Mitigation measures for bats in offshore wind farms

Evaluation and improvement of curtailment strategies

M. Boonman

Bureau Waardenburg
Ecologie & Landschap

Mitigation measures for bats in offshore wind farms

Evaluation and improvement of curtailment strategies

drs. M. Boonman

Release status: definitive

Report number:	18-278
Project number:	18-0227
Release date:	12 October 2018
Project manager:	*drs*. M. Boonman
Second reader:	*drs.* G.F.J. Smit
Name and address of principal:	Rijkswaterstaat Water, Traffic and Environment A.R. van Bragt - Goli Zuiderwagenplein 2, 8224 AD Lelystad
Principal's reference:	31139627/van Bragt
Approved for release:	
drs. G.F.J. Smit	
Initials:	

Please quote as: Boonman, M. 2018. Mitigation measures for bats in offshore wind farms. Evaluation and improvement of curtailment strategies. Bureau Waardenburg Report no. 18-278. Bureau Waardenburg, Culemborg.

Keywords: Bats, wind energy, curtailment strategy, offshore

Bureau Waardenburg bv
Onderzoek en advies voor ecologie en landschap

Postbus 365 4100 AJ Culemborg
Telefoon 0345 51 27 10
info@buwa.nl www.buwa.nl

Summary

During the late summer and autumn Nathusius' pipistrelles migrate from the Baltic States and Russia to western Europe to mate and hibernate. Some of these bats cross the North Sea to the UK. By doing this they can enter offshore wind farms. The moving rotor blades of wind turbines are known to cause mortality among bats. This mortality rate is likely to rise as the total capacity of Dutch offshore wind farms is planned to increase from the current capacity of approximately 1,000 MW to 4,450 MW in 2023 and later. For the planned wind farms in the North Sea it was recognised that the mortality caused by wind turbines could affect the Nathusius' pipistrelle population. In order to prevent this, wind turbine operations are reduced between 15 August and 1 October during low to moderate wind speeds (at night between one hour after sunset until two hours prior to sunrise, the speed reduction is raised to 5 m/s and rotational speed is low during the idling phase). This curtailment reduces the risk of bat fatalities but also leads to a loss in energy production.

Since 2015 a substantial amount of new information about bat activity in the Dutch offshore wind farms has been generated by acoustic monitoring. This information was used in this study to define a more efficient curtailment strategy. The goal of this study was to reduce both mortality rate and energy production losses.

During the evaluation of the existing curtailment strategy, it became clear that improvements are highly advisable. If the existing curtailment strategy were to be implemented on modern wind turbines, the resulting fatality rate could still be considerable. The main reason for this is the fact that a large proportion of bat activity takes place during wind speeds above 5 m/s when wind speed is measured at wind turbine tower height (100 m). The only way to drastically lower the risk of fatalities is to raise the cut in speed to above 5 m/s. Since energy production significantly increases above 5 m/s, this can only be done during very specific conditions with high bat activity. High temperatures and easterly winds are two significant predictors of bat activity that are currently not being used. A more efficient curtailment strategy is possible by adding these parameters and by shifting the curtailment season to 25 August - 10 October.

To determine the settings of an optimal curtailment strategy a theoretical approach was used to estimate a theoretical fatality risk since the actual fatality rate is unknown. To estimate this fatality risk an association between the number of fatalities and both bat activity and the rotational speed of a wind turbine was assumed. Subsequently, this fatality risk was divided by energy production. The curtailment strategy was optimised by stepwise adding and subtracting conditions to the curtailment with small increments, including conditions with a high (above average) ratio of fatalities to energy production and excluding those with a low ratio until an optimal setting was achieved with both the lowest bat fatality risk and the lowest loss of energy production.

The optimal curtailment strategy consists of increasing the cut in speeds to 5.5 - 6 m/s when there is an easterly wind and an unaltered cut in speed (the turbine default setting) when temperatures are low and the wind westerly. Compared to the existing curtailment strategy, this new strategy results in a 12% lower loss in energy production and a substantially lower risk of fatalities (15%).

Foreword

The Dutch government has committed itself to the Paris climate agreement, which sets an upper limit for global warming of 2 degrees centigrade. In order to achieve this goal, a transition is now under way to produce energy from renewable energy sources. One of the approaches adopted to achieve this transition is the construction of large wind farms in the North Sea.

The rotating rotor blades of wind turbines can cause bird and bat mortality. The most effective way of preventing this mortality is to shut down the wind turbines at specific times when there is a high risk of victims. The aim of this study is to tailor the curtailment strategy for offshore wind turbines to these high-risk times as well as possible in order to limit energy production losses.

The study was monitored on behalf of Rijkswaterstaat by Maarten Platteeuw and Martine Graafland. Ine Wijnant of KNMI (the Royal Netherlands Meteorological Institute) provided important information to ensure the use of the correct weather data. Bob Prinsen and Leon van der Meijden (Eneco) shared their experiences and insights on behalf of the energy sector. Guido Hommel of the Dutch Wind Energy Association (NWEA) provided additional information. I thank them for their contribution.

Contents

1 Introduction

1.1 Background

In late summer and autumn, Nathusius's pipistrelles migrate from the Baltic States and Russia to the Netherlands to mate and hibernate here (Hutterer *et al.* 2005). For several years now, ringed animals have been recaptured to establish with certainty that Nathusius's pipistrelles also cross the North Sea to the United Kingdom (Anonymous 2018). As they cross the North Sea, Nathusius's pipistrelles pass or fly through offshore wind farms.

The Framework for Assessing Ecological and Cumulative Effects (KEC; Rijkswaterstaat 2015) established that it cannot be ruled out in advance that bats will fall victim to collisions in Dutch offshore wind farms. Because bats are strictly protected by the Nature Conservation Act and the European Habitats Directive, mitigation measures to reduce the risk of collision victims among bats have been included in the site decisions. These mitigation measures consist of raising the cut-in wind speed and preventing the rotor blades from rotating faster than 1 rpm in neutral when bats can be expected to be present in wind farms (hereinafter: 'the curtailment strategy') Shutting down wind turbines in this way reduces losses of energy production.

Since 2015, more information has become available about the presence of Nathusius's pipistrelles in the North Sea. Bat detectors have been installed in various offshore wind farms that automatically record the sounds of bats (Lagerveld *et al.* 2017). The question that now arises is whether these new data justify changes to the curtailment strategy. In this report, we make it clear whether there is any point to a stricter curtailment strategy and we describe the optimal balance between the reduction in the number of victims and losses of energy production.

1.2 Underlying assumptions

An altered or stricter curtailment strategy is intended to increase energy production without causing an increase in bat mortality.

The current strategy is as follows (http://wetten.overheid.nl/BWBR0037802/2017-11-08):

> '… A measure was therefore chosen where the cut-in wind speed of the turbines is increased to 5.0 m/s at hub height during the period from 15 August to 30 September between 1 hour after sunset and 2 hours before sunrise. Below this wind speed the number of rotations per minute per wind turbine shall be reduced to less than 1.'

The annual number of bat victims in the Dutch offshore wind farms is not known. In addition, the bandwidth is large for the estimated population size of Nathusius's pipistrelles migrating across the North Sea (100 - 1,000,000; Limpens *et al.* 2017). It is therefore not possible on the basis of current knowledge to provide grounds for the position that accepting an increase in the number of bat victims is possible without compromising the favourable conservation status.

The conditions applicable to the curtailment strategy should be as simple as possible so that these arrangements can be applied and enforced satisfactorily, and so that proper predictions can be made of the impact on energy production and the risk of bat fatalities.

2 Method

2.1 Evaluation of the current curtailment strategy

The times when offshore wind turbines are now shut down to reduce bat fatalities (the current curtailment strategy) are set out in Section 1.2 (Underlying Assumptions). The description draws on the analysis and data set provided by Wageningen Marine Research relating to the presence of bats in the Dutch offshore wind farms PAWP, OWEZ and UUD (Lagerveld *et al.* 2017). The analysis describes the conditions that affect the likelihood of bats being present in the wind farms. This analysis was compared with the current curtailment strategy to determine which parameters could be added to the strategy in order to improve it.

The relationship between bat activity and the season, time of night, temperature, wind direction and wind speed was mapped out to assess whether the limit values used in the current strategy are satisfactory.

Lagerveld *et al.* (2017) describe in their analysis the presence or absence of bats on a night by night basis in relation to weather conditions and time of the year. This provides a picture of the animals' 'migration decision': the conditions in which they start the crossing. However, it does not show the time of night when the probability of activity is highest, in other words when the animals arrive at the offshore wind farms or the level of activity in the wind farms. The higher the bat activity in the wind farms, the higher the probability of fatalities. In order to formulate a curtailment strategy based on the risks of victims, it is important to know whether there has been only one recorded observation or many dozens. To establish a clearer picture of the risk level, hourly bat activity was linked to data from the KNMI's Royal Netherlands Wind Atlas (KNW Atlas): temperature, wind direction and wind speed at 20 m altitude. This is close to the height at which bat activity was measured (15 m).

2.2 Risk of victims

It is not known how many bats fall victim to collisions with wind turbines annually in the offshore wind farms. It is therefore not possible to make statements about the consequences of a curtailment strategy on the absolute number of collision victims. However, the sound recordings of bats made in the offshore wind farms do provide an indication of the times and weather conditions when there is most activity and therefore the risk of victims. The number of recorded bat observations per unit of time is a measure of bat activity. On land, there is a significant relationship between bat activity at hub height and the number of collision victims (Korner-Nievergelt *et al.* 2013). This relationship makes it possible to make statements about the risk of collision victims in a relative sense.

In the offshore wind farms, activity was measured at 15 m above the sea surface, in some cases from Offshore High Voltage Stations (OHVS; Lagerveld *et al.* 2017) and not from the nacelles of wind turbines. An explicit assumption is that bat activity in an OHVS is comparable to that around wind turbines. Offshore wind turbines have a relatively low tip height. For example, the wind turbines in PAWP have a hub height of 59 m and a rotor diameter of 80 m. This means that, in the lowest position, the tip is only 19 m above the surface of the sea. Nathusius's pipistrelles have a detection distance of 35 m (Barataud 2015). A large part of the lower rotor swept area is therefore within the reach of the bat detector. The measured bat activity is representative for the lower rotor swept area but animals at and above hub height were not observed. Based on the vertical activity profiles (Wellig *et al.* 2018), the lower part of the rotor swept area is also where the risk of victims is highest. At higher altitudes, activity levels for Nathusius's pipistrelles are lower (Wellig *et al.* 2018). For the higher parts of the rotor swept area, this method therefore overestimates the risk of fatalities.

The probability of collision victims is determined by the number of bats present and the probability of a collision. The number of bats is determined in practice by recording the level of activity. The theoretical probability of collision victims is calculated as follows:

$$\lambda = \log(\mathrm{Act}+1) * \beta * \mu$$

This is a theoretical approach that allows for a comparison of curtailment strategies but not for the determination of the actual number of victims. λ represents the number of victims. This depends on bat activity (the number of sound recordings of bats; Act) and the collision probability (β). Bats are sometimes recorded dozens of times in the space of a few minutes. Bats are attracted by wind turbines and they will fly around a wind turbine for some time (Cryan *et al.* 2014). A large number of recorded observations in a short period of time will therefore, in many cases, represent only one animal or just a few animals. The probability of an animal falling victim to a collision does of course increase as it flies around for a longer period of time (and is observed more often) but an animal can fall victim once and so it is entirely possible that this risk will be overestimated. We therefore adopt the logarithm of the number of observations to ensure that a relatively small number of hours with very high levels of bat activity does not skew the picture. This is a common approach in models that use acoustic activity to predict the number of victims (Korner-Nievergelt *et al.* 2013). We use μ to show whether or not a curtailment strategy applies. For example, the strategy will not apply during the first hour after sunset. It is assumed that there will be victims only when there is no curtailment. We interpret collision probability β as the probability of an animal falling victim to a collision on the basis of the rotation speed of the rotor blades.
A wind turbine with a relatively small rotor diameter (< 100 m) can start rotating at a wind speed of 1 m/s. Initially, the rotational speed increases linearly with the wind speed (Figure 2.1). The rotational speed in neutral can be considerable (6-8 rpm). Neutral refers to the condition in which a wind turbine turns without producing energy. A turbine can produce energy only when the wind speed is higher than the cut-in

speed. The cut-in wind speed of the wind turbines still used at present is generally 3.5 m/s.

The most modern offshore wind turbines with larger rotor diameters start to rotate at a wind speed of about 2 m/s (Korner-Nievergelt *et al.* 2013) and their cut-in wind speed is 3.0 m/s (oral statement from Bob Prinsen and Guido Hommel). There is therefore no risk of collision victims at wind speeds below 2 m/s. The rotational speed increases linearly with the wind speed. The risk of collision victims increases with increasing rotor blade rotational speed because:

1. Bats have less time to avoid the rotors.
2. There is a larger pressure difference between the inside and outside of a rotor blade and this makes barotrauma more likely.
3. A rotor blade passes by more often, increasing the probability of a collision with a bat.

Nevertheless, it emerges that the highest collision probability is already reached at relatively low wind speeds. Korner-Nievergelgelt *et al*. (2013) developed a model to determine the number of collision victims based on the acoustic activity of bats (measured from the nacelle). This model also includes the wind speed. The models show that, given constant bat activity, the highest collision probability is already reached at 3.5 to 5.7 m/s.

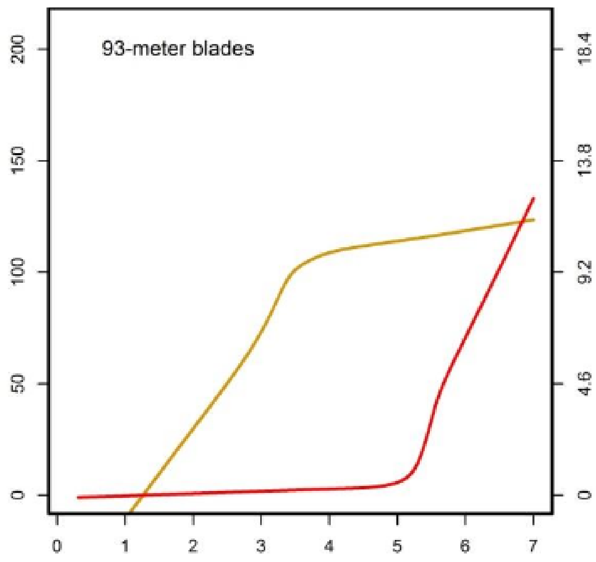

Figure 2.1 Relationship between rotational speed (tip speed left y-axis, rpm right y-axis) and wind speed (m/s x-axis). This relationship is shown for a curtailed wind turbine (increased cut-in wind speed and prevention of high rotational speed in neutral; in red) and for the same wind turbine running without restrictions (in beige). The figure comes from Arnett et al. 2013.

It is not known why the collision probability (at a constant activity level) does not increase further above 5 m/s. Above the cut-in speed (usually 3.5 m/s) the rotational speed does not increase as quickly with increasing wind speed (lower pitch; See Figure 2.1). In addition, at a wind speed of 5 m/s, a rotational speed may be reached at which victims can easily occur. As with road victims, where it does not really matter whether cars drive 120 or 130 km/h, an increase in rotational speed from this point will not result in a significant difference.

Based on the above we assume that:

in the case of a wind turbine operating without restrictions

at wind speeds < 2 m/s, the rotor blades will be stationary: β = 0
at wind speeds between 2 and 5 m/s, the probability of victims increases linearly (as does the rotational speed) from 0 at 2 m/s to 1 at 5 m/s: β = 1/3 * wind speed - 2/3
at wind speeds above 5 m/s: β = 1

In the case of a curtailed wind turbine (cut-in wind speed = 5 m/s; 1 rpm in neutral)

at wind speeds below the cut-in wind speed, β = 0
at wind speeds above 5 m/s. β = 1

The highest collision probability has therefore been set at 1 for the sake of convenience. In actual fact, this probability will be much lower but our aim is not to calculate the actual number of victims and so this is adequate to determine the effectiveness of curtailment strategies. When the wind speed increases above the cut-in wind speed and when a wind turbine is curtailed, the scada system will instruct the wind turbine to turn the rotor blades (which were pitched 90 degrees) back into the wind so that it can produce energy again. Within a few minutes, a wind turbine will reach the rotational speed that is usual for that wind speed. In our calculation of the collision probability for this situation, we ignore these first minutes in which the rotational speed may be even lower and assume the same collision probability as for the higher wind speeds.

2.3 Energy production

Because the power curves of modern wind turbines are not publicly available, we calculated energy production using the following formula:

$$P = \begin{cases} 0, & U < U_{\text{cut-in}} \\ \frac{1}{2}\rho U^3 \cdot \frac{\pi}{4} D^2 \cdot C_P, & U \geq U_{\text{cut-in}} \end{cases}$$

Where

- ρ = air density [kg/m³] (= 1!!.225 kg/m³)
- U = wind speed [m/s],
- D = rotor diameter [m],
- C_P = power coefficient,

The power coefficient depends on the wind speed and the type of wind turbine. Eneco supplied appropriate values representative for modern wind turbines for this study. Both the NWEA and Eneco have stated that it is best to use a cut-in wind speed of 3.0 m/s for modern offshore wind turbines. A rotor diameter of 164 m was used. To calculate energy production, the wind speed at hub height was entered in the formula above. Here, we used the hourly values at 100 m altitude from the KNW atlas of the KNMI. The wind speeds between 1979 and 2017 were used for the relevant period (15 August - 15 October, at night). By dividing energy production by the number of years (38), we obtained a figure for the annual production per turbine.
The calculation of energy production does not take wake effects into account (the wind speed can be lower straight behind a wind turbine than in front of it).
A loss of energy production is defined as the amount of energy that could have been produced when the curtailment strategy was in place.

2.4 Optimisation

To assess the efficiency of a curtailment strategy, the victim risk was compared with the loss of energy production. The theoretical number of victims and loss of energy production were determined for each combination of temperature and wind direction. The number of victims was divided by the corresponding loss of energy production (hereinafter: 'the ratio'). A high ratio means large numbers of victims with a limited loss of energy production. A limited probability of victims with a very low loss of energy production can also lead to an increased ratio. The ratio was calculated for each combination of temperature and wind direction.
A curtailment strategy is most efficient when it is applied at a high ratio, and not applied at a low ratio. The optimisation consisted of applying the curtailment strategy only when the ratio is above average. In order to improve on the current curtailment strategy, curtailment was extended to a few specific moments with a high ratio, while not applying the strategy to a large number of points in time with a low ratio. The aim was to reduce both the number of victims and the energy loss as much as possible by adding points in time and removing them from the curtailment strategy in a step-by-step approach. Starting from the initial situation (current curtailment strategy: increase in cut-in speed to 5 m/s and no operations in neutral), changes upwards and downwards were made in steps of 0.5 m/s.

3 Results

3.1 Evaluation of the current curtailment strategy

Parameters

Lagerveld *et al.* (2017) make it clear that bat activity is very predictable on the basis of wind speed, time of year, wind direction and temperature. More moonlight would seem to make bat activity more likely. Clouds reduced the probability of activity in their study. Wind speed and time of year are included in the current curtailment strategy (see Underlying Assumptions, Section 1.2). However, wind direction, temperature, moonlight and clouds are not. A number of important parameters are therefore missing from the current curtailment strategy. Wind direction and temperature are easy to implement because both are measured by wind turbines. Despite the fact that moonlight and clouds are significant predictors in the analysis, we advise against using them in a curtailment strategy. Although a positive effect on bat activity was found for moonlight and a negative effect for clouds, almost all the literature states that moonlight has a negative effect and clouds a positive effect (for instance, Lang *et al.* 2006; Cryan & Brown 2007). This raises the question of whether the finding relating to moonlight and clouds is robust. In addition to the phase of the moon, the amount of moonlight also depends on cloud cover. The amount of moonlight can vary greatly during the course of a night because of clouds, and cloud cover can be different on the coast where the animals depart than at the offshore wind farms. When bats decide to start migrating across the North Sea, the moon will probably not have risen. Moonlight and clouds may not therefore be good predictors of bat activity at sea.

Time of year

The current curtailment strategy applies to the period between 15 August and 1 October. However, no bat activity at all has been observed (in five years) between 15 and 20 August. On the other hand, there is still activity in early October. Without extending the period, a shift in the period for the application of the curtailment strategy to between 25 August and 10 October would seem to cover the risks better. The presence of two peaks in seasonal variation mentioned by Lagerveld *et al.* 2017) is not confirmed by Figure 3.1. It would therefore not appear to be advisable to draw on this observation to formulate a curtailment strategy.

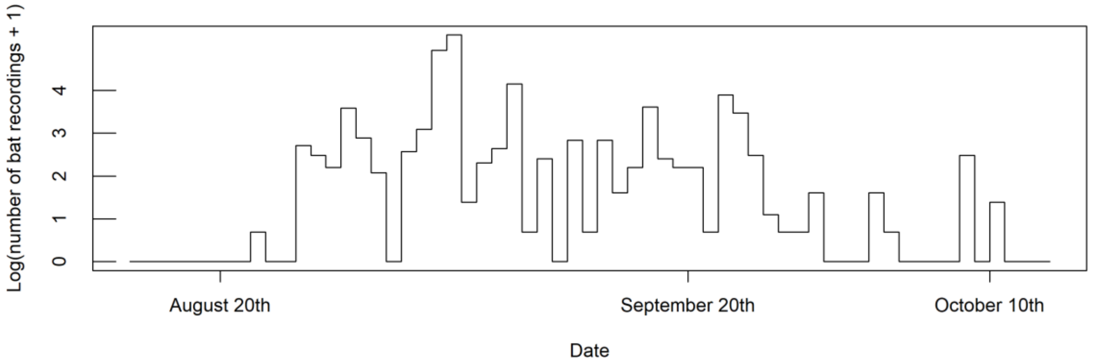

Figure 3.1 The number of recorded bat observations a night in the late summer/autumn, as measured from 2012 to 2016 (inclusive) in the offshore wind farms.

Time of night

The current curtailment strategy is valid for the period between 1 hour after sunset and 2 hours before sunrise. This corresponds fairly well to observations of bat activity in the wind farms (Figures 3.2 and 3.3). There is almost no bat activity during the first hour. About 80% of all activity is between 2 and 6 hours after sunset. There is a slight increase in activity shortly before sunset. However, this observation relates to a single hour, during which it is suspected that there is considerable activity involving a single animal, resulting in a relatively high number of observations.

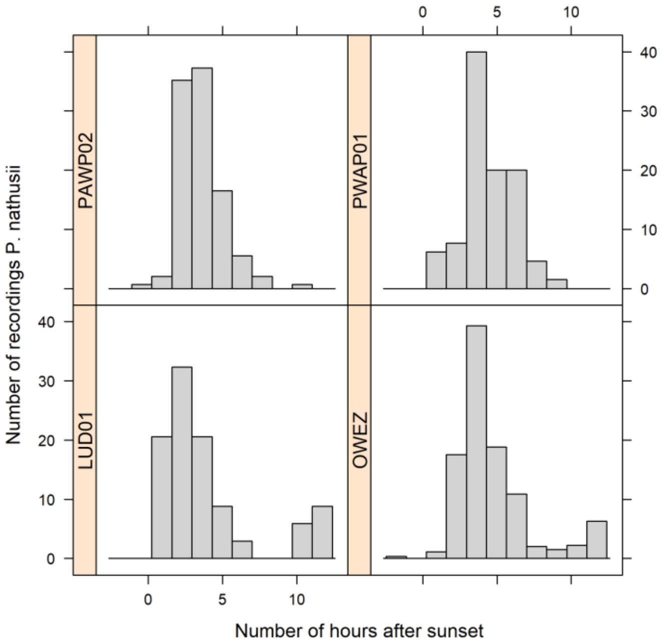

Figure 3.2 Frequency distribution of the number of recorded bat observations per night

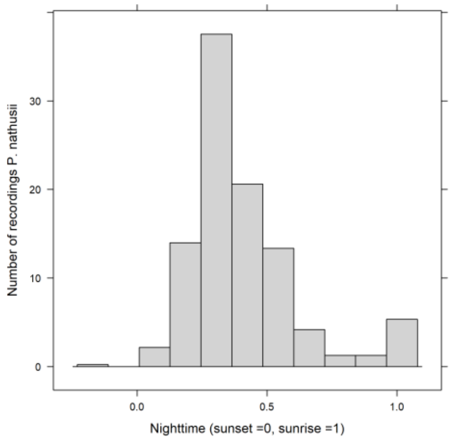

Figure 3.3 Frequency distribution of the number of recorded bat observations per night

Wind speed

The current curtailment strategy consists of raising the cut-in wind speed to 5 m/s when bat activity is expected. Figure 3.4 shows that bat activity is also relatively common above 5 m/s and that it falls off clearly only above 7.5 m/s. As already explained in Chapter 2, the dataset used may not be adequate for the higher parts of the rotor swept area. In the lower part of the rotor swept area, it seems likely that the cut-in wind speed used is quite low. A much larger reduction in the number of victims would be achieved by raising the cut-in wind speed.

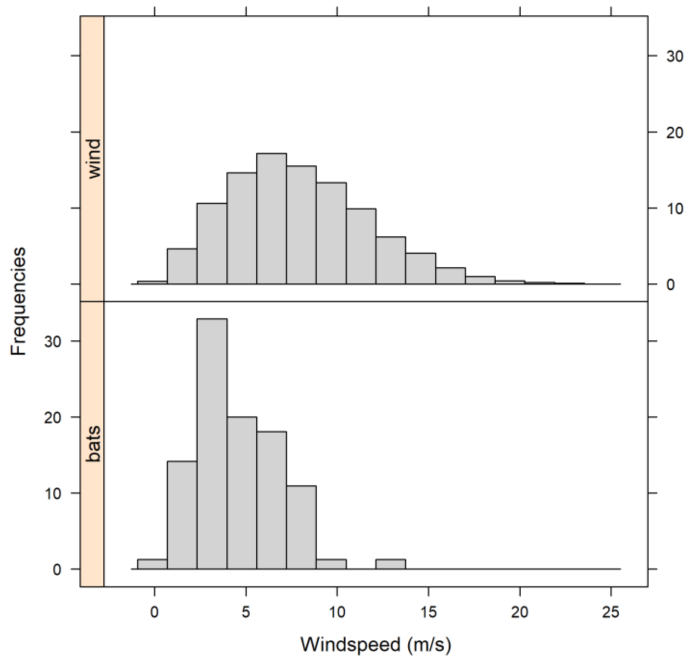

Figure 3.4 Frequency distribution of the number of recorded bat observations and different wind speeds in the relevant period

Wind direction

Wind direction is not included in the current curtailment strategy but it is a significant predictor of bat activity (Lagerveld *et al.* 2017). Figure 3.5 clarifies this. Bat activity occurs mainly when the wind is north-easterly and easterly. This is also the most favourable wind direction for migration to United Kingdom. South-westerly winds are frequent in the relevant period but bat activity is then scarce. This is particularly applicable to the wind speeds relevant for a curtailment strategy (3 to 6 m/s; green and orange in Figure 3.5).

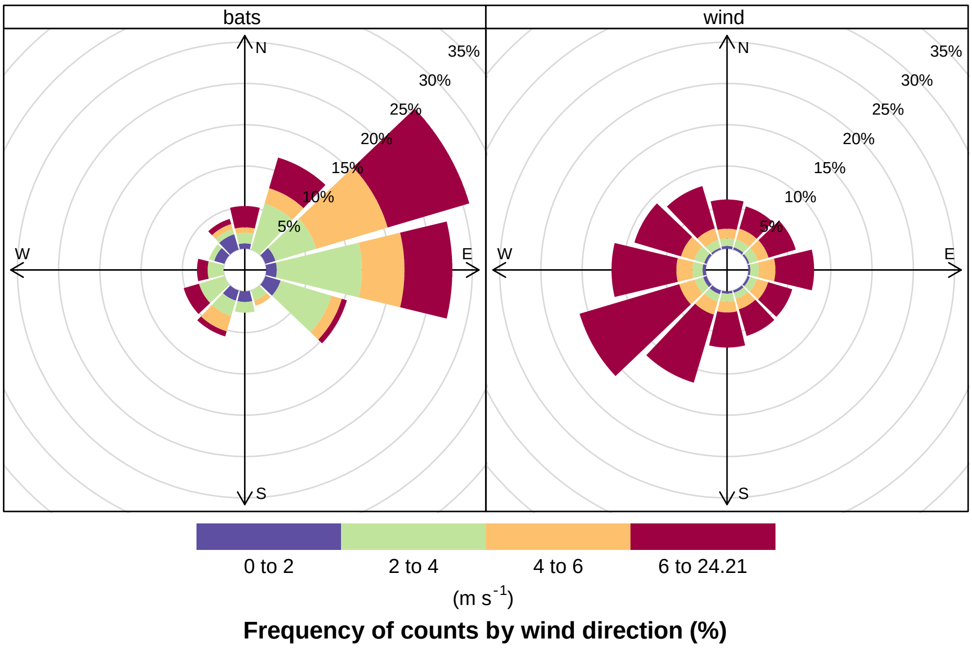

Figure 3.5 Wind rose showing the frequency of different wind directions The distribution on the left is the one at which bats have been observed.

Temperature

Temperature is not included in the current curtailment strategy but it is a significant predictor of bat activity (Lagerveld *et al.* 2017). Figure 3.6 clarifies this. Most bat activity is seen at relatively high temperatures. There is slightly less bat activity at the highest temperatures (>19 degrees). This is because the highest temperatures occur in the first hour of the night when bats that have left the mainland have not yet arrived in the wind farms.

Inversion was seen in a quarter of the hours in which there was bat activity. At those points in time, the temperature was higher at higher altitudes (100 m) than just above sea level. This phenomenon was seen significantly less frequently on average (regardless of whether or not there was bat activity) during 8.5 percent of the hours. It is quite possible that there is no causal link here. The phenomenon is probably relatively common in weather conditions that bats prefer, such as high temperatures and low wind speeds. It was decided to disregard inversion because it is not expected to add much to a curtailment strategy that already includes wind speed and temperature.

Efficiency

If the current curtailment strategies were to be implemented for modern wind turbines with a hub height of about 100 m and a rotor diameter of 164 m, the theoretical reduction in the number of victims would be only 25%, with a corresponding loss of energy production of about 15 MWh per turbine per year.

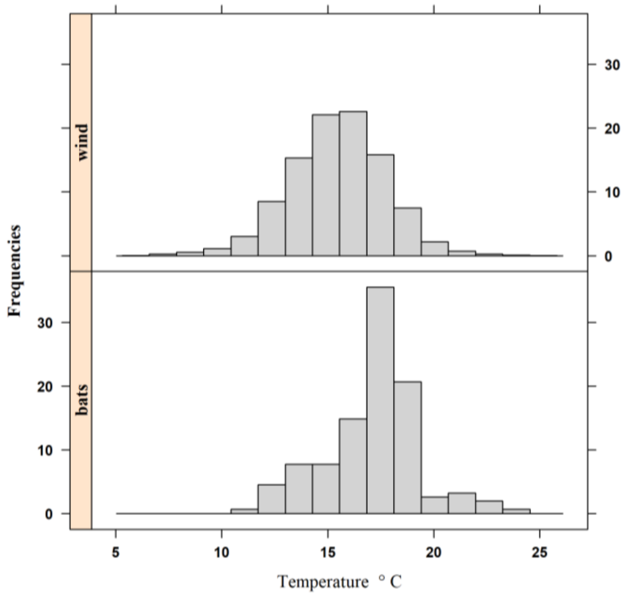

Figure 3.6 Frequency distribution of the observed temperature in the relevant period (15 Aug - 15 Oct at night) and the number of recorded bat observations.

3.2 A stricter curtailment strategy

The evaluation in Section 3.1 indicated that some important parameters are lacking in the current curtailment strategy (temperature and wind direction) and that the best limit values were not used in all cases. This chapter explores the options for making the current curtailment strategy stricter. We look here at the consequences for the probability of collision victims and energy production.

Time of year

By shifting the time of the year during which the curtailment strategy applies from 15 August-1 October (current situation) to 25 August-10 October, the schedule will correspond !!better with the season in which bat activity takes place (Figure 3.1). Although nights get longer as 21 December approaches, this has no significant effect on the loss of energy production (which is still 15 MWh/turbine per year). The number of victims can therefore be reduced without there being any effect on energy production.

Time of day
A very efficient way to reduce the number of victims is to avoid high rotational speeds in neutral (at wind speeds below the cut-in speed). The wind speed is very low when a turbine is operating in neutral. Precisely because bats are primarily present in the rotor swept area at low wind speeds, there is therefore a risk of collision victims during operations in neutral. Arnett *et al.* (2013) found in their study that, by reducing the rotor blade rotational speed to 1-2 rpm (the rotor blades are pitched 90 degrees parallel to the wind) in neutral, it was possible to reduce the number of victims by 72%. This is very cost-effective because it is done at wind speeds when no energy can be produced. In the current curtailment strategy, high rotational speeds in neutral were only prevented at night between one hour after sunset and two hours before sunrise. A small portion of bat activity is still located outside this time window. Implementing the measure throughout the night reduces the probability of fatalities. Because the measure applies during wind speeds below the cut-in wind speed, this has no effect on energy production.

If the two measures mentioned above under 'time of year' and 'time of day' are included in the curtailment strategy, the reduction in the number of victims is slightly higher: 28% instead of 25% (Section 3.1, Efficiency).

3.3 Optimisation

It is expected that the risk of bat victims can be better predicted and therefore that the curtailment strategy can be improved by including temperature and wind direction (Section 3.1). The ratio between the number of victims and the corresponding energy production is shown for wind direction in Figure 3.7. A high number of victims in combination with low levels of energy production is mainly seen at low wind speeds. Energy production is then low. There are clear differences between the wind directions. When the wind is from the westerly to north-westerly direction, there is hardly any bat activity, even at low wind speeds. Shutting the wind turbines down is not cost-effective when the wind is blowing from this direction. When the wind is from the north easterly to south-easterly direction, however, curtailment is effective, even at slightly higher wind speeds. Significantly more energy is produced above 6 m/s than at 5-6 m/s. Increasing the cut-in wind speed above 6 m/s when the wind is easterly may reduce the number of victims but this entails disproportionately high costs in terms of losses of energy production. The black line in Figure 3.7 shows the optimal curtailment strategy based on the wind direction.

	N	NNO	NOO	O	ZOO	ZZO	Z	ZZW	ZWW	W	NWW	NNW
3-3.5	3,544	1,116	3,298	1,921	7,38	3,113	0	1,872	3,152	0	0	0
3.5-4.0	0	1,676	1,754	4,584	2,274	0	1,071	0	0	0,508	1,554	0
4.0-4.5	0	1,374	0	3,051	2,605	1,927	0	0	1,314	0,794	0	0
4.5-5.0	0	0	4,546	0,586	3,881	0	0	3,207	0	0	0	0
5.0-5.5	0	0,426	1,533	5,549	2,425	1,576	0	0	0	0,295	0	0
5.5-6.0	0,329	0	0,209	3,957	0	0	0	0,134	0	0	0	0,349
6.0-6.5	0	0,975	0,492	0	2,868	0	0	0	0	0	0	0
6.5-7.0	0,505	0,208	0,443	0	1,33	0	0	0	0	0,567	0	0,043

0 | 0-1 | 1-2 | 2-3 | 3-4 | >4

Figure 3.7 The number of victims divided by energy production for different combinations of wind direction (x-axis) and wind speed (y-axis). A high value indicates a high number of victims in combination with low energy production. Zero means that no bat activity has been observed. The black line indicates the optimal limit for the curtailment strategy.

The same has been done for temperature (Figure 3.8). The curtailment strategy is most effective at higher temperatures. Temperatures above 19°C are not adequately reflected because they are usually seen early at night when bats have not yet arrived at the wind farms. Shutting down the turbines is not cost-effective below 11°C. A slight increase in the cut-in wind speed from 5 m/s to 5.5 m/s would only seem to be effective at the highest temperatures.

	<10	10	11	12	13	14	15	16	17	18	>19
3-3.5	0	0	2,055	2,605	0	0	0,559	6,386	3,298	10,49	0
3.5-4.0	0	0	0	0	2,886	0	4,297	2,261	0	2,445	0,189
4.0-4.5	0	0	0	0	0,661	0,794	0	0	2,427	4,793	0,198
4.5-5.0	0	0	0	0	1,076	0	1,733	0,586	3,528	1,522	0,49
5.0-5.5	0	0	0	0	0	0,235	0,754	0,426	0	2,308	0,675
5.5-6.0	0	0	0,329	0	0	0,558	0,463	0	0,134	0	0,292
6.0-6.5	0	0	0	0	0	0	0	0	1,63	0	0,172
6.5-7.0	0	0	0	0	0,043	0,208	0,691	0	0,47	0,567	0,06

0 | 0-1 | 1-2 | 2-3 | 3-4 | >4

Figure 3.8 The number of victims divided by energy production for different combinations of temperature (x-axis) and wind speed (y-axis). A high value indicates a high number of victims in combination with low energy production. The black line indicates the optimal limit for the curtailment strategy.

A diagram showing the ratio (number of victims divided by energy production) for each combination of temperature and wind direction was created but it contained too many missing values (no bat activity determined). The dataset is not large enough to show the limits for the curtailment strategy at that scale.

Table 3.1 Optimal curtailment strategy The cut-in wind speed is displayed for each combination of temperature (left vertical) and wind direction (top horizontal).

	N	NNE	NEE	E	SEE	SSE	S	SSW	SWW	W	NWW	NNW
<11	3	3	3	3	3	3	3	3	3	3	3	3
11-15	3.5	4.5	5.5	6	5.5	5.5	3.5	3.5	3.5	3	3	3
15-17	3.5	4.5	5.5	6	5.5	5.5	4.0	3.5	3.5	3	3	3
17-19	3.5	4.5	5.5	6	5.5	5.5	4.0	3.5	3.5	3	3	3
>19	3.5	4.5	5.5	6	5.5	5.5	4.0	3.5	3.5	3	3	3

In general, bat activity is predicted better by wind direction than temperature (Lagerveld *et al.* 2017). In order to formulate an effective curtailment strategy, it is important to define those specific parameters that can predict the probability of bat victims at higher wind speeds (> 5 m/s). If it is possible to accurately forecast when a higher cut-in wind speed is most effective, it is also possible to drastically reduce the length of time for applying this measure. As explained earlier, the probability of victims at higher wind speeds can be predicted very accurately on the basis of wind direction. This makes sense: strong winds help bats during migration only when they are tailwinds.
However, there is little reason to extend the curtailment strategy in line with wind direction (Figure 3.7) at higher temperatures. When the wind was westerly to north-westerly, almost no bat activity was measured, even at higher temperatures. When the wind is easterly, a cut-in wind speed of at least 5.5 is effective (Figure 3.7). A further increase cannot be justified on the basis of temperature because activity above 5.5 m/s is very low, even at the highest temperatures. However, temperature can be used to limit the duration of the application of the curtailment strategy. The probability of bat victims is very low at temperatures below 11°C. There is therefore no point in raising the cut-in wind speed at these temperatures. The optimal curtailment strategy is shown in Table 3.1.

The above curtailment strategy applied between 25 August and 10 October between one hour after sunset and two hours before sunrise leads to a theoretical 40% reduction in the number of victims. This is an improvement of 15% by comparison with the current curtailment strategy (25%; see Section 3.1). The improved curtailment strategy includes the prevention of high rotational speeds in neutral **throughout** the night. The corresponding loss of energy production was calculated at 13 MWh/turbine/year. This is 12% less than in the current curtailment strategy (rounded off to 15 MWh, see Section 3.1).

A larger reduction in the number of victims than 40% can almost only be achieved by further raising the cut-in wind speed. This leads to a disproportionate loss of energy production. Conversely, the loss of energy production can also be reduced but this is only possible by not curtailing turbines when the probability of victims is relatively high.

3.4 Implementation

Regulation using measurements in the last time interval

In this section, we consider how the curtailment strategy for a wind turbine should be implemented. The curtailment strategy (Section 3.3) has been formulated on the basis of wind speeds at an altitude of 100 m and it therefore corresponds to the wind speed at hub height. Every offshore wind turbine has a wind meter on the top of the nacelle, where there is usually a thermometer as well. The average wind speed, wind direction and temperature are saved every ten minutes. The most logical and common approach is to use these measurements. The decision to reduce the rotational speed or not (by pitching the blades 90 degrees) is based on, among other things, the average wind speed, wind direction and temperature **in the last time interval**. Schirmacher *et al.* (2017) investigated the difference between using a time interval of 20 minutes and 10 minutes. A time interval of 20 minutes resulted in a lower number of victims, more power was produced and this approach resulted in a lower number of switch-off and switch-on moments. We therefore strongly advise using a time interval of 20 minutes.

Regulation of wind turbine or wind farm?
In certain conditions, bats decide to start migrating and end up in offshore wind farms. The prevailing wind speed and direction above the North Sea determine to a major extent the probability of bats entering wind farms. The probability of bats encountering a wind turbine is expected to be approximately the same for all wind turbines in a given wind farm. Regulating an entire wind farm would therefore seem to be a more natural approach than regulating individual wind turbines.

Wind speeds in a wind farm can vary due to wake effects. The wind speed is lower directly behind a wind turbine than in front of one. In the case of wind turbines in a cluster, the wind speed will therefore not be the same for all wind turbines. If the curtailment strategy is implemented in individually regulated wind turbines by using the wind speed measured at hub height, this could (theoretically) result in spatial variations within a wind farm for the application of a curtailment strategy. This would appear to be undesirable because the risk of collision victims is expected to be the same for all wind turbines in a wind farm. In practice, however, it is unlikely that wake effects will be a major factor in the implementation of the curtailment strategy for bats. Wake effects are not expected to play a significant role at low wind speeds (oral statement by B. Prinsen and L. Van der Meijden). Moreover, wind farms are configured spatially in such a way that wake effects are minimised. The individual regulation of wind turbines is therefore expected to lead to the same results as central regulation.

If evaluation shows that wake effects also play a significant role at low wind speeds (< 5-6 m/s), central regulation is advisable. The monitoring location for central regulation should establish the best possible picture of the 'undisturbed', prevailing, conditions. Under no circumstances should a location in a wind farm be used where wake effects may occur.

4 Discussion

4.1 Method

Underestimation of victim risk?

The bat activity as measured in the offshore wind farms is representative for the lower part of the rotor swept area (Section 2.2). If bats behave differently above sea than above land, measured activity may be less suitable as a basis for defining a curtailment strategy. However, there are no indications that this is the case. Bat activity as measured above the North Sea in relation to the weather conditions is very similar to what has been observed on land from the nacelle. Bat activity is most common at low wind speeds in late summer/autumn. Even at sea, bats would not seem to simply pass by the wind turbines. After a period of days in which no activity is observed, several observations of calling bats have been made in a period of a few minutes. In view of the times at which the observations are made, it seems likely that animals will continue to fly around a wind turbine for some time, exactly as has been seen on land (for instance, Brinkmann *et al.* 2011; Limpens *et al.* 2013). Because of this strong similarity with bat activity on land, there is no reason to assume that bats behave significantly differently in offshore wind farms than on land.

In the U.S., observations have been made of bats (*Lasiurus borealis*) at an altitude of more than 200 m above the sea (Hatch *et al.* 2013). Because the wind speed increases with increasing height, this could be a way of taking full advantage of a tailwind. If this behaviour were also to be found in Nathusius's pipistrelles, this would result in a higher risk of victims than emerges on the basis of bat activity. Bats species vary greatly in the extent to which they tend to fly at higher altitudes and Nathusius's pipistrelles are not one of the species that flies highest (Roemer *et al.* 2017, Wellig *et al.* 2018). Nathusius's pipistrelles prefer a flight height during migration that allows them to maintain contact with the ground by means of echolocation (several tens of metres; Šuba 2014, Roemer *et al.* 2017, Wellig *et al.* 2018).
In Sweden, bats have been observed above the sea with radar. The smaller species, which include Nathusius's pipistrelles, generally flew 0-10 m above the surface (Ahlen *et al.* 2007). In a Swedish offshore wind farm, the activity of Nathusius's pipistrelles measured just above the surface was significantly higher than activity measured from the nacelle (Ecocom 2015). So there is no reason to assume that Nathusius's pipistrelles at sea are more numerous higher in the rotor swept area than they are at a lower height. Given these altitudes, the risk of fatalities may even be overestimated because bats regularly fly under the rotor swept area.

Another potential cause of the underestimation of the risks to which bats are exposed in offshore wind farms is the possibility that many Nathusius's pipistrelles no longer use echolocation when flying over the North Sea. There is no concrete evidence for this possibility either. In general, the use of echolocation when flying does not cost bats any extra energy (Speakman & Racey 1991). Not using echolocation therefore results in no energetic benefit for the animals.

This seems to justify a curtailment strategy based on bat activity as measured above the surface.

Theoretical and actual reduction

This study calculated the theoretical reduction in the number of victims for curtailment strategies. The actual reduction may differ from the theoretical reduction for various reasons. We will discuss two of them here. 1. In actual practice, the curtailment strategy is not applied throughout the year. Even in spring and autumn, the probability of collision victims is low when the curtailment strategy is not in place. 2. A wind turbine with a curtailment strategy is switched on (or off) on the basis of wind speeds measured in the past; there is therefore a certain delay. We assume that these discrepancies play a role in all curtailment strategies and that they can therefore be compared on the basis of the theoretical reduction.

4.2 Effectiveness of current curtailment strategy

The current curtailment strategy reduces the theoretical number of victims by a quarter only. The main reason for the low reduction is the fact that a large part of bat activity is at times when the wind speed at hub height is higher than 5 m/s. When the curtailment strategy was formulated, the relationship between bat activity and the wind speed measured by KNMI offshore weather stations was probably taken into consideration. These measurements state the wind speed at 10 m altitude, which is significantly lower than the wind speed at hub height (100 m). Because the curtailment strategy is based on the wind speed at hub height (see Section 2.1, Underlying Assumptions), wind turbine curtailment will already be stopped at increasing wind speed when there is still virtually no wind below and there is a relatively high probability of bat activity. To a lesser extent this plays a role in the existing wind farms such as PAWP and OWEZ because these wind turbines do not have an hub height of 100 m but of 60-80 m. This factor will play a role with the planned larger wind turbines.

4.3 Area in which the stricter strategy applies

The curtailment strategy formulated here is based on bat activity measured in wind farms relatively close to the coast. This was a deliberate decision because the bat activity here, in combination with the weather conditions, provides a picture of the 'departure decision'. It shows the conditions in which bats decide to start migrating across the North Sea. The presents of bats in wind farms further away from the coast is expected to be less predictable. It takes more time for bats to reach these wind farms and so there is a chance that the weather conditions will change after the time of departure. Due to the limited opportunities to rest and forage above the North Sea, bats have little choice but to continue the migration, even when conditions are less favourable. As a result, the presence of bats in wind farms further away is less predictable.

The question is to which part of the North Sea the stricter curtailment strategy is applicable. For locations further away from the coast, which cannot be reached by the bats on the same night as they depart, factors other than the 'departure decision' play a role. It is therefore expected that the curtailment strategy will be applicable in a generic way only to the coastal zone west of the Dutch Zeeland coast which can be reached by bats within one night after departure.

The daily migration rate was taken into account in order to determine this distance. A minimum flight speed of 5-10 km/h has been established (Petersons 2004) on the basis of reports of ringed animals. The distance covered is 31 to 77 km per night (48 km on average; Petersons 2004). These are minimum values because, in reality, a larger distance is covered than a straight line between the ringing location and the location where the animal is recovered. In addition, migration may be interrupted during that period of time in order to feed or forage.

The daily migration rate was also examined on the basis of phenological data. An **average** migration rate of 55 km per day was established on the basis of geographical differences (at different locations in the Baltic Sea) at the time of a peak in acoustic activity (Rydell *et al.* 2014). This is therefore close to the values reported by Petersons.

Above the North Sea there are fewer options for resting or foraging than for animals that follow the coast of the Baltic Sea. It can therefore be expected that the animals above the North Sea will migrate in a more targeted and continuous way so that they can cover longer distances. As a result, migration above the North Sea can be expected to be relatively fast. It therefore seems justified to assume a **maximum** daily migration distance of about 70 km.

The dataset used by Wageningen Marine Research does not contain any monitoring locations in the area to the north of the Wadden Islands. Wind farms such as PAWP, UUD and OWEZ would not seem to be representative for this area. Bat activity in the area to the north of the Wadden Islands is expected to be lower because animals probably largely follow the coastline from Germany.

Which wind energy areas are considered?

Figure 4.1 shows the wind energy areas in the North Sea. As stated above, the locations studied are not expected to be representative of the area to the north of the Wadden Islands. The IJmuiden Ver site is located 75-80 km offshore and it is therefore not inside the area that Nathusius's pipistrelles are expected to reach within a night. All the other locations in Figure 4.1 are. A stricter curtailment strategy will therefore apply to the wind farms in these areas.

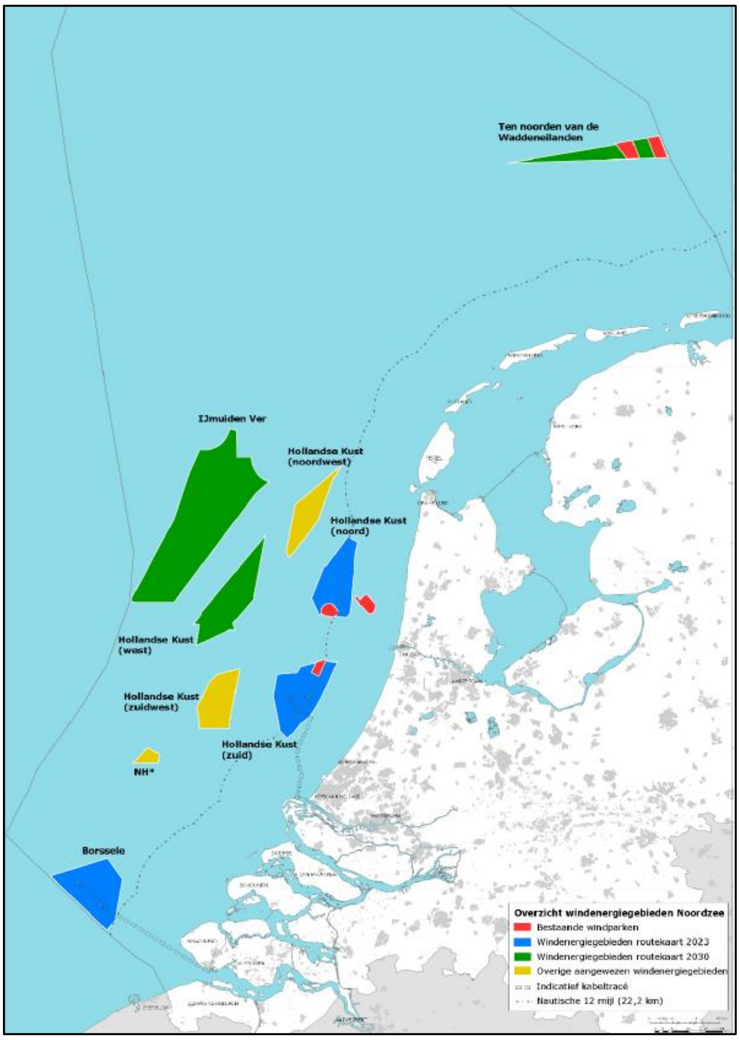

Figure 4.1 Overview of wind energy areas in the North Sea

4.4 Alternative curtailment strategies

The optimal curtailment strategy calculated in this study on the basis of measured bat activity is much more efficient than the curtailment strategies adopted in the site decisions until now. The reduction in the number of victims and the loss of energy production are both significantly lower (Section 3.3).

There are various curtailment strategies for bats on the market and it would therefore be useful to determine whether these result in added value for the offshore wind farms.

Curtailment on demand

Because the system is only shut down when bats are detected, there can be a considerable reduction in the loss of energy production. There are two systems that are known to result in a reduction of more than 80% in the number of victims (EPRI 2017 & DT Bat system (https://www.dtbat.com/). The major disadvantage in terms of use in offshore wind farms is that every wind turbine has to be fitted out with the system because bat activity is never identical at all wind turbines in a wind farm. The microphones installed on both the mast and in the nacelle would have to be replaced regularly because sensitivity can decline sharply within a few months. This makes the system impractical and expensive for the offshore wind farms.

Pro Bat

Pro Bat is a curtailment strategy that reduces the number of victims by shutting down the wind turbine when the conditions are in place that are most likely to result in collisions. The strategy can be formulated after acoustic monitoring has been conducted throughout a season. The basis for the strategy is the relationship between acoustic activity and victims, which was investigated by identifying victim numbers at dozens of locations in Germany with relatively small wind turbines (rotor diameter 70 m). The settings in a curtailment strategy are in line with the boundary conditions resulting from German legislation and they ensure that the number of victims per turbine is limited to two bats per turbine annually (Behr *et al.* 2017).

There are several drawbacks affecting application in the Dutch offshore wind farms. The system was developed for onshore wind farms in Germany, where common noctules account for a significant proportion of the victims. Eurobats (2018) states that the system is not suitable for locations with large numbers of Nathusius's pipistrelles. An explanation is not given but it may be related to the higher wind tolerance of the Nathusius's pipistrelle by comparison with, for example, the common noctule and the common pipistrelle (Brinkmann *et al.* 2011; Limpens *et al.* 2013). In addition, it is questionable whether the strategy can be applied to offshore wind turbines that are more than twice as large in terms of rotor diameter and the wind turbines covered by the German study at the time.

Chirotech

Chirotech from the French company Biotope is not open source. Its exact operation cannot therefore be verified without purchasing the system. The effect is probably very similar to the method used in this report. It assumes different cut-in wind speeds. The cut-in wind speed is tailored to the risk of collision, which is determined on the basis of acoustic monitoring.

5 References

Ahlen I., L. Bach, H.J. Baagoe, J. Petersson 2007. Bats and offshore wind turbines studied in southern Scandinavia. Swedish Environmental Protection Agency,Stockholm, Sweden, 36 pp.

Anonymus, 2018. National Nathusius' Pipistrelle Project. http://www.bats.org.uk/pages/national_nathusius_pipistrelle_project.html.

Arnett E.B., G.D. Johnson, W.P. Erickson & C.D. Hein 2013. A synthesis of operational mitigation studies to reduce bat fatalities at wind energy facilities in North America. A report submitted to the National Renewable Energy Laboratory. Bat Conservation International. Austin, Texas, USA.

Barataud, M. 2015. Acoustic ecology of European bats. Species Identification and Studies of Their Habitats and Foraging Behaviour. Biotope Editions, Mèze; National Museum of Natural History, Paris (collection Inventaires et biodiversité), 340 p.

Behr O., R. Brinkmann, K. Hochradel, J. Mages, F. Korner-Nievergelt, I. Niermann, M. Reich, R. Simon, N. Weber & M. Nagy 2017. Mitigating Bat Mortality with Turbine-Specific Curtailment Algorithms: A Model Based Approach. In: Köppel J. (eds) Wind Energy and Wildlife Interactions. Springer, Berlin.

Brinkmann R., O. Behr, I. Niermann & M. Reich 2011. Entwicklung von Methoden zur Untersuchung und Reduction des Kollisionsrisikos von Fledermäuse an Onshore-Windkraftanlagen. Bericht eines Foschungsvorhabens. Cuvillier Verlag, Göttingen.

Cryan P.M & A.C. Brown 2007. Migration of bats past a remote island offers clues towards the problem of bat fatalities at wind turbines. Biological conservation 139: 1-11.

Cryan P.M., P.M. Gorresen, C.D. Hein, M.R. Schirmacher, R.H. Diehl, M.M. Huso, D.T.S. Hayman, P.D. Fricker, F.J. Bonaccorso, D.H. Johnson, K. Heist & D.C. Dalton 2014. Behavior of bats at wind turbines. http://www.pnas.org/cgi/doi/10.1073/pnas. 1406672111.

Ecocom 2015. Uppföljande studie av fladdermöss vid Kårehamnporten – En jämförelse mellan förekomst och aktivitet av fladdermöss före respektive efter etablering av vindkraftverk. unpubl. report to E.On Vind Sverige AB: 14 pp.

EPRI 2017. Bat Detection and Shutdown System for Utility-Scale Wind Turbines. Technical report prepared by Normandeau Associates, Inc. for Electric Power Research Institute (EPRI). 3002009038 Final Report, July 2017. Palo Alto, California, U.S (98 pp).

Eurobats 2018. Report of the IWG on Wind Turbines and Bat Populations. -1- Doc.EUROBATS.StC14-AC23.9.

Hatch S.K., E.E. Connelly, T.J. Divoll, I.J. Stenhouse & K.A. Williams 2013. Offshore observations of Eastern red bats (Lasiurus borealis) in the Mid-Atlantic United States using multiple survey methods. PLoSOne 8 (12): e83803.

Hutterer R., T. Ivanova, C. Meyer-Cords & K. Rodrigues 2005. Bat migrations in Europe, a review of banding data and literature. Naturschutz und Biologische Vielfalt 28: 1-162.

Korner-Nievergelt F, R. Brinkmann, I. Niermann & O. Behr 2013. Estimating Bat and Bird Mortality Occurring at Wind Energy Turbines from Covariates and Carcass Searches Using Mixture Models. PLoS ONE 8(7): e67997. doi:10.1371/journal.pone.0067997.

Lagerveld S., D. Gerla, J.T. van der Wal, P. de Vries, R. Brabant, E. Stienen, K. Deneudt, J. Manshanden & M. Scholl, 2017. Spatial and temporal occurrence of bats in the southern North Sea area. Wageningen Marine Research (University & Research centre), Wageningen Marine Research report C090/17; 52 p.

Lang A.B., E.K.V. Kalko, , H. Römer, C. Bockholdt, & D.K.N. Dechmann 2006. Activity levels of bats and katydids in relation to the lunar cycle. Oecologia 146: 659–666. http://dx.doi.org/10.1007/s00442-005-0131-3.

Limpens H.J.G.A., M. Boonman, F. Korner-Nievergelt, E.A. Jansen, M. van der Valk, M.J.J. La Haye, S. Dirksen & S.J. Vreugdenhil 2013. Wind turbines and bats in the Netherlands

- Measuring and predicting. Report 2013.12, Zoogdiervereniging & Bureau Waardenburg.

Limpens H.J.G.A., S. Lagerveld, I. Ahlén, D. Anxionnat, T. Aughney, H.J. Baagøe, , L. Bach, P. Bach, J.P.C. Boshamer, K. Boughey, T. Le Campion, M. Christensen, J.J.A. Dekker, T. Douma, M.-J. Dubourg-Savage, J. Durinck, M. Elmeros, A.-J. Haarsma, J. Haddow, D. Hargreaves, J. Hurst, E.A. Jansen, T.W. Johansen, J. de Jong, D. Jouan, J. van der Kooij, E.-M. Kyheroinen, F. Mathews T.C. Michaelsen, J.D. Møller, G. Pētersons, N. Roche, L. Rodrigues , J. Russ, Q. Smits, S. Swift, E.T. Fjederholt, P. Twisk, B. Vandendriesche & M.J. Schillemans 2017. Migrating bats at the southern North Sea - Approach to an estimation of migration populations of bats at southern North Sea . Rapport 2016.031. Zoogdiervereniging, Nijmegen/ Wageningen Marine Research.

Petersons G. 2004. Seasonal migrations of north-eastern populations of Nathusius' bat Pipistrellus nathusii (Chiroptera). Myotis 41-42: 49-56.

Rijkswaterstaat 2015. Kader Ecologie en Cumulatie t.b.v. uitrol windenergie op zee Deelrapport B - Bijlage Imares onderzoek Cumulatieve effecten op vogels en vleermuizen. Ministerie van Economische Zaken en Ministerie van Infrastructuur en Milieu, Den Haag.

Roemer C., T. Disca, A. Coulon & Y. Bas 2017. Bat flight height monitored from wind masts predicts mortality risk at wind farms. Biological conservation 215: 116-122.

Rydell J., L. Bach, P. Bach, L. Guia Diaz, J. Furmankiewicz, N. Hagner-wahlsten, E-M. Kyheroinen, T. Lilley, M. Masing, M.M. Meyer, G. Pētersons, J. Šuba, V. Vasko, V. Vintulis & A. Hedenström, 2014. Phenology of Migratory Bat Activity Across the Baltic Sea and the South-Eastern North Sea. Acta Chiropterologica. 16. 139–147. 10.3161/150811014X683354.

Schirmacher M., A. Prichard, T. Mabee & C. Hein. 2017. Multi-year operational minimization study in West Virginia: potential novel strategy to reducing bat fatalities at wind turbines. Presentation at WW2017, Estoril.

Šuba J. 2014. Migrating Nathusius's pipistrelles Pipistrellus nathusii (Chiroptera: Vespertilionidae) optimise flight speed and maintain acoustic contact with the ground. Environmental and Experimental Biology (2014) 12: 7–14.

Speakman J.R. & P.A. Racey 1991. No cost of echolocation for bats in flight. Nature. 1991 Apr 4;350(6317):421-3.

Wellig S.D., S. Nusslé, D. Miltner, O. Kohle, O. Glaizot, V. Braunisch, M.K. Obrist & R. Arlettaz 2018. Mitigating the negative impacts of tall wind turbines on bats: Vertical activity profiles and relationships to wind speed. PLoS One. 2018 Mar 21;13(3):e0192493. doi: 10.1371/journal.pone.0192493. eCollection 2018.