementing a curtailment procedure for offshore windfarms on the Dutch NCP on behalf of the Ministry of Economic Affairs and Climate Policy. The curtailment procedure is based on a prediction model for mass-bird migration, which has been developed by the University of Amsterdam. Part of the implementation is the decision on the height of the threshold for a curtailment. Krijgsveld *et al.* (2015) was based on data from the offshore windfarm OWEZ. In order to make an informed decision on the height of the threshold and the potential differentiation between wind speed categories, Rijkswaterstaat asked us to answer the research questions below.

Research questions:

1) explore the temporal and spatial variation in migration intensity on two other offshore windfarm locations.
   We examined the variation in the frequency and timing of peak migration events at two Dutch offshore wind farms for which data were available from bird radars: Luchterduinen (LUD) and Borssele (BSA).
2) study the relation between migration intensity and wind speed for LUD.
   Possibly the same cumulative number of collisions can be avoided when shutting-down more often when winds, and therefore energy yields, are lower, as while shutting-down less often when winds and energy yields are higher. We explored whether curtailment rules can be optimized by minimizing the lost energy generation for varying percentages of collisions avoided.

2 Methods

Bird movements were monitored using Furuno radars[1] deployed at two offshore wind farms (OWFs): at Luchterduinen and Borssele, hereafter referred to as LUD and BSA. The data from both BSA and LUD were used to study to what extent peak migration events occur concurrently at two OWFs along the Dutch North Sea coast, separated approximately 100 km from each other. The data from LUD were used to study potential curtailment rules and their effect on the resulting proportion of avoided bird collisions and the loss of energy yield. The reason for using data from LUD for this optimization study is the prediction model from the UvA is also based on the LUD data (Bradarić *et al.* in prep).

Radar data were collected in 2019-2021. The radar in BSA was installed in August 2019, operational from 18 August onwards, but with configuration of the radar taking still place in September 2019, and hence this month was excluded from the analysis. The focus of this study was on the migratory periods. For spring migration, data between 15 February and 31 May were extracted, and autumn migration was based on data between 15 August and 30 November. This resulted in data for spring 2019 from LUD, autumn 2019 from LUD and partly BSA, while for spring 2020, autumn 2020, spring 2021 and autumn 2021 data was available both from LUD and BSA.

We used data from the horizontal radar, summarized per hour. This is comparable with the predictive model developed by the University of Amsterdam (UvA), for which the horizontal radar is used as well, and in which hourly predictions are made due to EMCWF meteorological data provided on hourly basis. As peak migration is known to occur mainly during night and the predictive model will only consider nocturnal migration, only data for nocturnal hours were used. Data filtering was performed by the University of Amsterdam (UvA), as described in Bradarić *et al.* (in prep). Bird migration intensity was expressed as Migration Traffic Rate (MTR), which is the density of tracks per time unit (see Bradarić *et al.*, in prep). This MTR is given as the number of birds per km per hour.

2.1 Frequency and co-occurrence of peak migration events

To compare the migration intensity in LUD and BSA with the migration intensity in OWEZ, the frequency table made by Krijgsveld *et al.* (2015) was reproduced with the data from LUD and BSA.

As turbine specifics changed over time, the collision estimates per flux class from OWEZ were updated based on more recent turbine characteristics. For this, the turbine characteristics of BSA have been used (for the frequency tables of both BSA and LUD), as these are likely to be the most similar with the OWFs for which the current curtailment procedure will be implemented in the future. These turbine characteristics were the same as those used in the latest 'Framework Ecology and Cumulation' (Kader Ecologie en Cumulatie; KEC 4.0 (Potiek *et al.* 2022)). Due to the updated turbine characteristics, the

[1] This type of radar of the brand Furuno is developed as a marine radar.

data on migration intensity used within the current study included tracks with an average flight height between 25 and 300 meters (*i.e.* assumed as rotor-swept zone), while Krijgsveld *et al.* (2015) used a range of 25 to 250 meters.

Bird characteristics were taken from Krijgsveld *et al.* (2015), which are based on the Redwing *Turdus iliacus*, a very abundant migrant that migrates mostly by nocturnally. For bird characteristics, see Krijgsveld *et al.* (2015).

Another adjustment in the calculation of the number of collision victims was the flux for each flux class. Krijgsveld *et al.* (2015) assumed the average flux to be the middle of the flux class (for example, 50 was the mid of the flux class 0 – 100 birds/km/hour. To get more realistic results, we calculated the average migration intensity per flux class based on the hourly migration intensities for each flux class.

2.2 Relation between wind speed, bird flux and turbine power

2.2.1 Wind and wind turbine power

Wind was measured in LUD using ultrasonic sensors (type FT-702), located on top of the nacelle of wind turbine 41. Wind speed and direction were recorded at 20 s intervals, which were averaged per hour for our analyses.

The relation between wind speed and energy yield is described as a 'power curve'. A power curve for offshore models of 12 MW was obtained from the NREL github repository (model 2020 ATB at https://github.com/NREL/turbine-models/). These curves were slightly modified based on discussions with offshore wind farm developers Ørsted and Vattenfall, so that the maximum yield was not attained at 11 $\mathrm{m/s}$ but at 12 $\mathrm{m/s}$ and with a smoother transition to the maximum yield. This smoother transition to maximum yield is obtained by recalculating the value at 11 $\mathrm{m/s}$ as the power yield at 12 $\mathrm{m/s}$ subtracted with 25% of the difference between the power yield at 10 and 12 $\mathrm{m/s}$. Turbines started to yield energy at wind speeds above 3 $\mathrm{m/s}$. The power curve was then scaled to arrive at the 9.5 MW capacity of the turbines currently deployed in the Borssele OWF by multiplying by 9.5/12 (Figure 2.1).

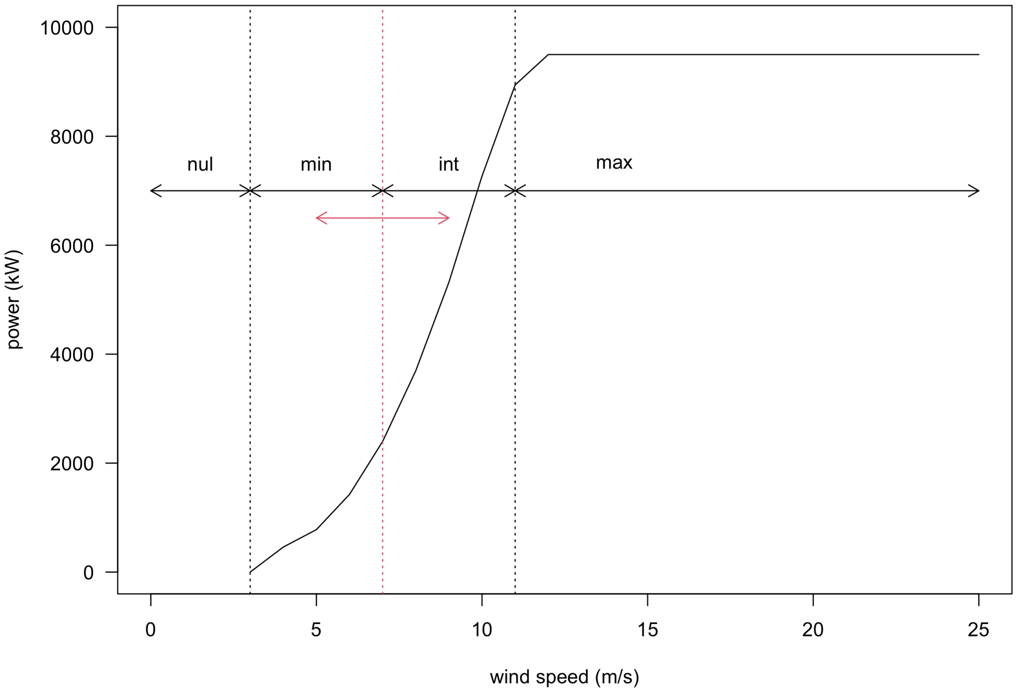


Figure 2.1 *Turbine power curve based on the NREL github repository, but with the inflection towards the maximum power rounded. Power was 0 kW at wind speeds up to 3 m/s and increased at higher wind speeds up to a plateau at 12 m/s, where maximum power is attained. The vertical dotted lines show the borders of the four power levels: 'nul', from 0 to 3 m/s, 'min', from 3 m/s to a moving divide (indicated by red arrow) between 5 and 9 m/s, 'int', from that same devide to 11 m/s, and finally 'max', from 11 m/s to higher wind speeds. In lowest category ('nul'), no power is generated and this category is therefore not considered in the analyses of potential threshold levels.*

2.2.2 Relation between thresholds, avoided collisions and power yield

Most peak migration occurs at relative low wind speeds, when power yield is relatively low, primarily below 8 m/s (see results section). Hence, most potential collisions can be avoided when concentrating curtailment periods during these winds, which would reduce the necessity to curtailment during nights with stronger winds. This means that if thresholds for curtailment can be defined for different classes of wind speed, the power loss can be minimized (with the same reduction of collision victims).

Therefore, we defined separate thresholds for four levels of wind speeds. The first category spans from 0-3 m/s (termed 'nul' in Figure 2.1), when turbines generate no power and therefore do not result in power loss during bird migration peaks. Therefore, they have no bearing on the percentage of avoided collissions or the power loss. The highest windspeed category spans from 11-25 m/s ('max'), when turbines reach their maximum power (Figure 2.1). The other two categories ('min' and 'int') are between 3 and 11 m/s, of which the division was varied between 5 and 9 m/s in steps of 1 m/s in the optimization procedure (Figure 2.1).

As a measure for the reduction of potential collisions, we took the sum of the bird flux during curtailment hours divided by the grand total of the flux in the study period, assuming that a fixed proportion of the flux collides with the turbine. In other words, the proportional reduction of collisions due to curtailments is assumed to reflect the proportion of flux during those curtailment hours. We refer to this measure as the *percentage of collisions avoided*, hereafter referred to as PCA. Then, we numerically explored the PCA and the amount of power generation lost for a single wind turbine as a function of 1) thresholds within each wind speed category (range of 0 – 1000 birds/km/h, in steps of 100 birds/km/h) and 2) wind speed category division (range of 5 – 9 m/s in steps of 1 m/s). The proportion of missing values in the wind data increased with wind speed (Figure 2.2). Because this can potentially lead to underestimates of the power loss, we calculated the 'corrected' power loss, extrapolating the proportion of hours that thresholds were exceeded (based on hours with MTR measurements and wind speed) to all hours with wind speed data (but not necessarily MTR measurements).

We extracted for each PCA between 20% and 90%, in steps of 5%, the threshold combination that resulted in the lowest loss of power yield to show the relation between PCA and loss of power. This excludes the 19% of the flux that occurred at wind speeds of 3 m/s and lower, when turbines are not generating power and therefore no curtailment is required. We chose for the upper limit for the PCA of 90%, as avoiding 100% of the collisions would require curtailment during all hours instead of only during migration peaks.

To illustrate the sensitivity of these selected threshold combinations, we selected the threshold combinations that resulted in PCAs of 30%, 70%, and 90%, and for each PCA level selected the 25 threshold combinations with the lowest power loss. Subsequently, we plotted their wind category divides, threshold levels and power loss levels. In case of a robust optimization, the power loss is clearly lower for the best threshold combination compared to other threshold combinations. In addition, a robust optimization is characterized by low variation in threshold levels and in the divide between the wind categories.

As a benchmark to compare the results to, we used the study of Krijgsveld *et al.* (2015). Based on Krijgsveld *et al.* (2015), the ministry of Economic Affairs and Climate Policy (EZK) and the Ministry of Agriculture, Nature and Food Quality (LNV) earlier proposed a curtailment threshold of 500 birds/km/h, resulting (according to Krijgsveld *et al.*) in 3.8% saved birds during daytime and nocturnal hours across the entire year.

To make a valid comparison the results were recalculated: As in the current study only the nocturnal migration periods were used, the percentage of birds covered within 500 birds/km/h during migration periods in the OWEZ dataset used by Krijgsveld *et al.* (2015) was recalculated to reflect this. This was done by selecting the migration periods in the OWEZ dataset, and calculating 1) the total nocturnal flux (summed MTRs) during the autumn and spring migration periods (374,133 birds / km), 2) the number of nocturnal hours where the threshold of 500 birds / km / hour was exceeded (70 h), 3) summing the total flux during these hours (49,084 birds / km) and 4) dividing the total flux during peak nights by the grand total of the nocturnal flux over the study period, which resulted in 13.1% (49,084

/ 374,133). This means that based on the OWEZ data, a curtailment of 3.8 % across the whole year means a curtailment during 13.1 % of the nocturnal hours during the migration periods. Note that this higher percentage is due to the migration period being a shorter time period, while still nearly all hours with an MTR above 500 (70 out of 72) fall within the nocturnal hours of the migration period.

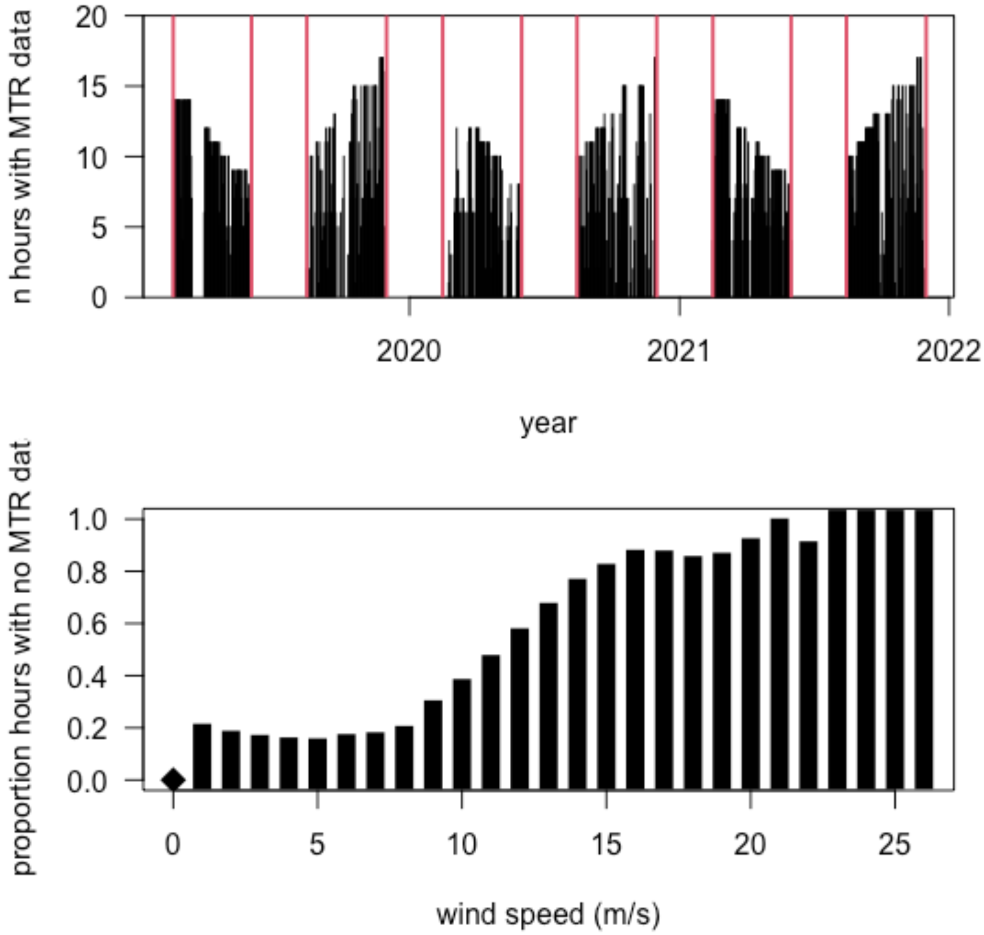


Figure 2.2 *Top: Distribution of data from LUD across the six study periods (demarcated by red lines), showing the number of nighttime hours with both MTR and wind speed data. Bottom: Proportion of missing MTR values in relation to wind speed.*

3 Results

Within this chapter, we first present results regarding the temporal and spatial variation in migration intensity, where the comparison with the OWEZ data from Krijgsveld *et al.* (2015) is made. Note that in this first section, we refer to the threshold of 500 birds / km / hour.

Subsequently, we present the results of the threshold optimization for LUD in paragraph 3.2. In this section, we no longer look at the threshold of 500 birds / km /hour (at all wind speeds), but calculated the PCA (% collisions avoided) and power loss for different combinations of thresholds per windspeed category.

3.1 Temporal and spatial variation in migration intensity

Migration intensity was higher and showed more peaks during autumn compared to spring. In addition to seasonal differences, there were also differences between years (Figure 3.1 and Figure 3.2). For both locations, the pattern of migration intensity within the autumn seasons 2019 and 2020 were similar, with peaks in October and November. The migration intensity during the autumn season of 2021 was on both locations lower than during the earlier autumns, with a larger difference for BSA. However, note that for BSA the amount of missing data was relatively large for this season. As a result, peak hours may have been missed in BSA. For autumn 2021, the radar in BSA provided no MTR data for most of the peak hours in LUD (Table 3.1). Generally, data availability for BSA was substantially lower than for LUD. Hence, comparing fluxes between the locations should be based on the relative number of hours exceeding the threshold, instead of the absolute number.

Comparison of hours with peak migration between BSA and LUD
Table 3.1 and Figure 3.3 give an overview of all hours exceeding the threshold of 500 birds / km / hour, either in BSA or LUD, or in both. In addition, the coinciding MTR at the other location is given. The comparison of the two locations gives an indication of spatial variation in migration intensity. In some cases, hours with high MTRs overlapped on both locations, but this was not always the case, among other things due to the reasons mentioned above.

In the *spring seasons*, none of the peak hours coincided in BSA and LUD. Although peak nights might actually overlap less during spring compared to autumn, this could also be caused by the rarer occurrence of peak hours due to the lower migration intensity during spring, as well as the lack of data. For the five peak hours measured during spring in LUD, no reliable data were available for BSA. In the spring of 2019, the radar in BSA was not yet installed. In 2020 and 2021, the measured MTRs in BSA were low during the hours in which a migration peak was observed in LUD. For the *autumn seasons*, seven peak hours coincided on both locations. In total, peak migration was observed on at least one location during 39 hours within the dataset.

Note that some problems occurred with both of the radars. As a result, in several cases data from the other location were not available for a peak migration hour. During the autumn season, such radar problems occurred in three peak hours (on the other location) in 2019, four peak hours in 2020 and three peak hours in 2021. In particular, technical problems at BSA during autumn 2021 resulted in several time periods with missing MTRs. In addition, the radar was regularly active for a short while, before shutting down again, which seemed to result in lower MTRs. This was the case for the hours during one night for which peak hours were measured in LUD, as indicated by two asterisks in Table 3.1 and orange points in Figure 3.3. If data from autumn 2021 would be excluded due to lower confidence in the measured MTRs, 32 hours remained with peak migration on at least one location. Of these 32 hours, seven peak hours occurred on both locations. During five other peak hours on one of the locations, the MTR on the other location was relatively close to the threshold (with values between 400 and 500).

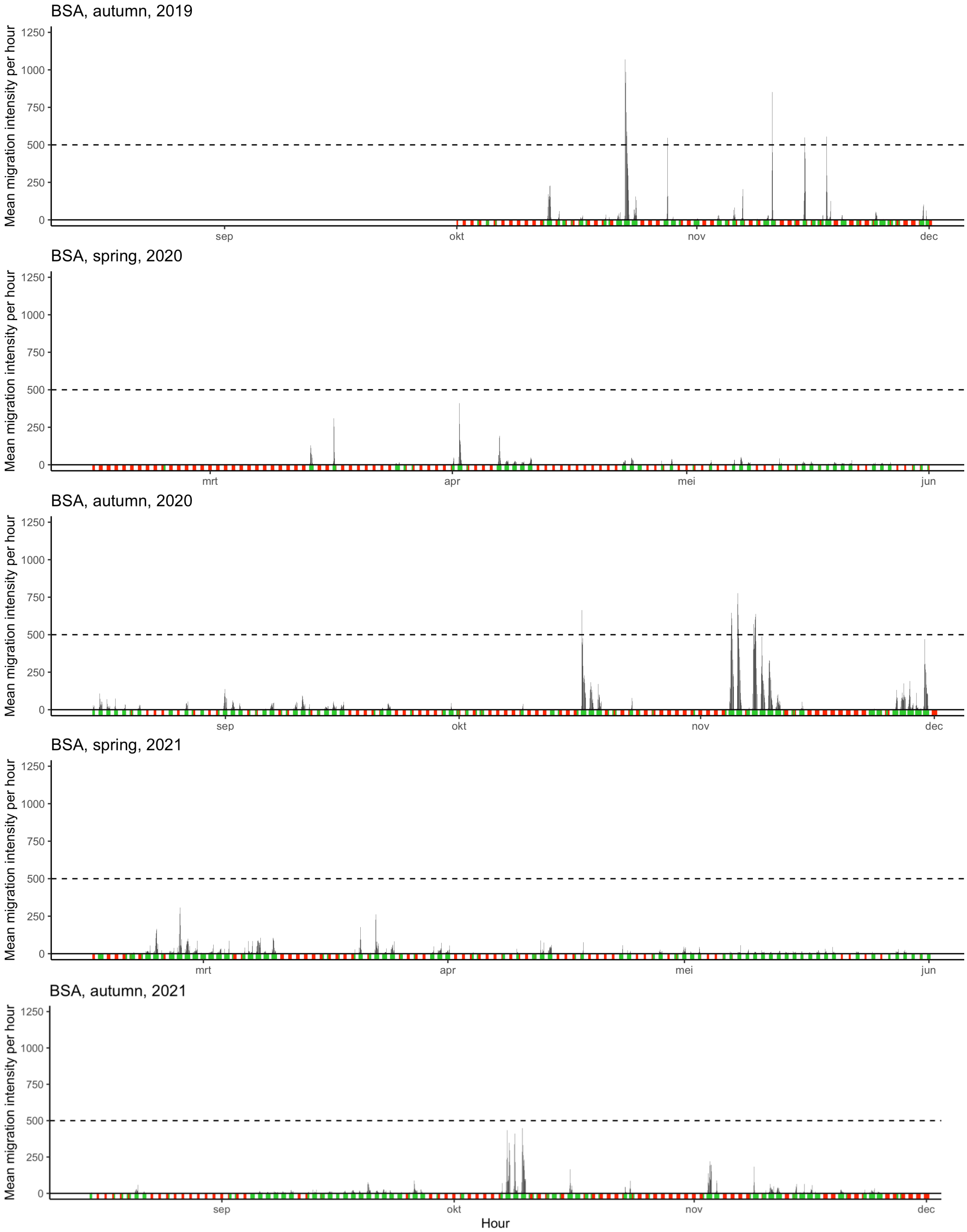


Figure 3.1 *Hourly migration intensity over time per season for Borssele. Green lines on the x-axis indicate nocturnal hours with radar data; red lines indicate nocturnal hours without radar data. The horizontal line represents the current threshold of 500 birds / km / hour.*

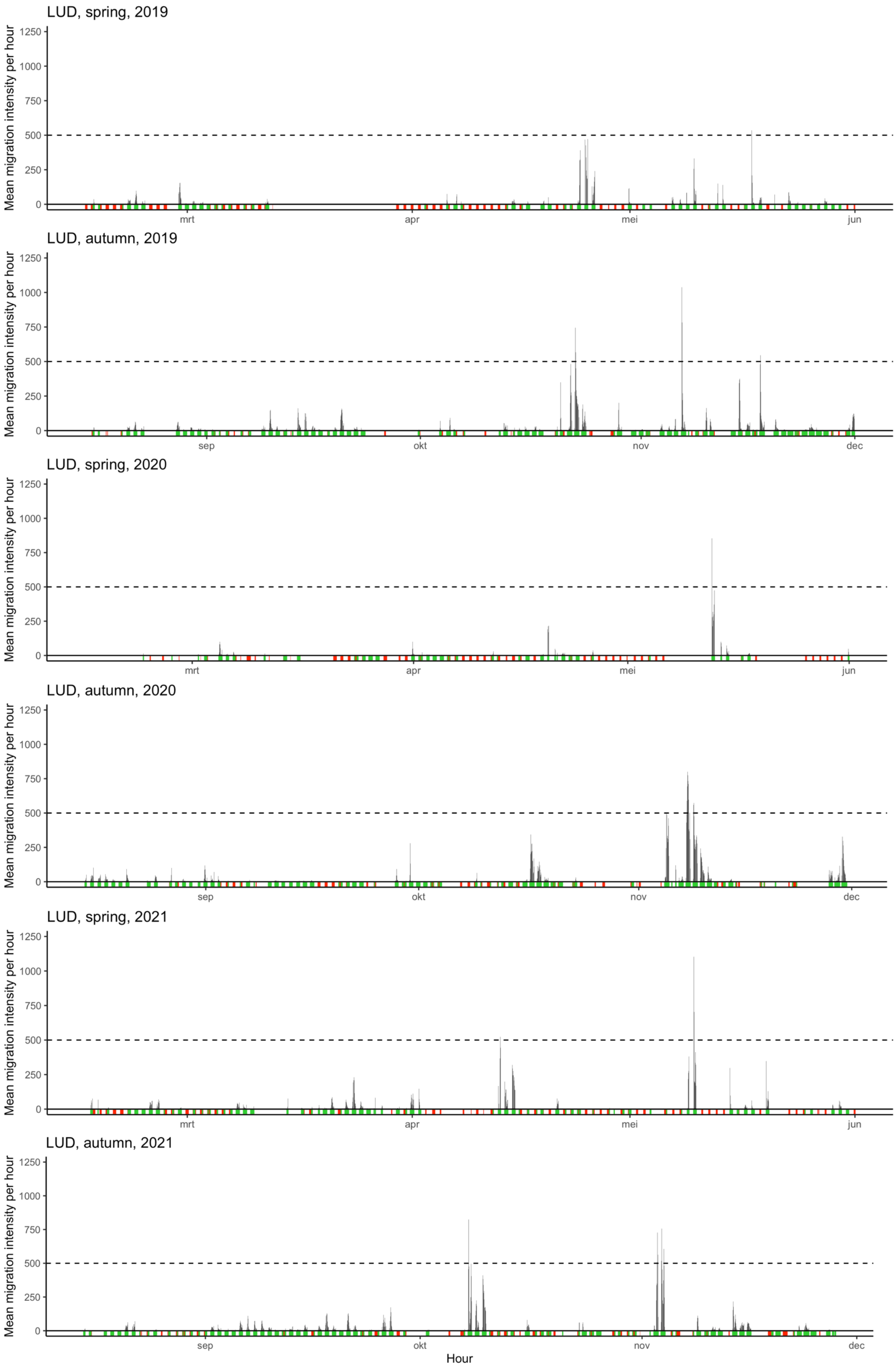


Figure 3.2 *Hourly migration intensity over time per season for Luchterduinen. Green lines on the x-axis indicate nocturnal hours with radar data; red lines indicate nocturnal hours without radar data. The horizontal line represents the current threshold of 500 birds / km / hour.*

Table 3.1 *Hours with migration intensity above 500 birds / km / hour in Borssele and/or Luchterduinen, with concurrent migration intensity on the other location. Bold numbers indicate MTRs above 500. Green shading represents hours with concurrent peaks on both locations. During several hours, no data were available for the other location. Some MTRs in Borssele, indicated with an asterisk (*), are remarkably low compared with Luchterduinen. During one night, MTRs were partly missing due to problems with the radar, which may have affected the measured MTR in the given hour as well (**).*

Season	Date and time	Maximum hourly MTR BSA	Maximum hourly MTR LUD
Spring 2019	17-05-2019 19:00	*no data*	**535**
Autumn 2019	22-10-2019 18:00	**1,070**	**745**
	22-10-2019 19:00	**913**	**567**
	22-10-2019 20:00	**987**	451
	22-10-2019 21:00	**717**	292
	22-10-2019 22:00	**559**	252
	22-10-2019 23:00	**590**	249
	28-10-2019 05:00	**547**	*no data*
	06-11-2019 17:00	*no data*	**1039**
	06-11-2019 18:00	*no data*	**782**
	10-11-2019 18:00	**852**	66
	14-11-2019 22:00	**549**	61
	17-11-2019 18:00	**555**	**545**
Spring 2020	12-05-2020 19:00	4 *	**854**
Autumn 2020	16-10-2020 18:00	**664**	200
	04-11-2020 22:00	495	**504**
	04-11-2020 23:00	**646**	486
	05-11-2020 00:00	**563**	318
	05-11-2020 01:00	**609**	332
	05-11-2020 18:00	**703**	*no data*
	05-11-2020 19:00	**776**	*no data*
	05-11-2020 20:00	**632**	*no data*
	05-11-2020 21:00	**537**	*no data*
	07-11-2020 19:00	**571**	**589**
	07-11-2020 20:00	496	**693**
	07-11-2020 21:00	406	**800**
	07-11-2020 22:00	437	**776**
	07-11-2020 23:00	**547**	**734**
	08-11-2020 00:00	**600**	**712**
	08-11-2020 01:00	**619**	**596**
	08-11-2020 02:00	**639**	381
	08-11-2020 04:00	275	**502**
	08-11-2020 17:00	7 *	**560**
	08-11-2020 18:00	107	**574**
Spring 2021	13-04-2021 03:00	18 *	**524**
	09-05-2021 19:00	6 *	**1102**
	09-05-2021 20:00	3 *	**703**
Autumn 2021	07-10-2021 19:00	232	**824**
	03-11-2021 03:00	90 **	**509**
	03-11-2021 04:00	197 **	**727**
	03-11-2021 05:00	195 **	**562**
	03-11-2021 17:00	*no data*	**517**
	03-11-2021 18:00	*no data*	**756**
	04-11-2021 01:00	*no data*	**607**

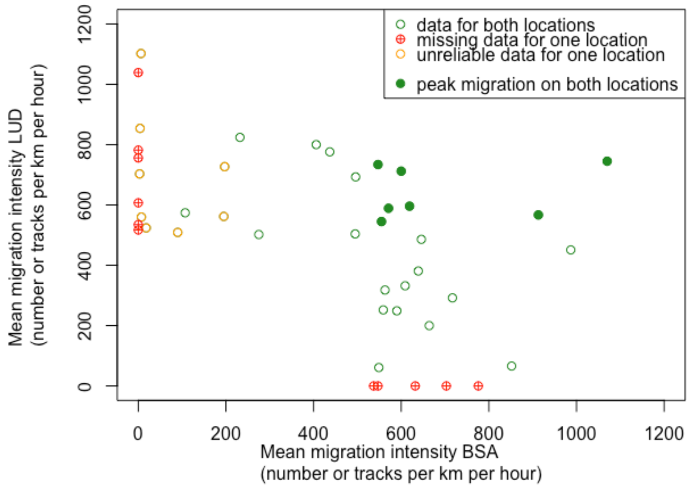


Figure 3.3 *Hours with migration intensity above 500 in either LUD or BSA, or on both locations.*

Comparison of frequency of peak migration between BSA, LUD and OWEZ

Number of hours above MTR threshold

While the frequency of peak migration is low during the spring season for both BSA and LUD, the frequency seems to differ between the two locations during the autumn season. For the autumn season, the percentage of hours with an MTR above 500 was higher for BSA than for LUD (Table 3.2, Table 3.4, Box 3.1). The frequency tables per location show that in the autumn seasons in BSA 1.7% of all measured hours have an MTR of 500 or higher (see column cumulative % hours idle), which equals to an extrapolated 24.9 hours per entire autumn season (corrected for missing data). In LUD, the percentage of hours reaching this MTR threshold of 500 is clearly lower, with only 0.5% of all hours above this threshold (extrapolated 7.1 hours per season). In the spring seasons, the percentage of hours with an MTR above 500 was (near) zero on both locations (0.1 and 0% for LUD resp. BSA).

In comparison, in OWEZ this threshold was reached in 0.3% of all measured hours (extrapolated 29 hours per year). Note that this percentage for OWEZ was based on the entire year (not only migration period), and not restricted to nocturnal hours. The percentage and absolute number of hours per year above the threshold of 500 are comparable between BSA and OWEZ (around 0.3% of all hours per year), but clearly lower in LUD (0.09%) (Box 3.1; Table 3.2).

Total flux during curtailment hours

In addition to the number of hours exceeding the MTR threshold, the total flux during these hours above the threshold can be compared. This total flux which can safely pass during curtailment is presented in the frequency tables (Box 3.1, Table 3.4: see column ‘nr of collisions prevented: cum. %’). At BSA, 14% of the total flux during the autumn migration occurred during hours with an MTR of 500 or higher. During spring migration, the threshold was never exceeded. At LUD, 6% of the total flux during the autumn migration occurred during hours with an MTR of 500 or higher. During spring migration, this was 1% of the total flux.

In comparison, in OWEZ, a total of 13.1 % of the nocturnal migration flux during both migration periods (spring and autumn combined) occurred during hours with an MTR of 500 or higher. Hence, with a threshold of 500, the percentage of the total flux during curtailment hours in BSA is relatively comparable with OWEZ, at least during the autumn season; for LUD, the percentage of the total flux during curtailment hours is lower. The potential causes of this contrasting finding for LUD are discussed in Chapter 4.1. Note that this may be ecological, as well as related to the radar specifications.

Note that this calculated flux during curtailment is based on measured MTRs, while curtailment will be based on the UvA model predicting MTRs in advance. Hence, the relation between predicted and measured MTRs needs to be studied. In general, peaks in migration intensity are expected to be underestimated by the predictive model. This means that the threshold to be used within the predictive model will need to be adjusted based on a comparison between predicted and measured MTRs. Without such an adjustment, the predicted MTRs would regularly not meet the threshold, while the measured MTRs (in hindsight) do exceed the threshold. In addition to this adjustment of the threshold value, the use of predicted instead of measured MTRs will reduce the efficiency of curtailment, depending on the predictability of periods with peak migration.

Box 3.1: Interpretation Table 3.4 Each table presents the results for one location and for either autumn or spring. Each row indicates a flux class, given as the number of tracks / km / hour (MTR).

Number and percentage of hours above a given threshold
When looking at LUD autumn, the dataset contains 17 + 5 + 1 = 23 hours with an MTR above 500. This includes three autumn seasons, and is uncorrected for missing data. After correction for missing data, the extrapolated number of hours per season is 7.1 (see hours idle, cumulative; this is the same as the sum of the the fourth column for the flux classes above 500), representing 0.5% of all hours.

Number and percentage of avoided collisions
In order to calculated the number of avoided collisions per flux class, the first step was to calculate the collision estimate (nr / hour / wind turbine). This collision estimate was based on the turbine specifications of BSA, as these are likely to be the most similar with the OWFs for which the current curtailment procedure will be implemented in the future (see Paragraph 2.1 for more details). This collision estimate in combination with the mean flux per flux class and the extrapolated number of hours in one season results in the number of collisions prevented when curtailment occurs during each particular flux class. For example, if curtailment is assumed above an MTR of 500, the first three rows are of interest:

- Extrapolated number of hours with an MTR above 1000 = 0.3; collision estimate for this class is 0.0647 victims / hour / turbine; mean flux for this flux class = 1039; this results in 0.020 victims prevented per season for this flux class when curtailment occurs for this flux class

- Extrapolated number of hours with an MTR between 750 and 1000 = 1.5; collision estimate for this class is 0.0503 victims / hour / turbine; mean flux for this flux class = 787.6; this results in 0.077 victims prevented per season for this flux class when curtailment occurs for this flux class. Combined with the higher flux class with an MTR above 1000, the cumulative number of collisions prevented is 0.097 victims / turbine per season (see column 'cumulative number per season').

- Extrapolated number of hours with an MTR between 500 and 750 = 5.2; collision estimate for this class is 0.036 victims / hour / turbine; with a mean flux for this flux class of 602.4, this results in 0.188 victims prevented per season for this flux class when curtailment occurs for this flux class. Combined with the higher flux classes with an MTR above 750, the cumulative number of collisions prevented is 0.285 victims / turbine per season (see column 'cumulative number per season').

This means that when **for the autumn season in LUD** curtailment is assumed for all hours for which the (measured) MTR was above **500**, 0.285 collisions would have been prevented per turbine per season, accounting for 6% of the total flux during nighttime hours in the autumn season.

Table 3.2 *Comparison of frequency of exceeding threshold MTR (500 birds / km / hour) between LUD, BSA and OWEZ. Due to differences in data selection, season-specific data from LUD and BSA are first combined to include both seasons, which gives a more relevant comparison with OWEZ.*

Location and period	**Extrapolated number of hours with MTR above 500 per period (corrected for missing data)**	**Percentage of hours with MTR above 500**
LUD autumn	7.1	0.5 %
BSA autumn	24.6	1.7 %
LUD spring	1.2	0.1 %
BSA spring	0	0 %
LUD both seasons	**8.3**	0.28% of nocturnal hours during migration 8.3/(24*365) = **0.09%** of entire year (day+night)
BSA both seasons	**24.6**	0.77% of nocturnal hours during migration 24.6/(24*365) = **0.28%** of entire year (day+night)
OWEZ entire year	**29**	**0.3%** of entire year (day+night)

Table 3.3 *Frequency table for OWEZ. Source: Krijgsveld* et al. *(2015). Note that this table is based on the entire year, in contrast to Table 3.4 which is based on nocturnal data during the migration seasons.*

flux class (nr/km/hr)	nr hours /year	% time	coll.estimate nr/h/WT	nr collisions prevented nr/yr/WT	nr/yr/OWEZ (=36 WT) mean	min- max	cum.%	cum.time idle nr hrs /yr	%time	wind speed (Bft)
1000-1250	1,8	0,02	0,0550	0,1	2,6	2,0 - 3,3	0,4	1,8	0,0	4,6
750-1000	9	0,10	0,0428	0,3	9,8	7,3 - 12	1,7	11	0,1	5,0
500-750	19	0,2	0,0306	0,4	15	11 - 19	3,8	29	0,3	4,8
250-500	109	1,3	0,0183	1,5	53	40 - 66	11	139	1,6	4,2
100-250	538	6,1	0,0086	3,4	121	91 - 151	28	676	7,7	4,1
0-100	8084	92	0,0024	14	519	389 - 649	100	8760	100	4,1
Total				20	720	540 - 900				

Table 3.4 Frequency tables per location for autumn and spring. The percentage of hours per flux class in the dataset is extrapolated to give the number of hours for each flux class for one entire autumn or spring season. The collision estimates per flux class are based on the specifications of BSA turbines (for BSA as well as LUD). In combination with the mean flux per flux class and the extrapolated number of hours in one season, this results in the number of collisions prevented when curtailment occurs during each particular flux class. In the second grey box, the cumulative number and cumulative percentage indicate the collisions prevented when curtailment occurs in that particular flux class and all higher fluxes. The column hours idle presents the number and percentage of curtailment hours when curtailment is activated in that particular flux class and all higher fluxes. For each flux class, the average wind speed is presented. See Box 3.1 for further explanation.

LUD autumn (2019, 2020, 2021)

flux class (nr/ km / hr)	nr hours in dataset	% hours	nr hours extrapolated to 1 autumn season LUD	collision estimate (nr / hr / WT)	mean flux per class	nr of collisions prevented			hours idle		mean wind speed (m/s)
						per flux class per WT per season	cumulative number per season	cum. %	cumulative nr hours idle per season	cumulative % hours idle	
> 1000	1	0.02%	0.3	0.0647	1039	0.020	0.020	0%	0.3	0.02%	NA
750-1000	5	0.10%	1.5	0.0503	787.6	0.077	0.097	2%	1.8	0.12%	2.9
500-750	17	0.35%	5.2	0.036	602.4	0.188	0.285	6%	7.1	0.5%	3.8
250-500	58	1.2%	17.8	0.0216	354.8	0.385	0.671	13%	24.9	1.7%	4.1
100-250	112	2.3%	34.4	0.0101	158	0.348	1.019	20%	59.3	4.0%	4.1
0-100	4659	96%	1432.7	0.0029	5.7	4.155	5.173	100%	1492	100%	7.2

BSA autumn (part of 2019, 2020, 2021)

flux class (nr/ km / hr)	nr hours in dataset	% hours	nr hours extrapolated to 1 autumn season BSA	collision estimate (nr / hr / WT)	mean flux per class	nr of collisions prevented			hours idle		mean wind speed (m/s)
						per flux class per WT per season	cumulative number per season	cum. %	cumulative nr hours idle per season	cumulative % hours idle	
> 1000	1	0.07%	1.1	0.0647	1070	0.069	0.069	1%	1.1	0.07%	NA
750-1000	4	0.29%	4.3	0.0503	882	0.215	0.285	4%	5.4	0.36%	1.3
500-750	18	1.29%	19.3	0.036	602.6	0.694	0.979	14%	24.6	1.7%	3.1
250-500	47	3.4%	50.3	0.0216	373.7	1.087	2.066	30%	75.0	5.0%	4.1
100-250	96	6.9%	102.8	0.0101	164.4	1.039	3.105	45%	177.8	11.9%	3.7
0-100	1227	88%	1314.2	0.0029	15.9	3.811	6.916	100%	1492	100%	5.2

LUD spring (2019, 2020, 2021)

flux class (nr/ km / hr)	nr hours in dataset	% hours	nr hours extrapolated to 1 spring season LUD	collision estimate (nr / hr / WT)	mean flux per class	nr of collisions prevented			hours idle		mean wind speed (m/s)
						per flux class per WT per season	cumulative number per season	cum. %	cumulative nr hours idle per season	cumulative % hours idle	
> 1000	1	0.02%	0.2	0.0647	1102	0.016	0.016	0%	0.2	0.02%	3.9
750-1000	1	0.02%	0.2	0.0503	854.5	0.012	0.028	1%	0.5	0.04%	6.9
500-750	3	0.06%	0.7	0.036	587.3	0.026	0.054	1%	1.2	0.1%	4.8
250-500	29	0.6%	7.1	0.0216	342.8	0.153	0.208	5%	8.3	0.7%	7.3
100-250	53	1.0%	13.0	0.0101	169.9	0.131	0.338	9%	21.3	1.7%	6.9
0-100	4967	98%	1213.7	0.0029	2.6	3.520	3.858	100%	1235	100%	7.7

BSA spring (2020, 2021)

flux class (nr/ km / hr)	nr hours in dataset	% hours	nr hours extrapolated to 1 spring season BSA	collision estimate (nr / hr / WT)	mean flux per class	nr of collisions prevented			hours idle		mean wind speed (m/s)
						per flux class per WT per season	cumulative number per season	cum. %	cumulative nr hours idle per season	cumulative % hours idle	
> 1000	0	0.00%	0.0	0.0647	NA	0.000	0.000	0%	0.0	0.00%	NA
750-1000	0	0.00%	0.0	0.0503	NA	0.000	0.000	0%	0.0	0.00%	NA
500-750	0	0.00%	0.0	0.036	NA	0.000	0.000	0%	0.0	0.0%	NA
250-500	7	0.8%	9.8	0.0216	297.2	0.212	0.212	5%	9.8	0.8%	4
100-250	17	1.9%	23.8	0.0101	151.4	0.241	0.453	11%	33.6	2.7%	4.2
0-100	857	97%	1201.4	0.0029	15.9	3.484	3.937	100%	1235	100%	6.7

3.2 Relation between wind speed, bird flux and turbine power

Bird flux was highest at lower wind speeds (Figure 3.4). Most hours with migration intensities > 100 birds/km/h occurred at wind speeds between 2 and 8 m/s, with a peak at 4 m/s (Figure 3.4c). The proportion of the nocturnal flux when mean wind speed was below 3 m/s (thus when no wind energy is generated) was 19%. Due to the fact that most birds migrate at low windspeed, the PCA (% collisions avoided, assumed to be proportional to % flux during curtailment) was especially sensitive to the threshold at low wind speeds, less so at intermediate wind speeds, and largely insensitive to the threshold at strong winds.

We explored a range of fractions of the total flux, from 20% to 90% (note that 19% of the MTR occurred at wind speeds of 3 m/s or lower, when turbines are not generating power) (Figure 3.5). We show that for a PCA up to 50-60%, the increase in power loss is relatively low (Figure 3.5a and b). This means that a more cautious approach can be taken by requiring a higher PCA (i.e. curtailment during a higher percentage of the flux), with relatively low power loss.

At a PCA of 30%, power loss started at 11 MWh (representing 0.06% uncorrected and 0.05% corrected (extrapolated for hours without data on MTR)), increasing slowly to 545 MWh (representing 2.84% uncorrected and 1.65% corrected) at a PCA of 70%. At higher PCAs, power loss increased faster, due to lower thresholds at higher wind speeds. At 90%, power loss started at 2294 MWh (representing 11.96% uncorrected and 6.14% corrected).

In Figure 3.5c, three points above each other always represent one combination of thresholds for the PCA given on the x-axis. Moreover, open points indicate that within the used dataset there were no hours with an MTR higher than the indicated value for the wind speed category shown. This means that using that specific threshold would result in no curtailment for that wind speed category (900 birds / km /h for intermediate winds and 500 birds / km /h for strong winds). In other words, if the aim is a PCA of 30% (30 on the x-axis), the threshold combination with the lowest power loss is represented by a threshold for curtailment during low winds of 400 birds / km /h, and setting no threshold for intermediate and strong winds.

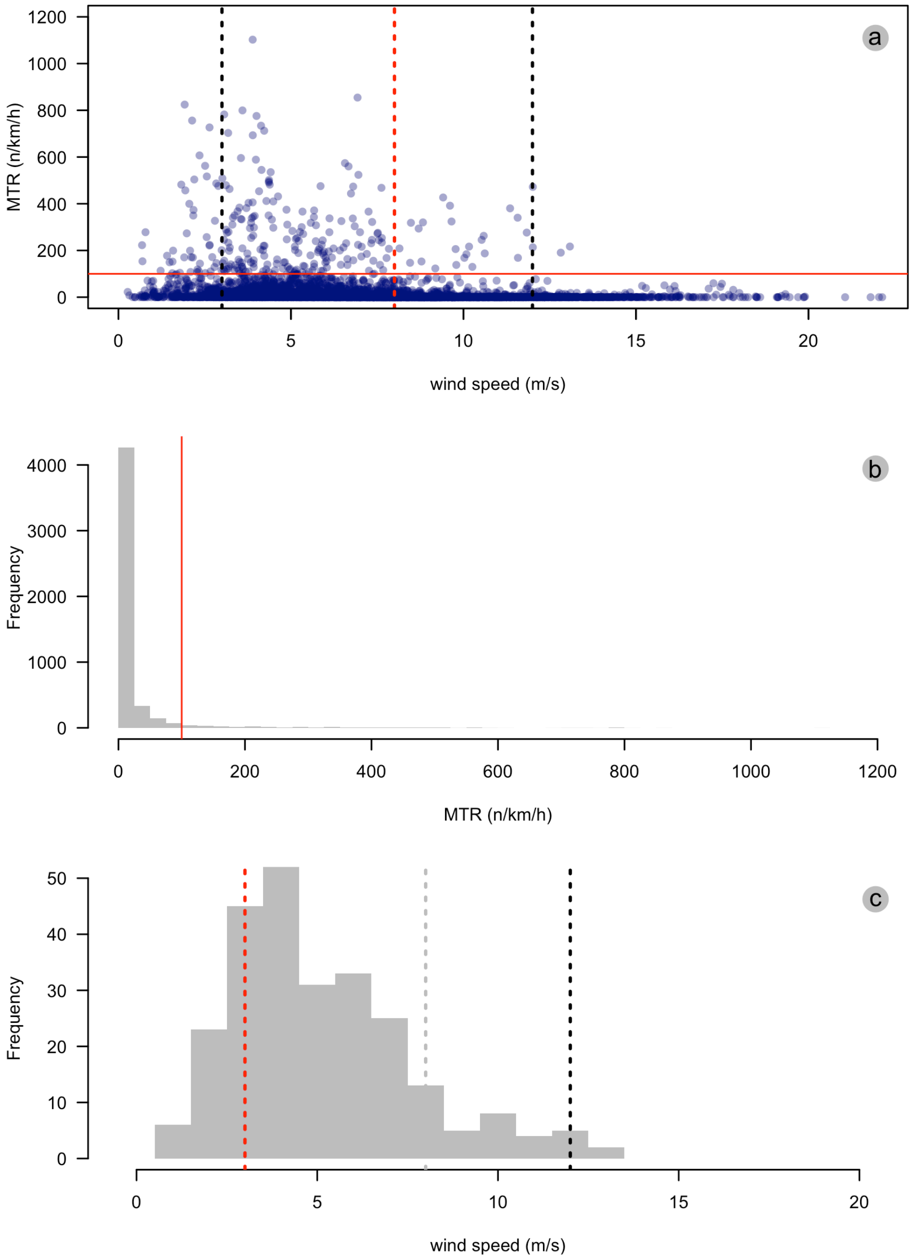


Figure 3.4 *a) Hourly bird flux (MTR) as a function of wind speed. The horizontal solid line at 100 birds/km/h marks the selection used for the histogram in the next figure, see subplot b. The vertical dotted lines mark the wind speed of 3 m/s, from which turbines start generating power and 11 m/s, from which turbines reach their maximum power. The red vertical line shows an example border between the lower and intermediate wind speed categories. b) Distribution of MTR, showing that the far majority hourly MTR are below 100 birds/km/h. c) Distribution of wind speeds during hours with high intensity, arbitrarily defined as hours with MTR values above 200. The red vertical dotted line marks the wind speed of 3 m/s, from which turbines start generate power. The black vertical lines show the borders between the wind speed categories for which separate thresholds are defined.*

Only the threshold combinations with the lowest power loss per PCA level were used to construct Figure 3.5. We aimed to assess the sensitivity of the PCA and power loss to slightly different threshold values. To explore this, we plotted the 25 models with the lowest power loss against their power loss and threshold levels within each wind category (Figure 3.7). At a PCA value of 30%, the 25 threshold combinations leading to the lowest power losses result in similar power losses and have the same threshold value at low wind speeds (400 birds/km/h). The division between the wind speed categories varied between 5 or 6 m/s, and this, in combination with certain thresholds at intermediate and strong winds, led to higher PCAs. More variation can be seen among the 25 threshold combinations resulting in PCAs of 70% or higher, although again the threshold at low winds was invariable, this time at 100 birds/km/h. The division between the wind speed categories appeared to have a stronger effect here, with the division at 8-9 m/s for the best few threshold combinations but varying down to 5 m/s for less profitable threshold combinations. At PCAs of 90% or higher, curtailment would always occur at low winds speeds of up to 6 or 7 m/s. This step to 7 m/s also incurred substantially higher power losses, while increasing the PCA only marginally. The threshold at intermediate wind speeds was fairly stable at 100 or 200 birds/km/h. At all PCA values, the threshold at strong winds (>11 m/s) had little effect on the PCA or the lost power. This is because no or very few hours occurred with a MTR higher than 500 birds/km/h (PCA >= 30%) or 100 birds/km/h (PCA >= 70%).

Box 3.2: Interpretation of Figure 3.5 and 3.6

The threshold combinations and the division between the lower (‘min’, 3-x m/s) and intermediate (‘int’, x – 11m/s) wind speeds that result in the lowest power loss are shown for aimed percentages of avoided collisions between 20 and 90%, in steps of 5%.

For example, if one would aim to avoid 30% of the collisions while minimizing the power loss, the division between the lower and intermediate wind speeds should be set at 6 m/s and the thresholds at the lower (3-6 m/s), intermediate (6-11 m/s) and strong (>11 m/s) wind speeds at 400, 900 and 500 birds/km/h, respectively.

Note that there were no hours in the data with wind intermediate and strong winds that exceeded these thresholds. This means that, when aiming for a PCA of 30% and chosing for this option with the lowest power loss, based on the current dataset no curtailment takes place at intermediate and high wind speeds (and 0 collisions are avoided during these wind speeds). The threshold at the lower wind speeds results in 14,979 birds passing by during curtailment. Adding the flux during winds below 3 m/s results in a total of 32,593 birds passing by during times that the turbines are not active (either due to low winds or due to curtailment). This flux represents 30% of the total number of birds that were registrered during the entire study period; hence the PCA of 30%.

This combination of thresholds for a PCA of 30% would, based on the current dataset, result in power loss only during low wind speed (3-6 m/s). Based on these data, the power loss is 11 MWh for a single turbine. In total, the curtailment to achieve a PCA of 30% while minimizing power loss would represent 26 hours for the entire time period (spring + autumn migration, 2019-2021), or 1.6% of the time.

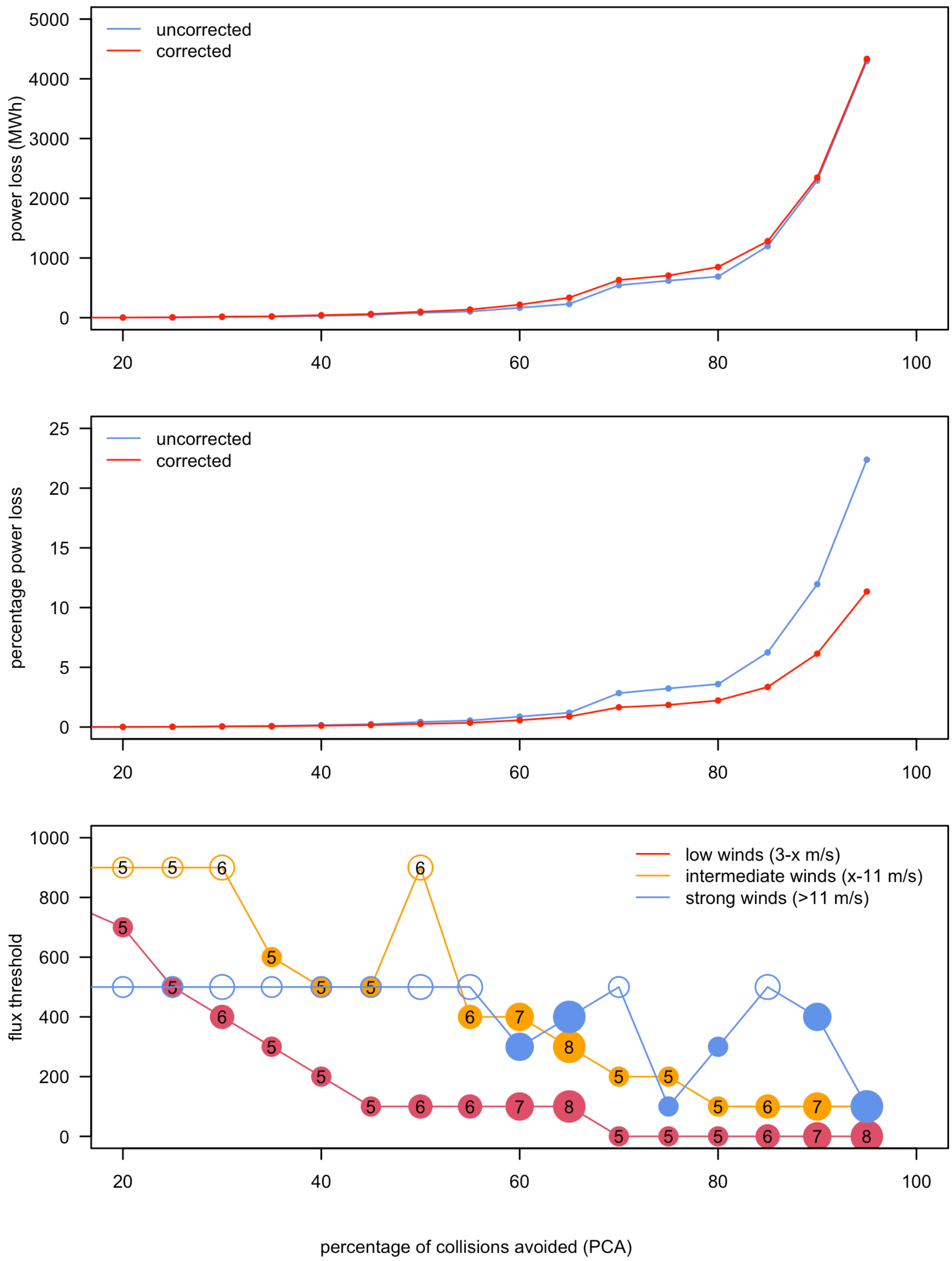


Figure 3.5 *Relation between percentage collisions avoided (PCA; x-axis) and a) power loss, b) percentage of power loss and c) the flux thresholds per wind speed category. In a) and b), the uncorrected power loss (blue) is calculated across hours with MTR data, the corrected power loss (red) extrapolates the percentage of curtailment hours across the nighttime hours with wind speed data. In c), the boundary between the lower and intermediate wind speed categories ('x' in legend) is depicted in the dots and also reflected in the dot size. Open dots indicate that the threshold exceeds the maximum observed MTR, meaning no curtailment at the corresponding wind speeds. Thresholds at the low, intermediate and strong wind speeds need to be combined (vertically) to arrive at the PCA shown on the x-axis. Note that the first 19% of the flux passed at wind speeds below 3 m/s, when no wind energy is generated and therefore no curtailment is required.*

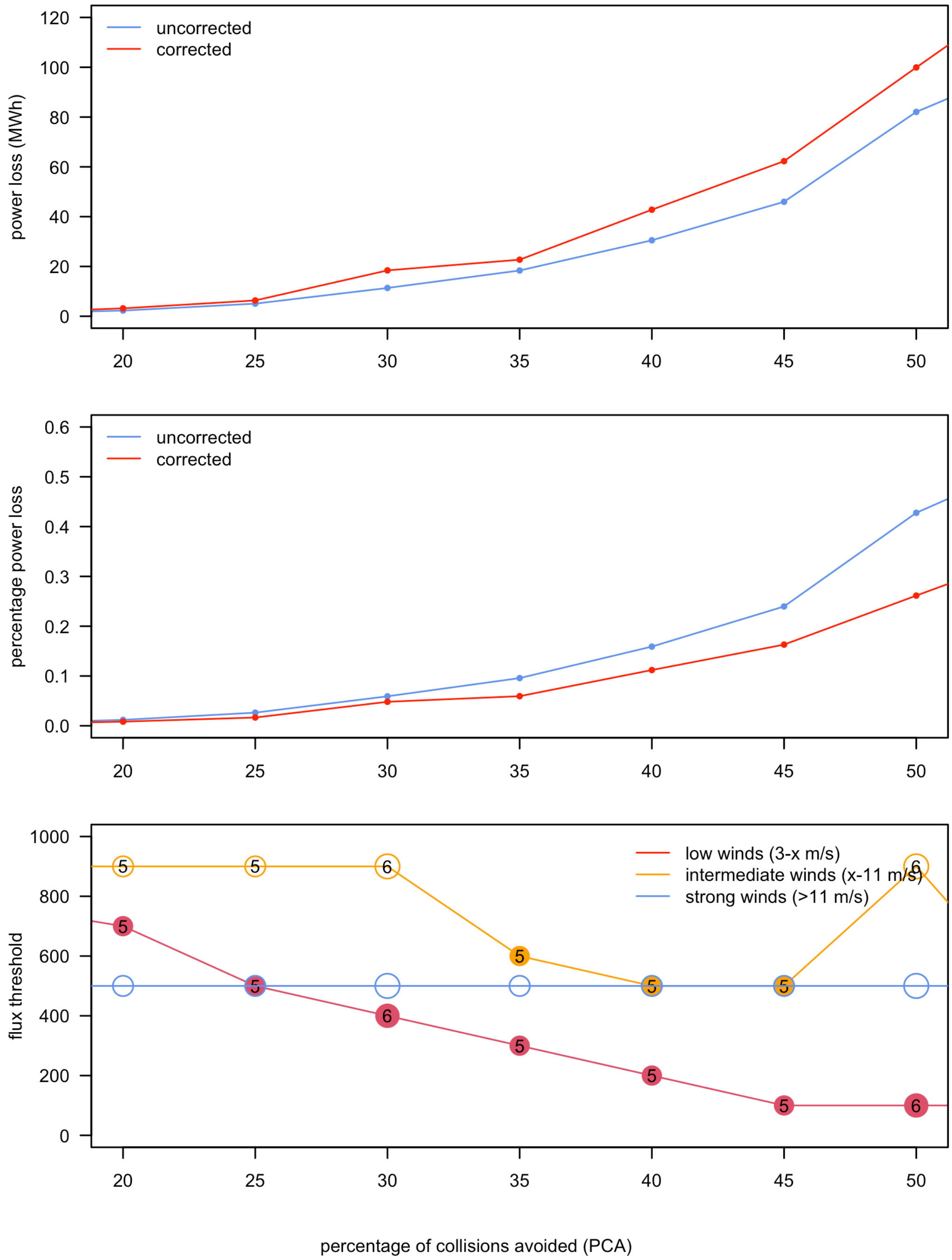


Figure 3.6 Repeat of figure 3.5, zooming in on the PCA range of 20-50%.

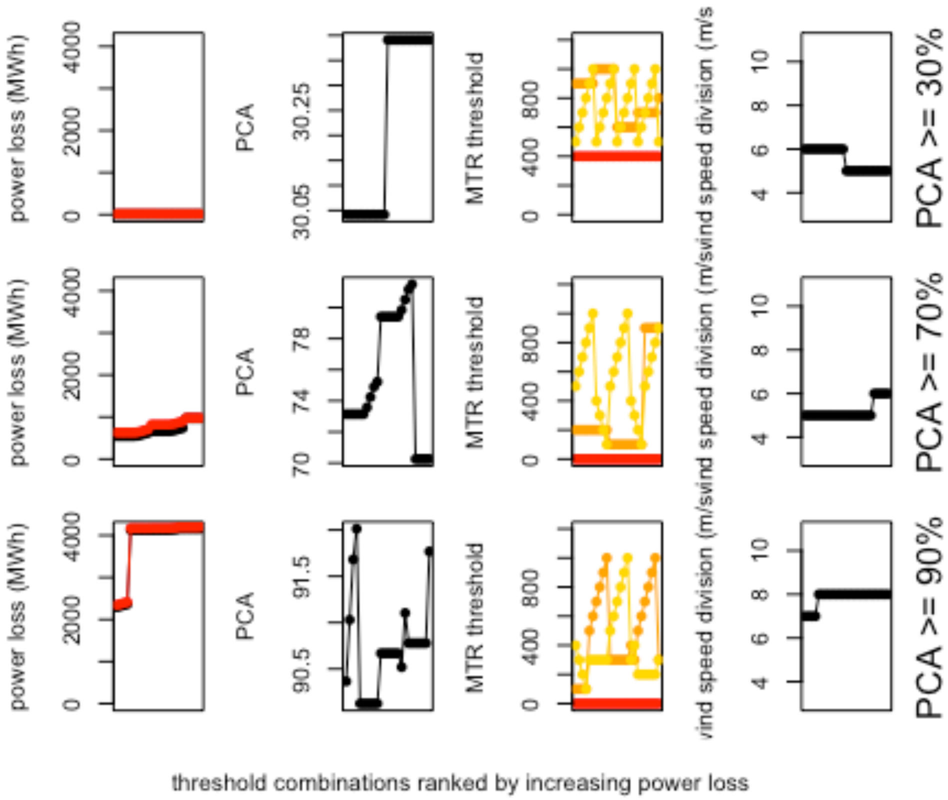


Figure 3.7 *Variation in threshold levels and the division between wind categories among the 25 models with the lowest power loss, at selected PCA values of 30% (upper row), 70% (middle row) and 90% (lowest row). From left to right: lost power, PCA, threshold levels per wind speed category and the division between the low and intermediate wind speed categories.*

Table 3.5 *The threshold combinations as well as the division between wind speed categories resulting in the lowest power loss for each PCA of 13.1% or between 20% and 90% in steps of 5%. Min, int and max refer to the wind speed categories, see figure 2.1. Note that the thresholds for intermediate and strong wind speeds are in most cases so high that no or very few hours had MTR values that exceeded these thresholds. Note that the number of hours refers to the entire dataset used, hence spring and autumn 2019-2021.*

PCA	wind speed divide (m/s)	flux threshold (n/birds/h)			sum flux during curtailment hours (n/km)				power loss for one turbine (MWh)				percentage hours curtailment			n hours curtailment (spring + autumn 2019-2021)
		min	int	max	min	int	max	total	min	int	max	total	min	int	max	
13	5	800	900	500	1,102	0	0	18,717	0	0	0	0	0.1	0.0	0.0	1
20	5	700	900	500	5,609	0	0	23,223	2	0	0	2	0.7	0.0	0.0	7
25	5	500	900	500	9,577	0	0	27,191	5	0	0	5	1.4	0.0	0.0	14
30	6	400	900	500	14,979	0	0	32,593	11	0	0	11	1.6	0.0	0.0	26
35	5	300	600	500	20,019	854	0	38,488	16	2	0	18	4.2	0.0	0.0	42
40	5	200	500	500	24,263	2,512	0	44,389	22	9	0	31	6.0	0.1	0.0	62
45	5	100	500	500	30,057	2,512	0	50,183	37	9	0	46	10.5	0.1	0.0	105
50	6	100	900	500	38,456	0	0	56,070	82	0	0	82	8.9	0.0	0.0	141
55	6	100	400	500	38,456	4,324	0	60,394	82	22	0	104	8.9	0.2	0.0	149
60	7	100	400	300	45,957	895	1,193	65,658	130	9	28	167	7.3	0.1	0.1	171
65	8	100	300	400	50,720	1,781	472	70,587	192	29	10	230	6.2	0.2	0.0	193
70	5	0	200	500	43,431	18,310	0	79,355	386	159	0	545	88.6	1.4	0.0	915
75	5	0	200	100	43,431	18,310	2,259	81,614	386	159	75	620	88.6	1.4	0.4	923
80	5	0	100	300	43,431	25,108	1,193	87,345	386	276	28	689	88.6	2.6	0.1	964
85	6	0	100	500	58,605	16,708	0	92,928	968	231	0	1,199	87.4	1.9	0.0	1,446
90	7	0	100	400	70,745	9,208	472	98,039	2,102	183	10	2,294	86.9	1.4	0.0	2,007
95	8	0	100	100	78,973	4,444	2,259	103,290	4,099	121	75	4,295	86.5	0.9	0.4	2,645

4 Conclusions and discussion

Our exploration of the relation between wind speed, bird migration and power from offshore wind turbines shows how power loss and the percentage of avoided bird collisions are related to potential threshold combinations at different wind speeds.

4.1 Variation between OWFs

The first goal of this research was to explore the temporal and spatial variation in migration intensity between two different offshore windfarm locations: Borssele (BSA) and Luchterduinen (LUD). In addition, the frequency distribution of MTRs is compared to an earlier analysis from offshore windfarm Egmond aan Zee (OWEZ) (Krijsveld *et al.* 2015).

Hours with peak migration in Borssele and in Luchterduinen do not always coincide. Although during a peak hour in LUD in most cases the MTR shows a peak in BSA as well, the other way around this is not the case. During a peak in BSA, the MTR in LUD is relatively variable. To allow comparison with OWEZ, we defined peak migration here as hours with an MTR above 500 birds/km/h. For the autumn season, the percentage of hours with an MTR above 500 birds/km/h was higher for BSA (1.7% of measured hours) than for LUD (0.5% of measured hours). In the spring seasons, the percentage of hours with an MTR above 500 is low on both locations (0.1 and 0% for LUD resp. BSA). Over an entire year, the percentage and absolute number of hours above the threshold of 500 birds/km/h are comparable between BSA and OWEZ (around 0.3% of all hours per year, extrapolated to resp. 24.6 and 29 hours for both migratory seasons per year), but clearly lower in LUD (0.09%, extrapolated to 8.3 hours for both migratory seasons per year). In comparison, based on vertical radar measurements in the Belgian C-Power wind farm, directly adjacent to BSA, the MTR exceeded the threshold of 500 birds/km/h during 14 hours in autumn 2019 (Brabant *et al.* 2022). Note that this was for one autumn season only. In autumn 2019, we measured 10 hours above an MTR of 500 birds/km/h in BSA.

Several factors may result in a difference in measured migration intensity between the two locations, including factors related to the spatio-temporal variation in migration intensity and direction, as well as methodological differences between the sites. The extent of east-west migration may differ between the two locations. In addition, the migration intensity from north-south migration does not necessarily have to be similar between locations along the migration route due to, e.g., different distances to potential departure locations and destinations, causing birds to be more spread out at a different location.

Radar measurements in the Belgian C-Power wind farm show a comparable temporal pattern for autumn 2019 and spring 2021 to our results for BSA with peaks in migration intensity in October (Brabant *et al.* 2022). Peaks measured in BSA were also measured in the C-Power wind farm. However, during two nights when the radar in BSA was not functioning resulting in no available flux data, a peak (MTR>500) was measured in the C-Power wind farm. This shows that, as mentioned previously, it is indeed likely that peaks in migration intensity could be missed in periods of radar malfunctioning.

Moreover, some of the differences may be caused by the differences in radar setup or data filtering. In particular, the radar in BSA is located higher than in LUD, which may affect the filtering process of the radar. In addition, the UvA performed additional filtering steps after downloading the data for LUD in order to remove non-bird tracks from the database, while this additional filtering was not carried out for BSA. This means that the proportion non-bird tracks in the BSA database may be higher than for LUD. However, the effect of this post-downloading data filtering is expected to be smaller than differences in radar setup. These differences in radar setup data filtering should be kept in mind when comparing radar data between locations. When in the future more radars are installed in wind farms for monitoring bird migration, it could be good to strive for identical radar setups in different wind farms. In addition, it would be good to investigate whether differences in bird migration are mainly due to ecological (i.e. migration pathways) or radar technical (i.e. settings, location etc.) reasons. Note that, when looking at temporal variation at one location, as is the case for the predictive model from the UvA (Bradarić *et al.,* in prep), the technical settings remain the same. Even though a filtering mechanism responds to rain and wave clutter during strong winds, peaks in migration intensity are less likely to occur in those weather conditions. This means that temporal variation at one location is likely to be reliable. Whether this temporal pattern, and the resulting curtailment procedure based on one location, is realistic for the entire spatial scale of the North Sea should be further evaluated.

Given the difference in timing of peak migration between the Borssele and Luchterduinen offshore wind farms, it may be good to consider spatio-temporal variation in migration intensity models in order to arrive at realistic regional estimates for short curtailments.

4.2 Curtailment rules

The second goal of this research was to explore the relation between migration intensity and wind speed for LUD, and based on the results explore whether curtailment rules can be optimized by minimizing the lost energy generation for varying percentages of collisions avoided.

Generally, curtailments during low wind speeds yield the largest gain in the percentage of avoided bird collisions (PCA) and a relative low loss in power yield. Hence, thresholds per wind category may be preferred to a single, overall threshold for curtailment, as curtailment during hours with low wind speed will lead to a lower loss of energy yield than during high wind speeds.

For some PCAs, the threshold combinations leading to the lowest power loss include thresholds that are above the maximum recorded MTR for the corresponding wind speeds (open dots Figure 3.5c). Thus, in these cases, no hours exceeded this threshold, meaning no curtailment was effectively imposed. *With the current data set*, this is equivalent to not resulting in curtailment for the wind speeds concerned. However, higher MTRs during those wind speeds than are currently in the data set can occur in the future, which may make other threshold combinations more profitable (at that PCA value) in terms of power loss than the currently proposed. This means that a larger dataset might be a reason to reassess optimal threshold(s).

Note that this calculated flux during curtailment is based on measured MTRs, while curtailment will be based on the UvA model predicting MTRs in advance. Hence, the relation between predicted and measured MTRs needs to be studied. In general, peaks in migration intensity are expected to be underestimated by the predictive model (Bradarić *et al.,* in prep). This means that the threshold to be used within the predictive model will need to be adjusted based on a comparison between predicted and measured MTRs. Without such an adjustment, the predicted MTRs would regularly not meet the threshold, while the measured MTRs (in hindsight) could exceed the threshold. In addition to this adjustment of the threshold value, the use of predicted instead of measured MTRs will reduce the efficiency of curtailment, depending on the predictability of periods with peak migration.

What percentage of bird collisions should be avoided? This is a decision to be made by policy-makers. From a legislative point of view, the aim is to ensure population viability of the species involved. However, note that radar data renders generic rather than species-specific information on migration intensity. Hence, no assessments can be made of the species-level effect of increased mortality due to collisions with offshore wind farms. Likewise, no species-level effects can be inferred for the earlier proposal of 13.1% either (recalculated from Krijgsveld *et al.* 2015), which is the basis for current proposal of the Dutch ministries of Economic Affairs (EZK) and Agriculture, Nature and Food Quality (LNV) for curtailment above a threshold migration intensity of 500 birds/km/h. Based on this study, the aim remains to curtail during peaks in migration intensity. Potentially, the threshold above which curtailment should occur can be varied between wind speed categories, which can optimize the relation between percentage avoided bird collisions and power loss.

The choice of required percentage of avoided bird collisions may not only depend on the power loss, but also on the relationship between the percentage of avoided bird collisions and the power loss. We show that for a percentage of avoided bird collisions up to 50-60%, the increase in power loss is relatively low. This means that a more cautious approach can be taken by requiring a higher percentage of avoided bird collisions (i.e. curtailment during a higher percentage of the flux) at relatively low additional power losses.

4.3 Recommendations

Influence of variation in years and seasons

In our study, we grouped data across several years. Alternatively, years or seasons could be analyzed separately to illustrate the variation between years in migration intensities. Furthermore, by applying the same thresholds for spring and autumn, the assumption is made that a certain percentage of collisions has the same effect on population viability on either season. However, a much larger share of the migrating individuals in autumn are juveniles, which have a considerably lower life expectancy than adults. Therefore, overall survival rates in spring will have a larger effect on population viability.

Influence of model uncertainties

The current study is based on actual measurements of bird migration and wind speeds, but the decision for curtailments will be informed by the predictive bird migration model which was recently finalized by UvA (Bradarić *et al.,* in prep). Models may underestimate bird migration intensities, but such uncertainties are not included in our assessment as it was based on actual measurements. While we were not able to explore the model yet, it is unclear how uncertainty in the model predictions would lead to differences in the percentage of avoided bird collisions and power loss compared to our study. In addition, defining thresholds that ensure that a pre-set goal of a certain percentage of avoided collisions is reached could be accompanied by a detailed assessment of the predictive accuracy of the UvA model to either select more or less cautious combinations of thresholds.

References

Brabant, R., B. Rumes, S. Degraer, 2021. Occurrence of intense bird migration events at rotor height in Belgian offshore wind farms and curtailment as possible mitigation to reduce collision risk, in: Degraer, S. et al. Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Attraction, avoidance and habitat use at various spatial scales. Memoirs on the Marine Environment: pp. 47-60

Bradarić, M., W. Bouten, R.C. Fijn, K.L. Krijgsveld & J. Shamoun-Baranes, 2020. Winds at departure shape seasonal patterns of nocturnal bird migration over the North Sea. Journal of Avian Biology 51(10): doi: 10.1111/jav.02562.

Bradarić, M., B. Kranstauber, W. Bouten & J. Shamoun-Baranes, in prep. Forecasting nocturnal bird migration to mitigate collisions with offshore wind turbines in the southern North Sea. In On the radar: weather, bird migration and aeroconservation over the North Sea (pp 95-115).

Hüppop, O., J. Dierschke, K.M. Exo, E. Fredrich & R. Hill, 2006. Bird migration studies and potential collision risk with offshore wind turbines. Ibis, 148, 90-109.

Krijgsveld, K.L., R.C. Fijn, M. Japink, P.W. van Horssen, C. Heunks, M.P. Collier, M.J.M. Poot, D. Beuker, S. Dirksen, 2011. Effect studies Offshore Wind Farm Egmond aan Zee. Final report on fluxes, flight altitudes and behaviour of flying birds. Bureau Waardenburg report nr 10-219.

Krijgsveld, K.L., R.C. Fijn, R. Lensink, 2015. Occurrence of peaks in songbird migration at rotor heights of offshore wind farms in the southern North Sea. Bureau Waardenburg report nr 15-119.

Potiek, A., J.J. Leemans, R.P. Middelveld & A. Gyimesi, 2022. Cumulative impact assessment of collisions with existing and planned offshore wind turbines in the southern North Sea. Analysis of additional mortality using collision rate modelling and impact assessment based on population modelling for the KEC 4.0. Report 21-205. Bureau Waardenburg, Culemborg.

Thieurmel B. & A. Elmarhraoui, 2019. suncalc: Compute Sun Position, Sunlight Phases, Moon Position and Lunar Phase. R package version 0.5.0. https://CRAN.R-project.org/package=suncalc

Bureau Waardenburg bv
Onderzoek en advies voor ecologie en landschap
Varkensmarkt 9, 4101 CK Culemborg
Telefoon 0345-512710
E-mail info@buwa.nl, www.buwa.nl