The State of the Science on Operational Minimization to Reduce Bat Fatality at Wind Energy Facilities

Prepared for:

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EXECUTIVE SUMMARY

Wind energy is rapidly growing in the United States and around the world. The growth of wind energy is stimulated by a desire to reduce carbon emissions from the electric power sector and reduce the effects of climate change. Projected industry growth and evolving turbine technology (i.e., taller turbines with larger rotor-swept areas and turbines with lower cut-in speeds) have heightened concerns about cumulative impacts on bat populations. In 2008, the Bats and Wind Energy Cooperative (BWEC) – an alliance of experts from government agencies, private industry, academic institutions, and non-governmental organizations – was formed to address these concerns. Since its formation, the BWEC has sought to develop and disseminate solutions to measure and mitigate the impacts of wind turbines on bats, while maintaining the ability to develop and operate wind energy facilities in a competitive and cost-effective manner. In 2008, the BWEC identified operational minimization, also referred to as curtailment, as a top priority for research. Since that time multiple studies testing the efficacy of various operational minimization techniques have been conducted. We assess the cumulative evidence of these studies by quantifying the efficacy of operational minimization using quantitative meta-analysis.

Publicly available studies that evaluated operational minimization across 19 treatments implemented at 8 wind energy facilities were summarized. These studies indicate that operational minimization is an effective strategy for reducing bat mortality at wind turbines and that the efficacy is measurable. We estimate that total bat fatalities are reduced by 33% with every 1.0 m/s increase in cut-in speed. Estimates of the efficacy of fatality reductions for every 1.0 m/s increase in cut-in speed on the three migratory tree-roosting species in North America are similar (28% for hoary bats [*Lasiurus cinereus*], 32% for eastern red bats [*L. borealis*], and 32% for silver-haired bats [*Lasionycteris noctivagans*]). Extrapolating these data across multiple facilities and years, a 5.0 m/s cut-in speed is estimated to reduce total bat fatalities by an average of 62% (95% CI: 54–69%). We estimate total bat fatality reductions at individual facilities in any given year to fall between 33%–79% (95% prediction interval). For individual species, average fatality reduction at 5.0 m/s cut-in speed was estimated as 48% (95% CI: 24%–64%) for hoary bats, 61% (95% CI: 42–74%) for eastern red bats, and 52% (95% CI: 30%–66%) for silver haired bats. Most variation in efficacy is attributed to inter-annual differences. The interannual differences in efficacy observed at the studies in our analysis outweighed any spatial difference in efficacy.

Several efforts that seek to improve the efficiency of operational minimization by minimizing both power loss and bat fatalities could not be included in this quantitative meta-analysis. We provide a narrative review of the current literature regarding other factors such as temperature, nocturnal timing, bat activity, and wind direction on improving the efficiency of operational minimization. We also review findings related to the reduction of fatalities due to feathering below the manufacturer's recommended cut-in speed and on species of regulatory concern.

We conclude with a section summarizing the publicly available data regarding the loss in annual energy production (AEP) associated with operational minimization. Data on the loss in AEP is limited to five wind energy facilities across 11 operational minimization comparisons. The reported loss in AEP ranges from 0.06–3.20%, and is influenced by several factors, such as the prescribed cut-in speed, number of nights implementing operational minimization, turbine model, and wind regime. Additional considerations include, but are not limited to, the financial (e.g., market and price structure), technological (e.g., technology replacement and maintenance), and contractual liability (e.g., power purchasing agreements) associated with lost generation. Therefore, the loss of AEP is not the only constraint on the wind energy industry. Moreover, the circumstances at one site may have limited applicability to others and it is not appropriate to generalize cost or liability across facilities. Therefore, developing strategies that meet both economic and conservation goals is necessary.

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INTRODUCTION

Wind energy generation is a rapidly growing sector in the electric generation market in the United States that is driven by an effort to produce electricity and reduce global carbon emissions. In the United States, the installed capacity of wind turbines grew over 2.5 times between 2010 and 2019 (AWEA 2019). The U.S. Department of Energy (DOE) estimated that wind energy generation reduced fossil fuel energy carbon emissions by 6% in 2015 (DOE 2015), demonstrating that sustained growth in wind energy can reduce national emission levels. The increasing number of wind energy facilities in the United States and around the world has raised concerns regarding unintended impacts to wildlife.

The impact of wind turbines on bat populations is of particular concern (Kunz et al. 2007, Arnett and Baerwald 2013, Arnett et al. 2016). Hundreds of thousands of bats are estimated to die each year in collisions with wind turbines in the United States and Canada (Arnett and Baerwald 2013, Hayes 2013, Smallwood 2013). North America's migratory species, the hoary bat (*Lasiurus cinereus*), eastern red bat (*L. borealis*), and the silver-haired bat (*Lasionycteris noctivagans*) comprise 72% of fatalities with hoary bats representing approximately 38% of fatalities (Arnett and Baerwald 2013). Given our current understanding of bat demographic parameters, range of plausible population sizes for hoary bats in North America, and installed wind capacity in 2014, this level of mortality could lead to rapid population declines or extinction of hoary bats (Frick et al. 2017). The possible population level impact of wind turbines on hoary bats underscores the need to develop and implement practicable solutions that reduce bat fatalities at wind energy facilities. Developing practicable solutions that acknowledge economic constraints can help assure the wind energy sector can persist and continue to reduce global carbon emissions without negative impacts to vulnerable species.

One strategy for reducing bat mortality at wind turbines is to alter turbine operations (i.e., feather turbine blades and raise the cut-in speed of wind turbines) during periods of high risk for bats. To implement, blades are rotated parallel to the wind in a process called feathering. This slows or stops the blades from rotating, thus eliminating risk of collision with bats. Raising the cut-in speed (i.e., the speed at which electricity is generated) above the manufacturer's setting limits blade rotation during times they would normally produce electricity (see Appendix 1 for formal definitions). Operational minimization, or curtailment, are umbrella terms for this strategy, but can be further refined depending on the data used to inform turbine operations. Blanket or standard curtailment refers to altering turbine operation based solely on wind speed. In 2013, Arnett et al. conducted a narrative synthesis of 10 operational minimization studies and concluded:

> *... increasing cut-in speed between 1.5 and 3.0 m/s or feathering blades and slowing rotor speed up to the turbine manufacturer's cut-in speed yields substantial reductions in fatality of bats.*

At that time, publicly available information on power loss was only available from two operational minimization studies. Both reported that less than 1% of power loss was likely if operational minimization was implemented during periods identified as high risk for bats (i.e., at night, autumn seasonal period when wind speeds are less than approximately 5.0 m/s). However, variability in wind speed regimes, markets, price structure, and numerous other factors make it difficult to extrapolate these results to other wind energy facilities. Furthermore, even 1% power loss may not be economically feasible for some projects. Therefore, developing strategies that maximize energy production while minimizing bat fatalities is necessary. Refining periods of high risk may help meet both economic and conservation goals and was recognized as a priority by Arnett et al. (2013) when they recommended that:

> *Research efforts should continue to focus on incorporating additional variables, in addition to wind speed (e.g., temperature, time of night, bat activity) into treatments and explore using automated systems to maximize wind production while still minimizing bat fatalities.*

Incorporating variables, such as weather (e.g., temperature) or bat activity, in addition to wind speed is referred to as smart curtailment. Since Arnett et al. (2013), two smart curtailment studies have been conducted incorporating additional weather variables into the decision-making process (e.g., Hale and Bennett 2014, Martin et al. 2017). One study included both weather and real-time bat activity when deciding when to curtail wind turbines (Hayes et al. 2019).

In 2004, the Bats and Wind Energy Cooperative (BWEC; www.batsandwind.org) was formed to develop solutions to measure and mitigate the impacts of wind turbines on bats that meet both economic and conservation goals. The BWEC identified operational minimization (i.e., feathering turbine blades and raising cut-in speeds during periods of high risk for bats to reduce collision mortality) as a top priority for research (BWEC 2009). In 2018, the BWEC recommended an update to Arnett et al. (2013) synthesis (BWEC 2019). Here, we provide a review of publicly available operational minimization studies. We incorporate recent studies completed since Arnett et al. (2013) and quantifying the effectiveness (amount of bat fatality reduction) using quantitative meta-analysis (USFWS 2012). Specifically, our objectives were to:

1. Quantify the effectiveness of operational minimization using quantitative meta-analysis,

2. Provide a narrative summary of key findings from studies completed since Arnett et al. (2013), and
3. Review the reported power loss associated with operational minimization.

OBJECTIVE 1: QUANTIFYING THE EFFICACY OF OPERATIONAL MINIMIZATION TO REDUCE FATALITIES OF BATS AT WIND TURBINES

Evaluating the efficacy of operational minimization to reduce fatalities of bats at wind turbines has been the goal of multiple studies (Appendix II). However, the unique conditions of each study make it difficult to extrapolate and compare results of studies from different facilities. One common way to compare results has been to correlate reported percent reduction in bat fatalities with a treatment cut-in speed (e.g., Figure 1.1). However, simply correlating reductions in bat fatalities across studies, ignores important factors of each study such as: turbine characteristics (e.g., start-up speed of different turbine models), the sample size of turbines assigned as treatment and controls, and the variation in observed fatalities. Ignoring these factors limits our ability to quantify the expected effect of operational minimization to reduce bat fatalities under specific conditions. We address these challenges by using quantitative meta-analysis to estimate trends in the efficacy of curtailment of wind turbines to reduce bat fatalities while accounting for the variation documented within and among a range of individual studies.

Overview of Quantitative Meta-analysis

Quantitative meta-analysis is used to describe the overall effect of an action by aggregating and comparing data from multiple studies (Lipsey and Wilson 2001). For control/treatment studies, such as those used to analyze the effectiveness of operational minimization to reduce bat fatalities at wind turbines, we use quantitative meta-analysis to calculate an effect size. The effect size has both a mean and variance to account for uncertainty in estimated effects of a treatment. Each study is given a weight based on the variation in the observed data with greater weight given to studies with less variation since the results of these studies are often more reliable. This weight is used to assign a contribution of each study to the later meta-regression.

The effect size of a continuous response such as bat fatality rate can be calculated using various standardized measures (Lipsey and Wilson 2001). In this instance, the effect size was measured as the difference of the log fatality rates between control and treatment scenarios. Because the fatality rate is on the log scale, this metric is the same as the ratio of control and treatment fatality rates. This metric can be transformed to a percent reduction in fatalities, which is a standard and easily interpreted metric to measure the efficacy of the treatment of operational minimization on reducing bat fatality rate.

One advantage to meta-analysis is the ability to examine the consistency of the effect sizes among studies. If among-study variation is greater than within-study error (i.e. sampling error), results are considered heterogeneous. Heterogeneity can be introduced by sampling differences (e.g., experimental design, geography, treatment differences, etc.). The presence of heterogeneity is determined by a Q test, while the size of variation can be calculated using the I^2 measure of variability. If heterogeneity is present, a random effect model can be used to search for moderators that explain the variation in a process referred to as meta-regression (Koricheva et al. 2013). Moderators can include any categorical or numerical factor differentiating studies. Commonly used moderators include factors related to study design, known differences between studies (e.g., temperature), spatial relationships (e.g., latitude and longitude or region), and temporal factors (e.g., if a treatment is more effective now or in the past). Mean effect size for specific scenarios is predicted by explaining how moderators influence effect size.

Section Objectives

We examine the effect of operational minimization on bat fatalities using meta-regression to account for variation across individual studies that experimentally tested the efficacy of curtailment. By coupling quantitative meta-analysis with meta-regression, we combined studies and explore moderators of between-study differences in a statistically robust way.

Specifically, our objectives are to:

1) Standardize study results across available operational minimization studies by calculating the effect size (log ratio of the means (ROM)) between estimated fatalities under control and curtailed conditions,
2) Identify moderators that explain the variation in observed effect size of operational minimization using meta-regression, and
3) Examine species-specific efficacy of operational minimization.

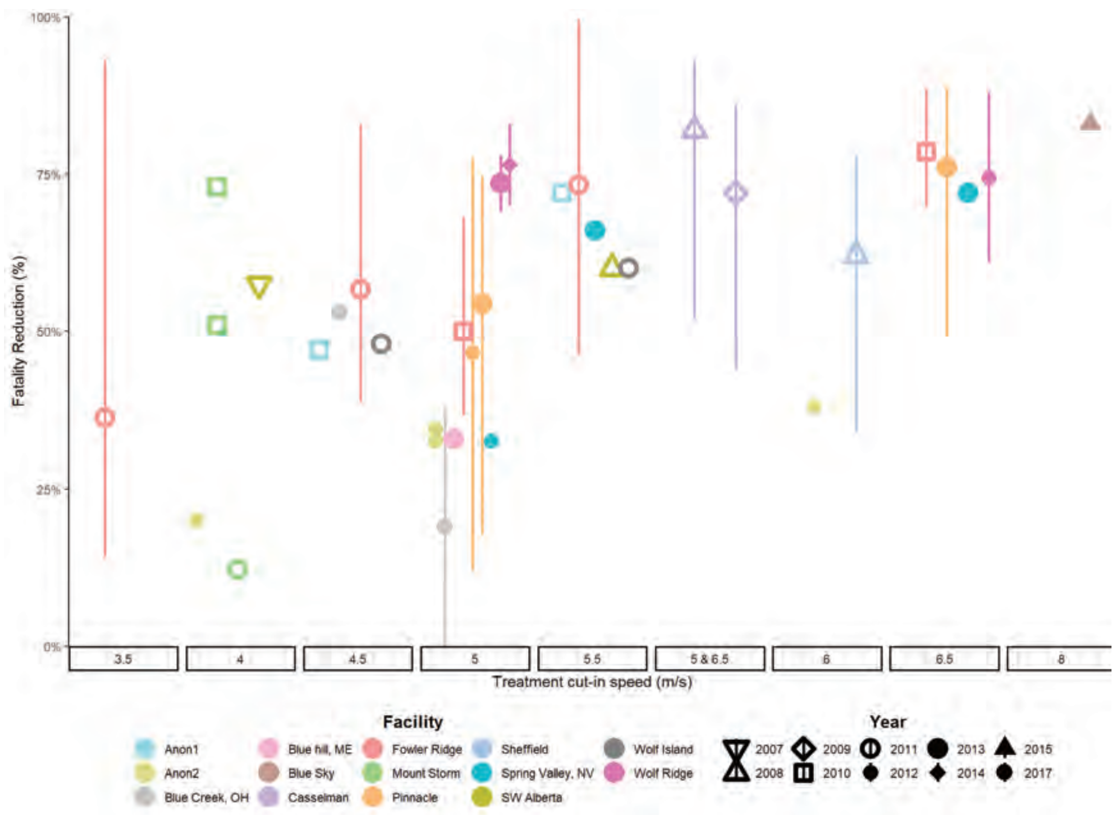

Figure 1.1: Reported percent fatality reduction for available studies of operational minimization. Studies on operational minimization occurred over an 11-year period (2007–2017), include a range of cut-in speed treatments (3.5–8.0 m/s), and had variable precision in estimates of fatality reduction. All studies are listed in Appendix II. Not all studies were used in the meta-analysis.

Methods

Data Collection and Curation

Calculating ROM for each study requires the mean and associated uncertainty (standard error, confidence interval, etc.) and sample size for both the treatment (i.e., the curtailment strategy) and control (i.e., normal operation). We manually extracted these values from each study using all information available for each study, including posters, presentations, reports, and/or published literature, when available. We gathered literature from the BWEC Bats and Wind Energy Bibliography and by using a Google Scholar search of 'bats wind curtailment.' To be included in the meta-analysis, documents had to report the fatality rate and associated measure of uncertainty (standard deviation, variation, standard error, or confidence interval) for a control and treatment conducted in the same year (or provide data that could be used to calculate these values).

Nineteen treatments at eight study sites reported appropriate data to be included in the meta-analysis, including peer-reviewed studies at four facilities (Table 1.1; Appendix II). For studies that did not report results of fatality rates, we used their raw data to calculate the estimated fatality rate for each treatment (Table 1.1). Details on our calculation of fatality rates using raw data are provided in Appendix III.

We log transformed fatality rates and associated confidence intervals prior to calculating effect size. Log transformation is necessary since fatality rates cannot fall below zero; it also helps account for many modeling techniques that use a log-link to calculate confidence intervals. We calculated effect size by taking the difference of the log transformed values of treatment and control turbines. We calculated the variance of each effect size on the log scale using Equation 1.1.

Equation 1.1: Calculation of variance for studies that provided fatality rates and confidence intervals, where t represents the value of the t distribution with n-1 degrees of freedom and p probability (90% or 95% depending on reported confidence levels. n = the number of turbines in the treatment, uci = upper confidence limit, lci = lower confidence interval.

$$\hat{\sigma}^2 = n\left(\frac{\boldsymbol{uci - lci}}{\boldsymbol{2t_{n-1}^{p}}}\right)^2$$

For the Baerwald et al. (2009) study, we used Equation 1.2 and Equation 1.3 to calculate effect size mean and variance because they reported standard error estimates instead of confidence intervals.

Equation 1.2: Calculation of variance when the mean ($\bar{X}$) and n turbines in sample when mean and standard error (SE) is provided

$$\hat{\sigma}^2 = log\left(\frac{SE_{\bar{X}}^2 * n}{e^{2log(\bar{X})}} + 1\right)$$

Equation 1.3: Calculation of mean ($\bar{\hat{\mu}}$) on log scale when mean and standard error are provided

$$\hat{\mu} = log(\bar{X}) - 1/2\hat{\sigma}^2$$

Variance of the mean effect size for a treatment was calculated with Equation 1.4**.**, implemented by the escalc function in metafor package (version 2.4; Viechtbauer 2010) in Program R (version 4.0; R Core Team 2020). We used the effect size calculation for mean difference (measure = "MD") since the difference of log values is equivalent to the log of the ratio of the means.

Equation 1.4: Calculation of the variance of the effect size given the control (subscript 1) and treatment (subscript 2) variance and sample size (N; number of turbines).

$$\hat{\sigma}^2 = \frac{\hat{\sigma}_1^2}{n_1} + \frac{\hat{\sigma}_2^2}{n_2}$$

We removed two studies from the meta-analysis and meta-regression because they each had curtailment strategies that were not used in other studies, thus not comparable with meta-analysis. At the Sheffield wind facility, curtailment was only implemented when temperatures were above 10°C (Martin et al. 2017). The curtailment treatment at BlueSky–Green Field was only implemented when bats were detected in the area with acoustic sensors (Hayes et al. 2019). Nonetheless, we include the effect size of these two sites in graphs to allow qualitative comparison of their results to other curtailment strategies. We also excluded the wind-speed and direction treatments at the Wolf Ridge facility (Hale and Bennet 2014) since this treatment was not repeated at another facility.

We examined how representative the meta-analysis dataset is of the fleet of utility scale wind turbines (>1.5MW and more than 1 turbine at a location) currently in operation (Hoen et al. 2018) that began operation during the same years as the study facilities (2007–2012). We used kernel density plots of the distribution of hub-height and rotor swept areas of turbines used in minimization studies to visually examine the distribution of these turbine characteristics compared to available turbines operating in the U.S. fleet. We used the overlap function of the overlapping package (version 1.6; Pastore 2018) to estimate the percentage overlap between the kernel density plots as a measure of similarity between turbines used in operational minimization studies and all turbines in the U.S. Geographic representation was examined visually by plotting facilities where studies were located and wind energy installations on a map.

Table 1.1: Publicly available operational minimization studies that include bat fatality rates at control and treatment turbines for the same year. Sources include all reports and peer-reviewed publications (*) that describe the study. The data source indicates the document that provided fatality rates used in the meta-analysis.

Facility	Year	Location	Source(s)	Data Source	Treatments	Species
Blue Creek	2017	Ohio, USA	Schirmacher 2020	Calculated from raw data[1]	5.0 m/s	*L. cinereus* *L. borealis* *L. noctivagans*
Blue Sky – Green Field	2015	Wisconsin, USA	Hayes et al. 2019* EPRI 2017	Hayes et al. 2019[2]	7.9 m/s (if bats present)	*L. cinereus* *L. borealis* *L. noctivagans*
Casselman	2008	Pennsylvania, USA	Arnett et al. 2011*[3] Arnett et al. 2009	Arnett et al. 2009	5.0 m/s 6.5 m/s	
	2009		Arnett et al 2010	Arnett et al. 2010	5.0 m/s 6.5 m/s	
Fowler Ridge[4]	2010	Indiana, USA	Good et al. 2011	Calculated from raw data in report[1]	5.0 m/s[5] 6.5 m/s[5]	*L. cinereus* *L. borealis* *L. noctivagans*
	2011		Good et al. 2012	Calculated from raw data in report[1]	3.5 m/s[6] 4.5 m/s 5.5 m/s	*L. cinereus* *L. borealis* *L. noctivagans*
Pinnacle	2012	West Virginia, USA	Hein et al. 2013	Combined species from Schirmacher et al. 2016[3] Species-specific from BCI raw data[1]	6.0 m/s	*L. cinereus* *L. borealis* *L. noctivagans*
	2013		Hein et al. 2014	Hein et al. 2014	6.0 m/s	*L. cinereus* *L. borealis* *L. noctivagans*
Sheffield	2012 2013	Vermont, USA	Martin et al. 2017*[3] Martin 2015	Martin 2015[2]	6.0 m/s	
Summer View	2007	Alberta, CA	Baerwald et al. 2009*	Baerwald et al. 2009*	5.5 m/s Low wind speed idle	*L. cinereus* *L. noctivagans*
Wolf Ridge	2011 2012 2013 2014	Texas, USA	Hale and Bennett 2014	Provided by authors	5.0 m/s	*L. cinereus*[7] *L. borealis*[7]

[1]See Appendix III for methods used to calculate fatality rates from raw data; [2]Data presented for comparison purposes only. Data are not used in the meta-analysis due to unique study design that involves acoustic detections (Blue Sky – Green Field) and temperature (Sheffield); [3]This later report included standardized results from multiple years; [4]Data from Fowler Ridge was split into to an effect size for each of 3 turbine models (GE, Vestas, and Clipper) that were used in the study to allow for meta-regression using turbine specific characteristics; [5]Treatments at Fowler Ridge in 2010 did not feather below the cut-in speed; [6]3.5 m/s at Fowler Ridge 2011 was simply feathering of blades below the cut-in speed; [7]Species fatality rates from Wolf Ridge were only available for 2013 and 2014.

Meta-analysis and Meta-regression

We conducted the meta-analysis and meta-regression for all bat fatalities combined and for three species that had enough data on species-specific fatalities: eastern red bats (*Lasiurus borealis*), hoary bats, and silver-haired bats (*Lasionycteris noctivagans*). Analysis for all species combined was conducted with 29 control-treatment comparisons at 6 facilities. Six facilities with 21 control-treatment comparisons reported data usable for analysis of curtailment efficacy for eastern red bats. For hoary bats, data from 21 control-treatment comparisons at seven facilities were used. Data from 19 control-treatment comparisons from six facilities were used when evaluating silver-haired bats.

We fit a multi-level null random effects model with intercept using the metafor package (Viechtbauer 2010) in Program R (R Core Team 2020) for each analysis set. We specified a nested random effect of year within facility to examine variation between years at the same facility and among facilities. We used the default process to assign weights to each comparison based on the inverse of the variability (sampling and random effects, accounting for covariance) of each comparison (Viechtbauer 2010).

Random effects models without moderators indicated heterogeneity in results (Q test p-value < 0.05) for all species combined and each species individually. We performed meta-regression to evaluate the influence of study-specific moderators on the variability in effect size using a set of candidate models. Moderators added to the null multi-level model represented four hypotheses to explain variation: study design differences, geographic variation, turbine characteristic variation, and treatment differences (Figure 1.2). Treatment differences were split into multiple models to explore which treatment measure best accounted for variation. Possible measures to describe treatments and control included the non-linear effect of treatment curtailment speed, feathering of blades, and cut-in speed of treatment and control turbines.

Table 1.2: Candidate model set (n = 17) to account for variation in effect size of curtailment studies. Moderators are the numerical and factor variables used to model the described prediction. All models included the same random effect of year nested within facility and a covariance matrix to account for multiple treatments being compared to a single control.

Model Name	Moderators	Prediction
Study design	Plot Size + Treatment Allocation[1]	The study design will determine the strength of the results
Geographic	Latitude*Longitude	Curtailment effect will vary based on location of the wind facility
Turbine characteristics	Rotor Swept Area + Hub Height	Curtailment effect will vary based on the size of the turbine
Treatment Difference Models		
Cut-in Speed & Feathering	Control Cut-In Speed + Control Feathering + Treatment Cut-In Speed + Treatment Feathering	Higher cut-in speeds and feathering reduce fatality levels
Cut-in Speed	Control Cut-In Speed + Treatment Cut-In Speed	Higher cut-in speeds reduce fatality levels
Non-linear Treatment Cut-in	Natural Spline of Treatment Cut-In Speed with 3 degrees of Freedom	Increasing cut-in speed has a diminishing effect on fatality reduction
Treatment Cut-in	Treatment Cut-In Speed	Increasing cut-in speed has a linear effect on fatality reduction

[1]Randomized Block Design—treatments were rotated so every turbine received all treatment or Completely Randomized Design—each turbine had a fixed treatment

All candidate models were fit using the maximum likelihood estimator with t-test for significance of fixed effect moderators. We compared support for candidate models using an information-theoretic model selection criteria approach (AICc; Burnham and Anderson 2002). The top model based on lowest AICc value was refit using restricted maximum likelihood estimation (REML) to produce unbiased estimates of variance and covariance parameters. This top model was used to describe the relationship of the relevant moderators to the effect of curtailment.

Studies with a stronger statistical result tend to be published more frequently than studies without statistically significant results (Møller et al. 2001, Song et al. 2000). This can bias the results of meta-analysis by overestimating the effect size. We used gray literature in addition to peer-reviewed studies, which may help protect against publication bias. We examined publication bias using funnel plots and rank correlation test (Begg and Mazumdar 1994).

Results

Representation of Installed Turbines

Facilities used in the meta-analysis are primarily located in the eastern Midwest (Indiana, Ohio) and Mid-Atlantic regions (West Virginia, Pennsylvania), with the addition of one facility in Texas and one in Alberta, CA. The greatest amount of installed turbines in the United States are located in the western Midwest (e.g., Iowa) and Southern Great Plains (e.g. Texas; Figure 1.2A). Therefore, facilities in the southwestern and northwestern United States are not well represented by available studies. Geographic distribution of facilities built in 2007–2012 (Figure 1.2D) is similar to the current fleet (Figure 1.2A), suggesting that lack of geographic representation in western regions is not due to recent trends in build-out.

The kernel density of rotor swept area of turbines used in minimization studies and turbines built during 2007–2012 overlap by 56% (Figure 1.2:E) and overlap by 42% with the current fleet (Figure 1.2:B), suggesting turbines used in operational minimization studies are generally smaller in term of rotor swept areas to turbines operating in the U.S. fleet. Similarly, the kernel density of hub height of turbines in the meta-analysis and the fleet built between 2007–2012 show an overlap of 35% (Figure 1.2:F) and 33% overlap with the current fleet (Figure 1.2C). Turbines with 100-m hub height tended to be over-represented while turbines of 80 m tended to be under-represented (Figure 1.2C).

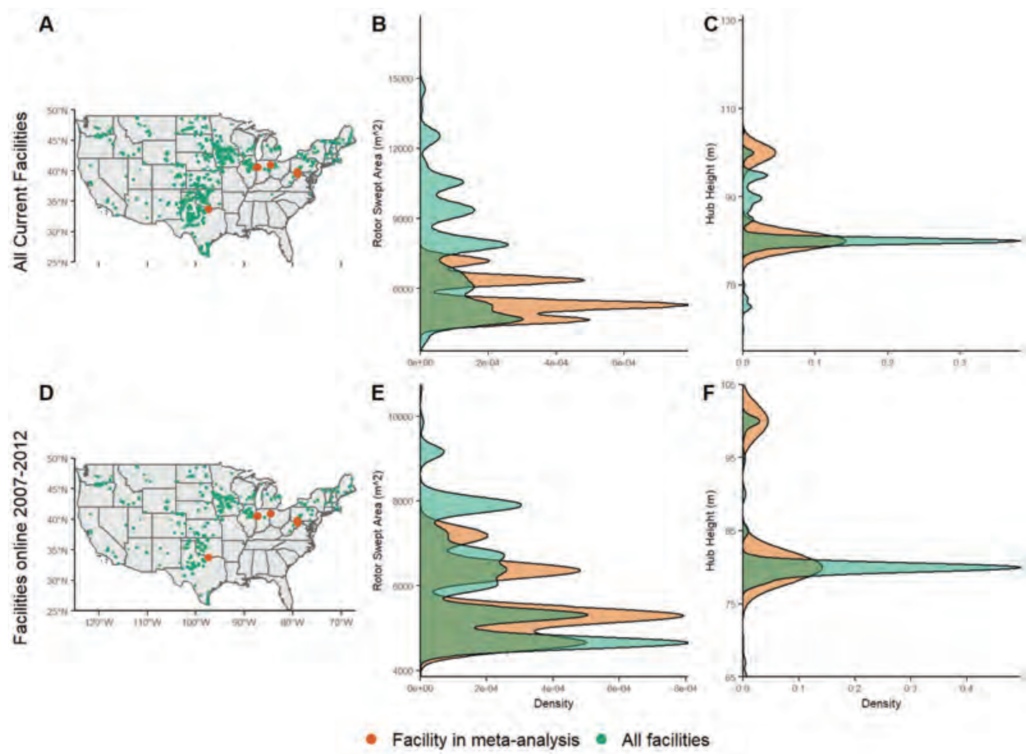

Figure 1.2: Comparison of geography (A,D), turbine rotor swept area (B, E), and hub height (C,F) for all utility scale wind turbines (>1.5 MW) in the United States Wind Turbine Data Base (A-C) and turbines from facilities that began operation in 2007-2012(D-E), the time period when facilities where operational minimization studies took place began operating. Our meta-analysis included an additional site in Alberta, Canada not shown here since we lack similar comparative data for Canada.

Total Bat Fatalities

The mean effect size (log Ratio of Means) was transformed to percent reduction in fatalities with a given treatment. For all but one study, the mean effect size was greater than 35.3% (Figure 1.3. The lower confidence intervals for six studies (including Sheffield and Blue-Sky-Green Field) overlapped zero. Wolf Ridge 2011 was the only study with a negative mean effect size (increase in fatalities at treatment turbines), however the results were not statistically significant. Hale and Bennett (2014) noted that there was an extreme drought in 2011 and overall fatality rates at Wolf Ridge were 1/10 to 1/20 of previous years. The greatest reduction was a 91.3% reduction in fatalities at Fowler Ridge when Vestas turbines cut in speed was raised from 3.5 to 6.5 m/s in 2010 (Figure 1.1).

As expected, there was significant heterogeneity in fatality reductions among operational minimization studies when no moderators were used (Q_{28} = 68.12, p-value <0.001). The top model using moderators to explain the variation included the linear effect of treatment cut-in speed and accounted for 72% of the weight in the model set (Table 1.3). No publication bias existed in the top model (p = 0.54, Kendall's tau = 0.08; Figure 1.4A). There was not statistically significant residual heterogeneity (variability was less than what would be expected given sampling variability) when treatment speed was used as a moderator (Q_{27} = 39.38, p-value = 0.06). However, a more liberal interpretation of the p-value would indicate that additional covariates could explain more heterogeneity. True heterogeneity accounted for 39.6% (I^2) of the observed variation, meaning 60.4% was attributable to sampling variation. Almost all heterogeneity was attributed to inter-annual heterogeneity at a facility and practically no variation ($3.7e^{-8}$%) was attributed to heterogeneity between facilities. The linear effect of cut-in speed was significant (t = 4.908, p-value <0.0001, β ± SE = 0.40 ± 0.08), indicating operational minimization reduced fatalities, on average, by 33% (95% CI: 21%–43%) for each 1 m/s increment of curtailment (Figure 1.5A, Figure 1.6). The result in efficacy is reported for each unit increase in cut-in speed (i.e., every 1 m/s). The compounding nature of percentages for increases in cut-in speed greater than 1 m/s creates a curvilinear appearance in the results when back-transformed to a percentage decrease (Figure 1.5A). The model coefficients describe a linear effect of cut-in speed on the logarithmic scale (Figure 1.6). The percent decrease for an X m/s increase in cut-in speed can be calculated with Equation 1.5.

Equation 1.5: If fatality is expected to decrease proportionally by D for every 1 m/s increase in cut-in speed, then the total proportional decrease (P) in fatality rate given an increase in cut-in speed of X m/s is

$$P = 1 - (1 - D)^X$$

The expected reduction at a given cut-in speed includes the effect of feathering below the cut-in speed.

Hoary Bat

Twenty control-treatment comparisons had data appropriate to analyze the efficacy of operational minimization for hoary bats (Figure 1.7). Three additional comparisons were made by studies; however, the variance estimates included infinity and could not be used in the meta-analysis (see Appendix III). Four comparisons had an effect size greater than or equal to zero. Positive effect sizes ranged from a <1% reduction in fatalities to an 88.9% reduction in fatalities (Figure 1.7). There was statistically significant heterogeneity among results (Q_{19} = 30.45, p = 0.046), indicating the need for moderators to explain variation greater than sampling error.

The initial candidate model set had two top models (<2 ΔAICc), the "*treatment cut-in speed*" model and the "*turbine characteristics*" model (Table 1.3). The only significant Beta coefficient estimate in the "*turbine characteristics*" model was the size of the rotor swept area. Therefore, we created a new model with treatment cut-in speed and the size of the rotor swept area. When added to the candidate model set, this new model was the top model and carried a weight of 47.6%. The next two models were the original top two models ("*treatment cut-in speed*" and "*turbine characteristics*") and had a ΔAICc of 1.60 and 2.31, respectively. These three models had a cumulative weight of 84.1%.

We proceeded with using the linear effects treatment cut-in speed and rotor swept area as our top model. Moderators in this model significantly accounted for variation ($F_{2,17}$ = 5.38, p-value = 0.016). There was no residual heterogeneity when using these moderators (Q_{17} = 16.64, p= 0.48), indicating that all remaining variation could be attributed to sampling error. No heterogeneity was attributed to variation among facilities ($7.1e^{-8}$%) while 22.7% of variability could be attributed to annual variation within a site. No publication bias was found (Kendall's tau = -0.05, p-value = 0.77; Figure 1.4B).

As in total bat fatalities, the relationship between treatment cut-in speed and reduction in hoary bat fatalities was linear (β ± SE = 0.33 ± 0.16, p-value = 0.05; Figure 1.5B; Table 1.5), indicating a 28% (95%CI 0.4-48%) additional reduction for every 1 m/s increase in cut-in speed. Hoary bat fatalities also decreased slightly as size of the rotor swept area increased (β ± SE = 0.0004 ± 0.16, p-value=0.0007; Figure 1.8).

Eastern Red Bat

Twenty-one studies were included in the meta-analysis of operational minimization efficacy for eastern red bats. All effect sizes indicated that operational minimization reduced fatalities of eastern red bats. Effect sizes ranged from a minimum of a 20% reduction in fatalities to a maximum of a 91%

reduction in fatalities. Eight studies had confidence intervals overlapping zero (Figure 1.9). A random effects model indicated significant heterogeneity between study results without the inclusion of moderators (Q_{20} = 37.65, p-value = 0.010).

The top model with moderators included the linear effect of treatment cut-in speed and carried 76% of the weight in the candidate model set (Table 1.3). There was no residual heterogeneity in effect size after accounting for cut-in speed of treatments (Q_{19} = 28.7, p-value= 0.07). Heterogeneity between studies accounted for 47% (*I^2*) of the variation while sampling variation accounted for 53% of the variation. Among facility heterogeneity accounted for 17% of the variance. Inter-annual heterogeneity accounted for 30% of variation. No publication bias was detected (Kendall's tau = 0.18, p-value = 0.27; Figure 1.4C).

Increasing treatment cut in speed significantly increased the efficacy of operational minimization at reducing eastern red bat fatalities (β ±SE = 0.38 ± 0.117, p-value = 0.004). Every 1.0 m/s increase in treatment cut-in further reduces fatalities by 32% (95%CI 13-47%; Figure 2.5C; Table 1.6).

Silver-haired Bat

A total of 17 control-treatment comparisons were used to evaluate the efficacy of operational minimization at reducing silver-haired bat fatalities. Models of silver-haired bat fatalities at Clipper turbines at Fowler Ridge Wind Facility in 2011 did not converge (Appendix III) and were not used in the meta-analysis. Four comparisons reported a mean effect size less than zero, indicating an increase in fatalities with treatments. All four had extremely wide confidence intervals that included zero. The remaining 15 comparisons reported a minimum mean effect size of 25% and a maximum of 93%. Eight of these had confidence intervals including zero (Figure 1.10). There was significant heterogeneity among results when no moderators were used in a random effects model (Q_{17} = 27.46, p-value = 0.05).

The top model to account for heterogeneity included the linear effect of treatment cut-in speed (weight = 43%; Table 1.3). The next model (ΔAICc = 0.5, weight =3 4%) included the linear effect of treatment cut-in speed and the cut-in speed of the control. While this model had similar support, the effect of the control cut-in speed was not statistically significant (p-value = 0.08). Therefore, we chose the most parsimonious model that only included the linear effect of treatment cut-in speed. This model had no publication bias (Kendall's tau = -0.15, p-value = 0.41; Figure 1.4D). Heterogeneity accounted for 23% of variation (I^2). All but $2.2e^{-7}$% of variation was attributable to inter-annual heterogeneity (i.e., $2.2e^{-7}$% of variation was attributable to among facility heterogeneity).

There was no residual heterogeneity in silver-haired bat fatality reduction when using treatment cut-in speed as a moderator (Q_{16} = 19.9, p-value = 0.22). Increasing cut-in speed had a significant effect on reducing silver-haired bat fatalities (β ± SE = 0.39 ± 0.17, p-value = 0.04). Raising cut-in speed by 1.0 m/s is estimated to reduce silver-haired bat fatalities by 32% (95%CI 3%-53%; Figure 2.5D; Table 1.7).

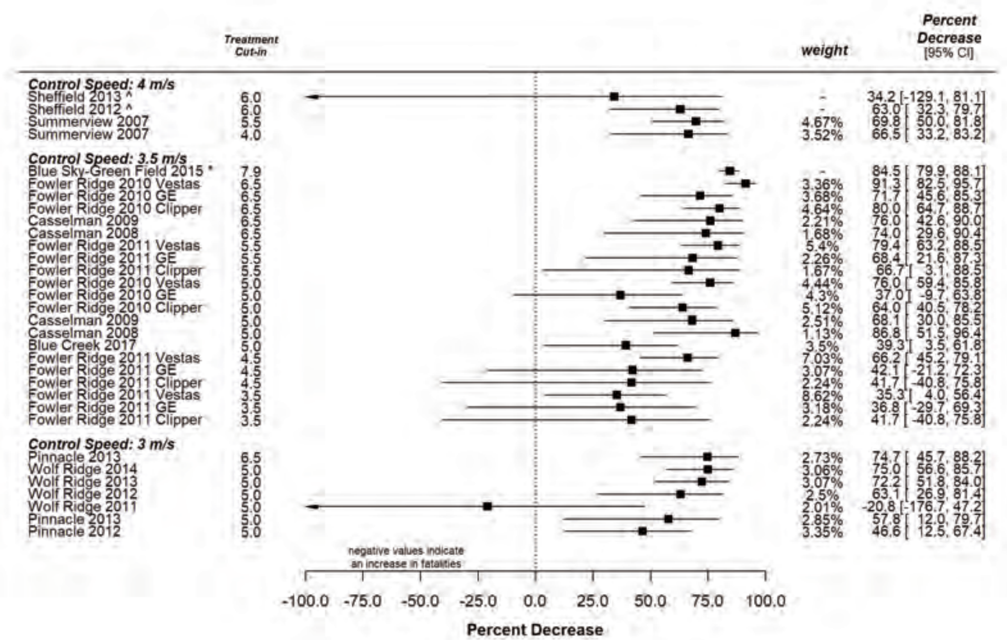

Figure 1.3: Effect size (log ratio of means transformed to percent decrease) of reduction in total bat fatalities from tested operational minimization strategies. Ratios are converted to percentages for interpretation. A higher percent indicates a greater reduction in fatality due to curtailment. A negative percentage indicates an increase in fatalities. Squares represent mean percent difference for individual studies; lines represent the 95% confidence interval. Results from the Sheffield and Blue Sky-Green Field facilities are included for reference only and were not used in the meta-analysis or meta-regression.

Table 1.3: Model ranks and delta AICc values (from top model) for candidate model set (n = 17) tested for each species and total bat fatalities. See Table 1.2 for model descriptions. All models included the same random effect of year nested within facility and a covariance matrix to account for multiple treatments being compared to a single control.

	Total Bats			***Hoary Bat*[1]**			***Eastern Red Bat***			***Silver-haired Bat***		
Model Name	**Rank**	**ΔAICc**	**Weight**	**Rank**	**ΔAICc**	**Weight**	**Rank**	**ΔAICc**	**Weight**	**Rank**	**ΔAICc**	**Weight**
Treatment cut-in speed	1	0	0.72	1	0	0.41	1	0	0.76	1	0	0.44
Cut-in speed (control & treatment)	2	2.25	0.23	4	2.34	0.13	2	3.12	0.16	2	0.51	0.34
Non-linear treatment cut-in	3	6.05	0.04	5	6.24	0.02	4	6.86	0.02	4	1.81	0.18
Cut-in speed & feathering	4	8.33	0.01	8	11.21	<0.01	3	6.82	0.03	5	5.53	0.03
Null model (Random effects only)	5	21.16	<0.01	3	2.06	0.15	5	6.91	0.02	3	7.5	0.01
Turbine characteristics	6	24.92	<0.01	2	0.72	0.29	6	8.97	0.01	6	8.15	<0.01
Study design	7	26.53	<0.01	6	8.35	<0.01	7	10.75	<0.01	7	8.29	<0.01
Geographic	8	29.68	<0.01	7	8.77	<0.01	8	12.86	<0.01	8	11.38	<0.01

[1]Because the turbine characteristics and treatment cut-in speed models were <2 ΔAICc units apart, we combined the significant effects of both models (RSA in turbine characteristics). This new model was the top model and had a weight of 0.48. Treatment cut-in speed had a ΔAICc of 1.60 and weight of 0.21. Adding 1.60 to the shown ΔAICc values determines the other model values.

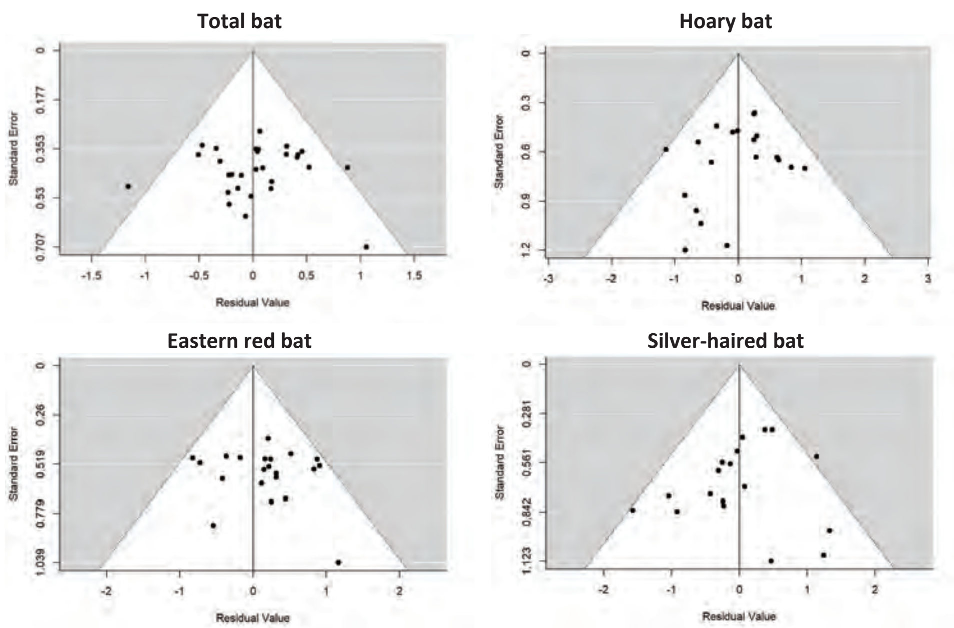

Figure 1.4: Funnel plots of studies used in meta-analysis and meta-regression of reduction in bat fatalities at operational minimization studies for total bat, hoary bat, eastern red bat, and silver-haired bat fatalities. The symmetry of study standard error and residuals around 0 shows lack of publication bias, confirmed by the rank correlation test (total bat fatalities: Kendall's tau = 0.08, p= 0.54; hoary bat fatalities: Kendall's tau = -0.05, p = 0.77; eastern red bat fatalities: Kendall's tau = 1.8, p = 0.27; silver-haired bat fatalities: Kendall's tau = -0.15, p = 0.41).

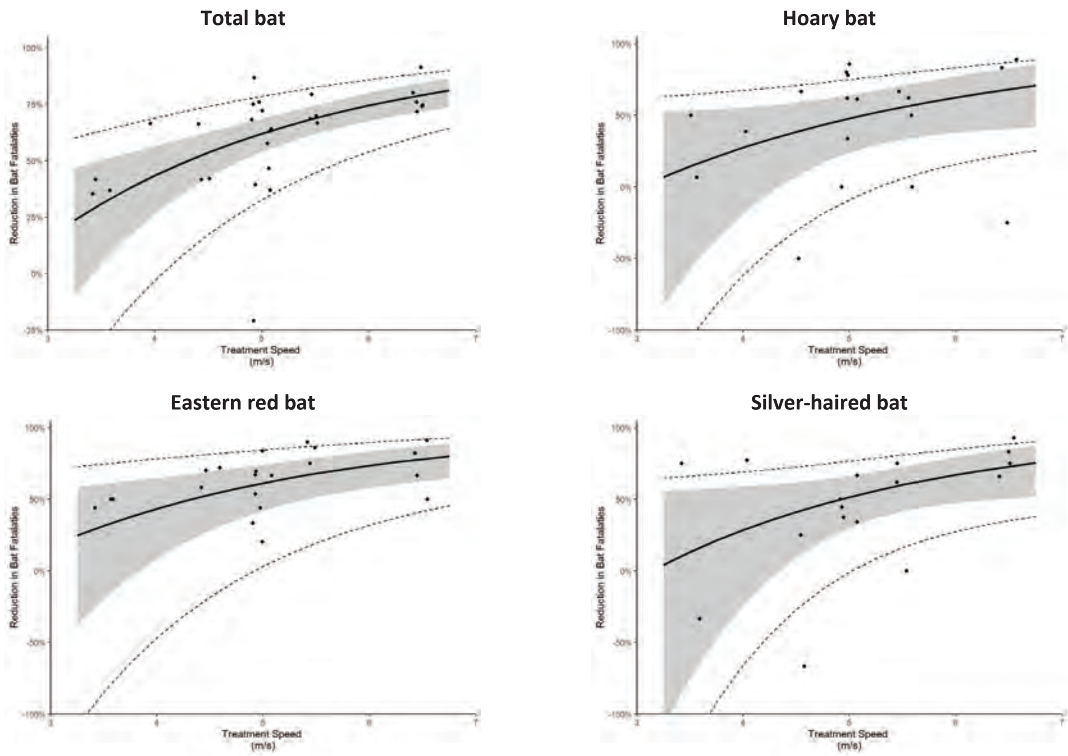

Figure 1.5: Percent reduction of bat fatalities for operational minimization strategies with different treatment cut-in speeds (x-axis) for total bat, hoary bat, eastern red bat, and silver-haired bat fatalities. Mean reduction is represented by the solid line, the 95% confidence interval is represented by the gray ribbon, and a 95% prediction interval (area where 95% of values will fall) is shown by the dashed lines. Data points represent the ratio of mean (ROM) from studies used in the model. No data were available for control or treatment cut-in speeds below 3.5 m/s. Hoary bat (B) fatality reduction is shown at the median rotor swept area of study turbines.

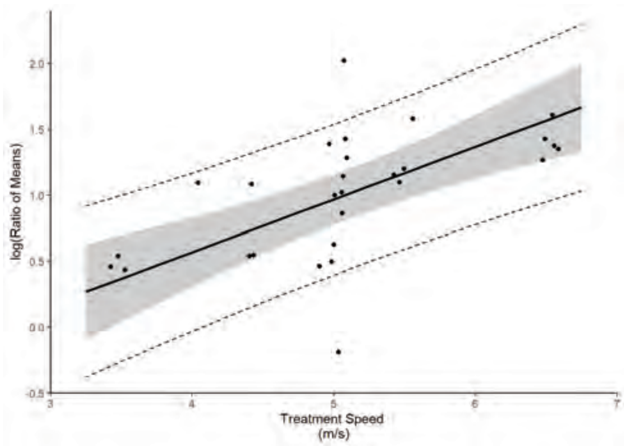

Figure 1.6: Predicted log ratio of control to treatment total bat fatalities for operational minimization strategies with different treatment cut-in speeds (x-axis). This figure represents the same data as Figure 3; however, the Y-axis is not transformed to percent reduction to show that the relationship between the ratio of fatalities and treatment speed is linear. Mean reduction is represented by the solid line with confidence interval represented by the gray ribbon. Prediction interval is shown by the dashed lines. Points represent the ratio of mean of studies used to build the model.

Table 1.4: Predicted total bat fatality reduction for operational minimization cut-in speeds. Mean percent decrease and 95% confidence interval of the mean represent the expected overall decrease in total fatalities at all facilities implementing operational minimization of that treatment cut-in speed. The prediction interval represents the range of values that might be observed at individual facilities.

Treatment Cut-in Speed (m/s)	Mean Percent Decrease	Confidence Interval of Mean		Prediction Interval	
		Lower	Upper	Lower	Upper
3.5	31%	4%	50%	-30%	63%
4.0	43%	26%	56%	-3%	69%
4.5	54%	43%	63%	17%	74%
5.0	62%	54%	69%	33%	79%
5.5	69%	62%	75%	45%	82%
6.0	75%	68%	80%	54%	86%
6.5	79%	72%	85%	61%	89%

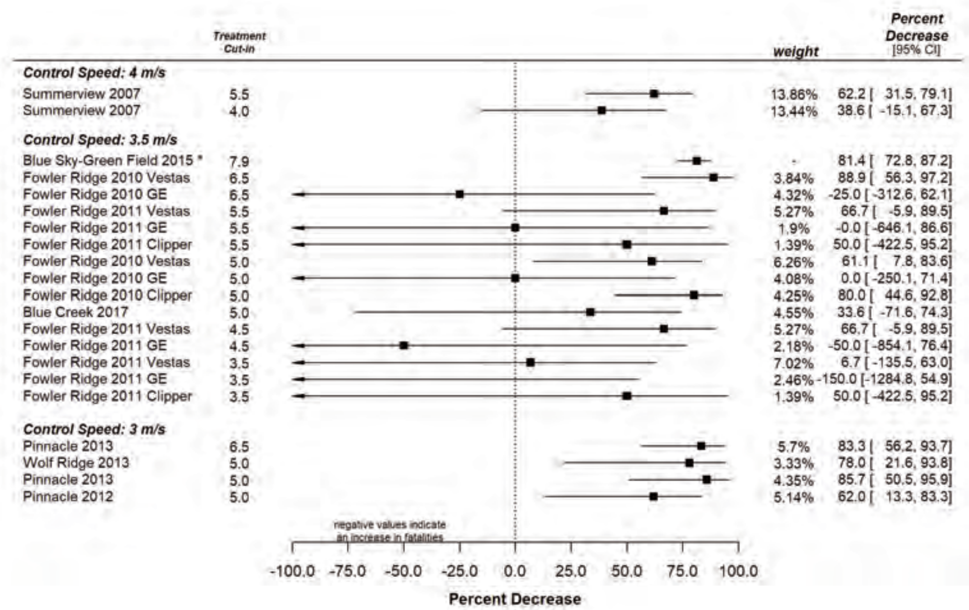

Figure 1.7: Effect size (log ratio of means transformed to percent decrease) of reduction in hoary bat fatalities from tested operational minimization strategies. Ratios are converted to percentages for interpretation. A higher percentage indicates a greater reduction in fatality due to curtailment. A negative percentage indicates an increase in fatalities. Squares represent mean percent difference for individual studies; lines represent the 95% confidence interval. Blue Sky-Green Field results are included for reference only and were not used in the meta-analysis or meta-regression.

Table 1.5: Predicted fatality reduction of hoary bats (*L. cinereus*) across various operational minimization cut-in speeds. Mean percent decrease and confidence interval of the mean represent the expected overall decrease in total fatalities at all facilities implementing operational minimization of that treatment cut-in speed. The prediction interval represents the range of values that might be observed at individual facilities.

Treatment Cut-in Speed (m/s)	Mean Percent Decrease	Confidence Interval of Mean		Prediction Interval	
		Lower	Upper	Lower	Upper
3.5	14%	-57%	53%	-106%	64%
4.0	27%	-19%	56%	-62%	67%
4.5	38%	8%	59%	-30%	71%
5.0	48%	24%	64%	-9%	75%
5.5	56%	33%	71%	6%	79%
6.0	63%	38%	77%	16%	83%
6.5	68%	41%	83%	23%	87%

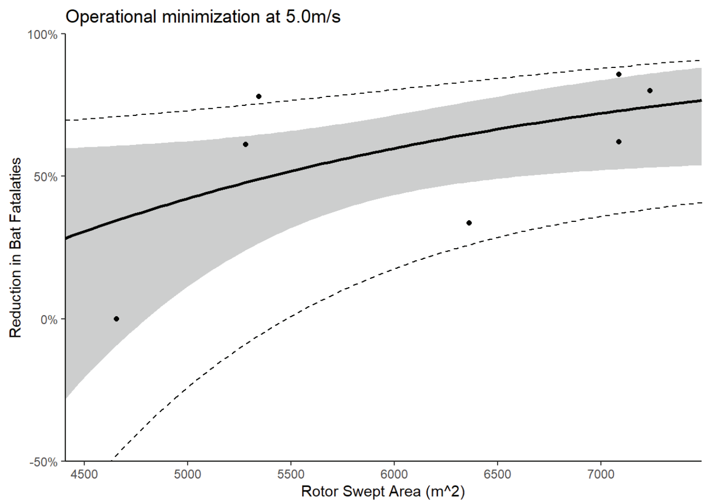

Figure 1.8: Relationship between rotor swept area and predicted percent reduction of hoary bats when turbines were curtailed at 5.0 m/s. Mean reduction is represented by the solid line with confidence interval represented by the gray ribbon. Prediction interval is shown by the dashed lines. Points represent the percent reduction of studies with operational minimization of 5.0 m/s.

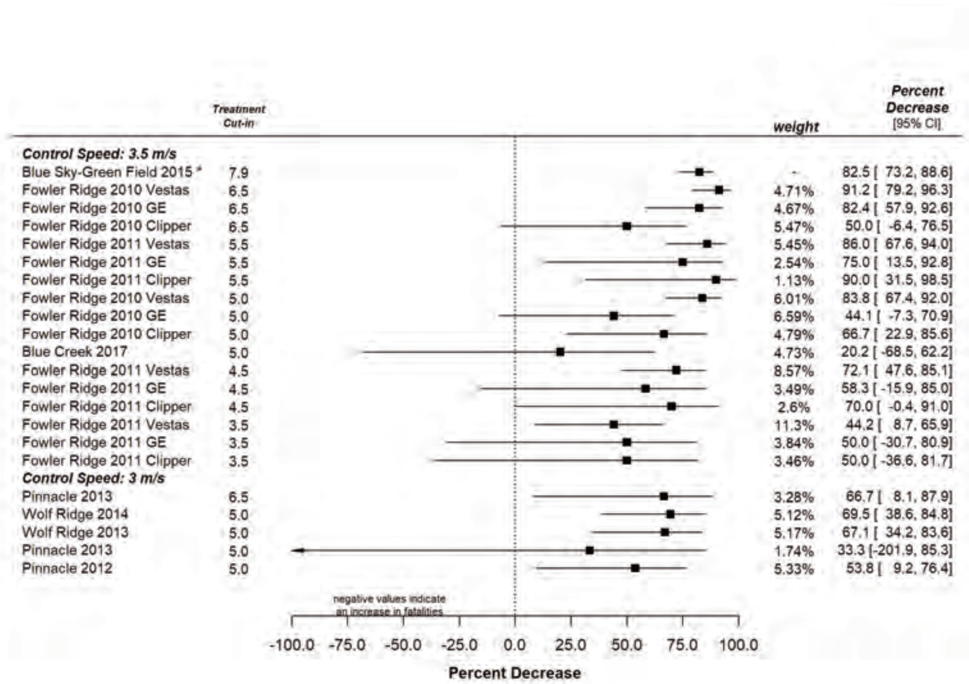

Figure 1.9: Effect size (log ratio of means transformed to percent decrease) of reduction in eastern red bat fatalities from tested operational minimization strategies. Ratios are converted to percentages for interpretation. A higher percentage indicates a greater reduction in fatality due to curtailment. A negative percentage indicates an increase in fatalities. Squares represent mean percent difference for individual studies; lines represent the 95% confidence interval. Blue Sky-Green Field results are included for reference only and were not used in the meta-analysis or meta-regression.

Table 1.6: Predicted fatality reduction of eastern red bats (*L. borealis*) across operational minimization cut-in speeds. Mean percent decrease and confidence interval of the mean represent the expected overall decrease in total fatalities at all facilities implementing operational minimization of that treatment cut-in speed. The prediction interval represents the range of values that might be observed at individual facilities.

Treatment Cut-in Speed (m/s)	**Mean Percent Decrease**	**Confidence Interval of Mean**		**Prediction Interval**	
		Lower	Upper	Lower	Upper
3.5	32%	-19%	61%	-85%	75%
4.0	43%	8%	65%	-47%	78%
4.5	53%	28%	69%	-18%	81%
5.0	61%	42%	74%	3%	85%
5.5	68%	51%	79%	20%	87%
6.0	74%	58%	83%	32%	90%
6.5	78%	63%	87%	42%	92%

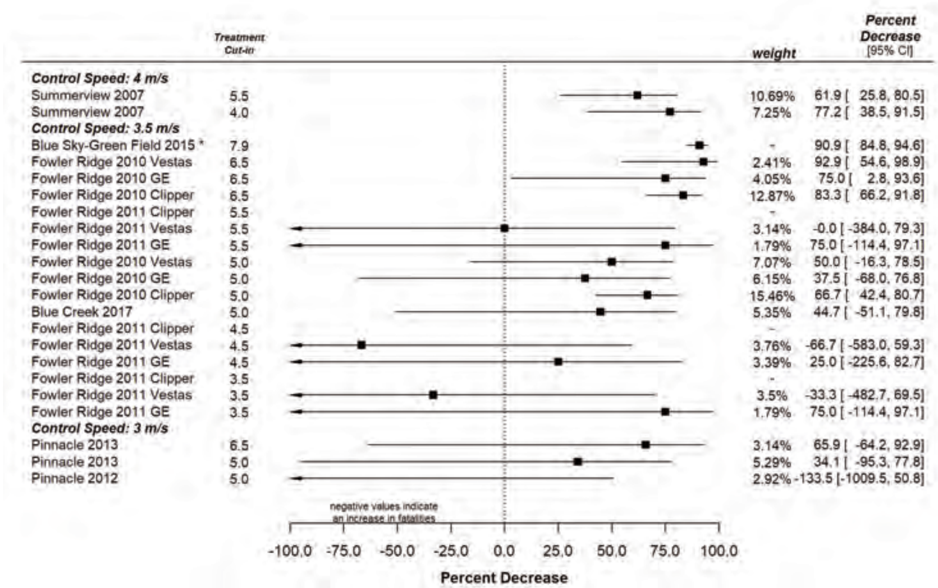

Figure 1.10: Effect size (log ratio of means) of reduction in silver-haired bat fatalities from tested operational minimization strategies. Ratios are converted to percentages for interpretation. A higher percent indicates a greater reduction in fatality due to curtailment. A negative percentage indicates an increase in fatalities. Squares represent mean percent difference for individual studies; lines represent the 95% confidence interval. Blue Sky-Green Field results are included for reference only and were not used in the meta-analysis or meta-regression. Clipper Turbines at Fowler Ridge in 2011 had almost zero silver-haired bat fatalities at control turbines and an increased fatality rate at treatment turbines; this resulted in large percent increases in fatalities that cannot be reasonably graphed or included in analysis.

Table 1.7: Predicted fatality reduction of silvered-haired bats (*Lasionycteris noctivagans*) across operational minimization cut-in speeds. Mean percent decrease and confidence interval of the mean represent the expected overall decrease in total fatalities at all facilities implementing operational minimization of that treatment cut-in speed. The prediction interval represents the range of values that might be observed at individual facilities.

Treatment Cut-in Speed (m/s)	**Mean Percent Decrease**	**Confidence Interval of Mean**		**Prediction Interval**	
		Lower	Upper	Lower	Upper
3.5	13%	-75%	57%	-123%	66%
4.0	29%	-24%	59%	-66%	69%
4.5	41%	9%	62%	-27%	73%
5.0	52%	30%	66%	-1%	77%
5.5	60%	42%	73%	16%	81%
6.0	67%	47%	79%	28%	85%
6.5	73%	51%	85%	35%	89%

Table 1.8 Summary of important statistics from top model explaining the heterogeneity of operational minimization for total bat fatalities and fatalities of individual bat species.

	Total bat	**Hoary bat**	**Eastern red bat**	**Silver-haired bat**
Beta coefficient (slope) of treatment cut-in speed	0.40	0.33	0.39	0.38
% reduction every +1 m/s	33%	28%	32%	32%
Expected reduction in fatalities with a 5.0 m/s treatment	62%	48%	61%	52%
I^2 – sum of facility + inter-annual	40%	23%	47%	23%
I^2 from Facility	<1%	<1%	17%	<1%
I^2 Inter-annual (within-facility)	40%	23%	30%	23%

Discussion

We show that operational minimization is an effective strategy for reducing bat fatalities at wind energy facilities in the United States. The efficacy is measurable, reducing total fatalities by 33% with every 1.0 m/s increase in cut-in speed and was similar for three individual species (28% for hoary bats, 32% for eastern red bats, and 32% for silver-haired bats). Our results show that a 5.0 m/s cut-in speed can reduce total bat fatalities across facilities and time periods by an average of 62% (95% CI: 54–69%). Similar declines in fatality for a 5.0 m/s cut-in speed was estimated for hoary bats (48%; 95% CI: 24%–64%), eastern red bats (61%; 95% CI: 42–74%), and silver-haired bats (52%; 95% CI: 30%–66%).

Our results from the meta-regression analysis demonstrate that efficacy of operational minimization to reduce bat fatalities was not highly variable among facilities nor among turbine types (i.e., rotor swept areas or hub height), suggesting that operational minimization can be expected to be effective at reducing bat fatalities across facilities and turbine types. For hoary bats, efficacy of operational minimization at reducing fatalities increased slightly with rotor swept area size. However, sampling is minimal especially at low RSA’s. These results suggest slightly greater reduction in hoary bat fatalities as larger turbine sizes become used in operational minimization; however more research is needed to investigate this possible relationship.

Individual studies of operational minimization often lack the statistical power to detect decreases in fatalities between multiple curtailment speeds or species given natural variability in fatality rates coupled with experimental design constraints (e.g., number of observed fatalities and low sample sizes (number of turbines)). Using meta-analysis, we were able to leverage the combined efforts of individual studies to determine the overall efficacy of operational minimization as well as understand key sources of variability that are helpful in determining the general applicability of operational minimization to reduce bat fatalities. We could not include individual studies that failed to report measures of variation in their estimates of fatality reduction in the meta-analysis, limiting their utility to inform broader inference and identify important sources of variation.

Our approach provides a framework that can incorporate results from future studies to make comparisons of regional differences or compare the efficacy of different minimization strategies (e.g., are acoustic sound emitters as effective as operational minimization?). Various research efforts are currently focused on improving ways to predict fatality risk to enable more precise conditions under which operations are minimized to reduce bat fatality rates (e.g., https://www.energy.gov/eere/articles/energy-department-awards-68-million-wind-energy-research-projects). Comparison of efficacy of these new approaches will be feasible as more studies become available.

Our results suggest an overall stronger effect of fatality reduction of 69% (95% CI: 62–75) compared to a mean reduction of 53% at a cut-in speed of 5.5 m/s reported by an unpublished study using quantitative meta-analysis of curtailment efforts at 12 facilities across Ontario, Canada (Zimmerling et al. 2016). This can be expected since our approach differed from Zimmerling et al. (2016). We restricted our meta-analysis to comparisons of control and treatments made in the same year at the same location. We show that most variation in the efficacy of operational minimization can be attributed to interannual variation, which can make comparing fatality rates among years difficult. Accounting for inter-annual variation in fatality rates improved the estimate of efficacy of operational minimization.

While plot size was not informative in our models (Table 1.3), there was little variability in the plot sizes included in our study and it still could influence results. If carcasses land farther from the turbine as wind speed increases, including more carcasses landing beyond the search plot perimeter, then fatality reduction will be underestimated at higher wind speeds and overestimated at low wind speeds. Huso (2018) found that the proportion of carcasses that land >60 m of the turbine base increased consistently with increasing wind speed. Most curtailment studies limit search area to within 60 m, which likely results in estimating a stronger curtailment effect on reducing fatalities than what actually occurs. Schirmacher et al. (2016) tested control turbines (3.5 m/s) and curtailed turbines (5.0 m/s) with 90 m radius plots and found a non-significant effect of 0–38% reduction in bat fatalities. They had enough statistical power to detect a 50% reduction for turbines curtailed to 5.0 m/s. Future studies should account for this bias by having plots sizes >60 m to quantify the effect of curtailment on reducing bat fatality.

Our understanding of how operational minimization is implemented across the United States remains largely unknown. Wind energy operators in the United States made a progressive action in 2015 and issued a best management practice to feather turbine blades below the manufacturer's cut-in speed during the autumn migration period when temperatures are above 50°F, when financially feasible (AWEA 2015). The implementation of this best management practice across facilities has not been compiled. In some cases, operational minimization up to 6.9 m/s has been voluntarily accepted by operators, in negotiation with the U.S. Fish and Wildlife Service, to minimize and avoid risks to bat species protected under the Endangered Species Act. These actions and accompanying fatality monitoring are sometimes made publicly available through the U.S. Fish and Wildlife Service or state wildlife agency (e.g., Fowler Ridge results included in this study). However, not all actions in response to state or federal regulation are reported or easily accessible. Moreover, when curtailment is implemented in coordination with government guidance or negotiation, there is rarely a research component associated with it to assess its effectiveness.

While we demonstrate that operational minimization is effective at reducing bat fatalities, specifying target levels of reduction to reduce risk to bat populations is a separate issue. Evaluating population viability relies on understanding the population size, underlying demographic parameters of populations (e.g. survival rate, reproductive rate), and fatality rates. Empirical estimates of bat fatalities at wind energy facilities in the U.S. and Canada suggest hundreds of thousands of bats were killed by wind turbines in 2012 (Arnett and Baerwald 2013, Hayes 2013, Smallwood 2013). However, data on population sizes of migratory tree bat species remains a critical knowledge gap (Frick et al. 2017, Electric Power Research Institute [EPRI] 2020). Population models for the hoary bat, which account for 38% of documented fatalities at wind farms (Arnett and Baerwald 2013), show that a 50% decline in hoary bats by 2050 may occur given current fatality rates and buildout—unless the initial population in 2012 was greater than 10 million (EPRI 2020). The effect of fatalities associated with wind energy buildout on hoary bats would be greater if populations are already declining due to other threats like climate change and habitat destruction (EPRI 2020). No modeling efforts have yet been made to assess risk of population declines or extinction for eastern red bats or silver-haired bats, which comprise 22% and 19% of documented fatalities at wind farms (Arnett and Baerwald 2013), respectively. Other substantial sources of observable direct mortality or quantifiable anthropogenic impact to migratory tree bats in North America are not documented (Cryan 2011, O'Shea et al. 2016).

OBJECTIVE 2: Narrative Review of Studies of Operational Minimization to Reduce Bat Fatalities at Wind Energy Facilities

We quantified the efficacy of operational minimization across various cut-in speeds using meta-analysis in Objective 1 of this report. However, additional studies and treatments were not included in the meta-analysis if they didn't report information that met the criteria for meta-analysis (i.e., did not include a measure of variation) or they conducted treatments that were too unique to be included (e.g., half-night treatments). Here, we review and discuss studies and topics that could not be addressed in our quantitative meta-analysis to review past efforts that might inform the direction of future research.

We gathered reports and peer reviewed literature cited in the BWEC bibliography, conducted a general google scholar search for "bats AND curtailment", consulted the Conservation Evidence database (www.conservationevidence.com), and used presentations and posters made available to us from authors or archived on conference websites. For detailed information on the list of each study reviewed, we include citation information and abstracts of each study in Appendix II.

Many of the studies we reviewed sought to improve the efficiency of operational minimization by maximizing fatality reduction while simultaneously minimizing the amount of power lost. Methods to do so broadly follow the areas recommended for future study made by Arnett et al. (2013) including temperature, time of night, and bat activity. We also identify areas of research that were common among the studies or are topics often raised in discussion of operational minimization results including wind direction, location and time-period of wind measurements, and the effect of feathering blades below cut-in speed. We discuss studies that examined the effects on individual species, particularly those of regulatory concern in the United States. Next, we briefly report results from studies that compared fatality rates in years with and without operational minimization. We conclude with a discussion of the factors that influence statistical power of studies to detect the anticipated changes in fatality rates.

Use of Temperature to Improve Efficiency of Operational Minimization

Only one publicly available study has evaluated the use of temperature to determine when operational minimization should occur to reduce fatality rates of bats. Martin et al. (2017) evaluated the efficacy of operational minimization implemented when wind speed was less than 6.0 m/s and temperature was above 9.5 °C (49.1 °F) at the Sheffield Wind Facility, VT. Over the course of two years, this curtailment strategy reduced bat fatalities by 62% (95%CI 34%–78%). Because treatments did not also include an operational minimization decision based exclusively on wind speed, it is impossible to compare the effectiveness of including temperature in a curtailment decision to only including wind speed. The authors compared the amount of time that both treatment types would have been implemented and found that the wind speed-temperature design was implemented an average of 44% each night, whereas the wind speed-only design would have been implemented 49% of the time. The minimal difference in implementation time makes it likely that results of both treatment strategies would be similar; however, this hypothesis remains untested. Additional public studies on the effectiveness of including temperature in operational minimization, especially in comparison to wind-speed only curtailment, are needed.

Use of Nocturnal Timing to Improve Efficiency of Operational Minimization

Three studies attempted to improve the efficiency of operational minimization by increasing the cut-in speed for only part of the night. At Mount Storm, West Virginia turbines were feathered up to the cut-in speed (4.0 m/s) for both 5 hours after sunset or 5 hours before sunrise (Young et al. 2011). These treatments reduced fatalities by 73% and 51%, respectively. No all-night treatment was applied. The other two studies (ANON 2—Arnett et al. 2013 and Pinnacle Wind Farm—Hein et al. 2013) did not show a statistically significant reduction in bat fatalities when the treatment was applied for the first 4 hours of the night. However, the anonymous study from the southwestern U.S. did show a similar estimated percent decline in fatalities between treatments implemented all night (32.6%) and those implemented for the first 4 hours (34.5%).

The use of post-construction acoustic monitoring and thermal video cameras are providing more insight into the timing and conditions of bat/wind turbine interactions (Cryan et al. 2014). However, more data are needed to determine whether a curtailment strategy based on the time of night will be effective. It will be difficult to evaluate if curtailment can be limited to a portion of the night until a nightly temporal distribution of bat fatalities can be determined, and this may vary across sites, species, or regions, making it challenging to apply a one-size-fits-all strategy for using time of night as part of a smart curtailment strategy.

Use of Bat Activity to Improve Efficiency of Operational Minimization

Recent research has shown that post-construction acoustic activity is sometimes correlated with bat fatality rates at wind turbines (Peterson 2020). Incorporating these predictive models of acoustic activity into curtailment efforts is an active area of research. The first efforts to use acoustics to inform curtailment include studies conducted in Europe. Behr et al. (2017) describe an approach that used acoustic activity to predict collision risk at 10-minute intervals to make curtailment decisions at individual turbines in Germany. The authors developed an n-mixture model to predict the number of nightly fatalities from acoustic data and then developed a model to predict 10-minute acoustic activity at a turbine from weather variables. The n-mixture model predicted a 10-minute fatality rate from the predicted 10-minute acoustic activity. Finally, a wind speed threshold was set based on an acceptable fatality rate. The effectiveness of this approach at reducing fatalities was not tested. However, real turbine data were used to calculate the expected power loss. When applied year-round, the power loss for this predictive method was 1.4% of annual revenue. The power loss for blanket curtailment based only on wind speed was 1.8%.

In Switzerland, wind facilities must reduce bat fatality risk by 95%. This is considered accomplished if the turbine is not operating when 95% or more of bat calls at the turbine are recorded. One study evaluated differences and similarities between making shut down decisions based on predicting activity with environmental variables and real-time acoustics. Both methods showed similar effectiveness.. Additionally, the time shutdown and associated power losses were equal between the real-time acoustic and environmental monitoring methods (Mehmet et al. 2015).

In North America, we know of only one study to use real-time acoustics to inform curtailment efforts (Hayes et al. 2019). Blue Sky Green Field implemented an 8.0 m/s cut-in speed when a bat was detected at any one of four bat detectors operating in real-time at the facility. The study found that this curtailment effort reduced overall bat fatalities by 83% and little brown bat (*Myotis lucifugus*) fatalities by 90% at model-operated turbines compared with normally operated turbines. Hoary bat fatalities were reduced by 81%. The lack of comparison to other operational minimization treatments during this study (e.g., curtailment at 5.0 m/s) makes it difficult to assess this 'smart curtailment' effort relative to blanket curtailment scenarios. Using acoustic activity to trigger 'smart curtailment' resulted in curtailment occurring only 48% of the time blanket curtailment would have been implemented.

Use of Wind Direction to Improve Efficiency of Operational Minimization

One study evaluated a variable cut-in speed based on wind direction. Hale and Bennet (2014) determined cut-in speed for wind directions based on the correlation between a daily fatality index and wind direction. Cut-in speeds varied from 3.0 m/s to 6.5 m/s. They conducted the effort for 4 years in conjunction with a control and standard treatment of increased cut-in speed to 5.0 m/s. In 2010, no treatment was effective at reducing the abnormally low fatality rates. In 2011, both treatments reduced fatality rates but were not statistically different in effectiveness. In 2013 and 2014, a modified wind direction treatment reduced fatalities more than the wind speed treatment alone. The wind direction treatment increased both the time the treatment was implemented and the loss in power production. Lost power production was approximately 3 times higher compared to wind speed only treatment.

Improving Measurements of Wind Speed to Improve Efficiency of Operational Minimization

How and where wind speed is measured affects when and how often curtailment efforts are implemented. However, information on how wind speeds are measured is not generally available in reports. Information on the location and timing of wind speed measurement is necessary to evaluate differences between curtailment studies and to recommend implementation practices.

Schirmacher et al. (2016) found a significantly greater decrease in fatalities at treatment turbines using wind measurements from the meteorological tower compared to treatment turbines making operating decisions with the onboard anemometer. Both treatments used the same cut-in speed of 5.0 m/s. Wind speed measurements from the turbines were on average 1.0 m/s higher than those measured at the meteorological tower at a similar height (within 4 m).

Measuring wind speed over a shorter period is more likely to capture hysteresis events (i.e., wind gusts), which inflate the average wind speed and cause turbines to operate at wind speeds lower than the curtailment threshold. Schirmacher et al. (2016) compared operational minimization treatments with a cut-in speed of 5.0 m/s using a 10-minute and 20-minute rolling average. Using a 20-minute rolling average treatment to make curtailment decisions reduced fatalities, the amount of lost power, and equipment wear and tear (i.e., associated with the repeated starts and stops). They hypothesized that changing the decision framework or increasing the time-period wind speed is measured might be a more cost-effective strategy compared to increasing the cut-in speed, although this has yet to be tested.

Feathering below Manufacturer's Cut-in Speed as Operational Minimization

Traditional operation of wind turbines usually allows blades to spin below turbine manufacturer's cut-in speed or the wind-speed at which the turbine generates usable electricity (i.e., cut-in speed). This process is generally referred to as 'free-wheeling'. Under normal operation, free-wheeling speed can increase with wind-speed even though electricity is not being produced (e.g., Figure 2.1 solid line). This movement allows the production of energy almost immediately when wind speeds reach the cut-in speed. If blades are feathered below the cut-in, blades must 'ramp up' to the appropriate speed to generate electricity, although the loss of production has been described as relatively minimal. Preventing turbine blades from turning at low wind speeds (e.g., feathering below manufacturer's cut-in speed) has been considered as a separate action than raising the cut-in speed and has been shown to be effective at reducing fatalities (Berthinussen et al. 2020). However, the fatality reduction achieved by raising the cut-in speed is the strongest driver of fatality reduction according to the model results from the meta-analysis.

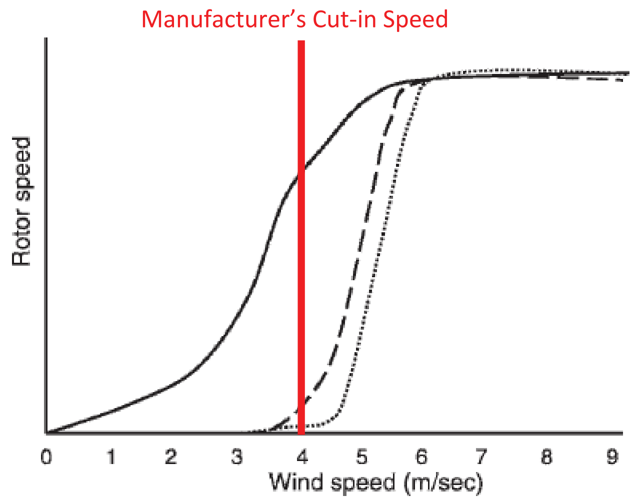

Figure 2.1: Recreated from Baerwald et al. (2009). Schematic of the relationship between wind speed (m/s) and turbine rotor-speed (revolutions/min) for the 3 turbine operations used to examine whether reducing the amount that turbine rotors turn in low wind speeds would reduce bat fatalities in Alberta, Canada, 2006–2007. Solid line represents operation of control turbines with a 4.0 m/second cut-in speed and high-speed idle operation at low wind speeds. Dashed line indicates operation of turbines under the low speed idle protocol in which blade angles were pitched (~30%) to reduce rotor speed in low wind speed. Dotted line indicates operation of turbines with increased rotor start-up speed of 5.5 m/s.

The inclusion of feathering as a separate model term in the meta-analysis did not explain additional variation. This does not suggest that feathering below cut-in speed is an ineffective tool. Feathering below cut-in speed has a highly variable impact on blade tip speed depending on turbine makes and models. For some models feathering is similar to raising cut-in speed, in that it raises the wind speed at which blades to spin. For example, at Fowler Ridge wind farm, GE turbines had similar blade tip speeds when feathered and operating normally; however, there was a large difference in blade tip speed when feathering below cut-in speed for Vestas Turbines (Figure 2.2). Feathering blades increased the blade tip speed of Clipper turbines at Fowler Ridge (Figure 2.2). Re-analysis of Fowler Ridge fatality data from 2011 indicated that GE turbine fatality rates were lower than the Clipper and Vestas turbines (Appendix III). However, the relationship between blade-tip speed and bat fatality rates remains unclear.

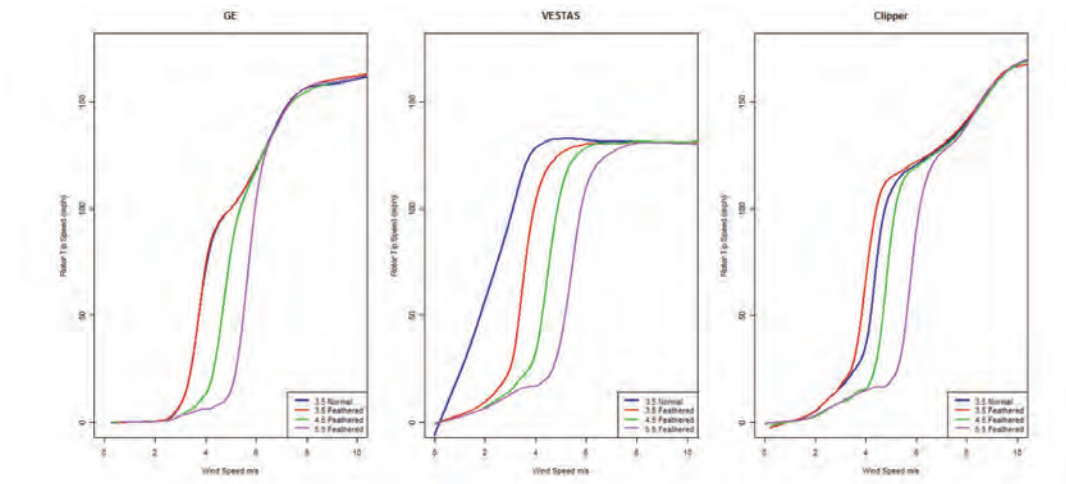

Figure 2.2: Recreated from Good et al. 2012 Figure 13 — Estimated tip speed by wind speed for cut-in speed adjustments at GE, Clipper, and Vestas wind turbines during the 2011 carcass monitoring at the Fowler Ridge Wind Farm. Estimates were made based on Friedman's SuperSmoother (Friedman 1984).

Efficacy of Operational Minimization on Individual Species

Effectiveness of curtailment for individual species, especially those legally protected by state and federal governments, is an area of interest for both industry and conservation groups. Unfortunately, statistically analyzing results of individual species is difficult given typically small sample sizes and limited available data. Objective 1 describes a similar efficacy of operational minimization for the three species most commonly reported at wind energy facilities in North America. We found no reports on the efficacy of operational minimization for federally protected species in the continental United States. One study (Hayes et al. 2019) reported fatality rates for the little brown bat (*Myotis lucifugus*), a species of concern due to precipitous declines caused by White-nose Syndrome (Frick et al. 2015, Frick et al. 2010). Hayes et al. (2019) estimated a 91.4% reduction in little brown bat fatalities using an operational minimization speed of 8.0 m/s when bats were present (see *Bat Activity* section above).

A comparison of bat fatalities at multiple wind farms in Ontario included species-level results for a *Myotis* species group (Zimmerling 2016). This study examined the effects of a 5.5 m/s cut-in speed at individual turbines. They found no significant difference in fatality rates between years with or without operational minimization. However, fatalities of *Myotis* species were estimated to be lower at all facilities with the increased cut-in speed. However, it is important to note that the effectiveness of curtailment were not evaluated during experimental studies comparing treatment to control conditions within the same year.

Inter-annual Variation in Fatality Rates Limits Comparing Efficacy of Operational Minimization

Five studies evaluated the effectiveness of operational minimization strategies by comparing fatality rates during separate time periods (most often years) during which turbines were operated under different protocols. Comparing fatality rates in separate time periods introduces problematic sources of variation that can confound results. To do this with high confidence, the variation in bat fatalities between time periods at a site needs to be quantified; however, no study that we reviewed did this. Thus, individual results are highly speculative and inconclusive. Nonetheless, patterns that emerge can be used to inspire more rigorous studies that examine the efficacy of treatments.

Wildcat Wind Farm in Indiana published spring and fall fatality rates over 5 years under different cut-in regimes (Stantec 2017). While difficult to make comparisons among years, there was a trend that indicated that 5.0 m/s might reduce fatalities compared to 3.5 m/s in the spring. Similarly, a trend of reducing fatalities was seen in the fall as cut in speeds increased from 3.5, 5.0, and 6.9 m/s.

Fowler Ridge Wind Facility reported fatality rates for six years (2012–2017) while operating under operational minimization with a cut-in speed of 5.0 m/s (Good et al. 2018). They compared these fatality rates to the initial year of monitoring (2010). They estimate a greater than 50% reduction in fatality for all years under operational minimization.

Criterion Wind Facility in Maryland raised the cut in speed from 4.0 m/s to 5.0 m/s for a similar study period in 2011 and 2012. They report a 51% decrease in fatality rate for 2012 while operating under the 5.0 m/s cut-in speed. Since the study was only reported over two years, the natural variation in fatalities for fully operational turbines is unknown; therefore, this result could be due to the high degree of natural variation seen between years at a single site.

Two wind energy facilities on the Hawaiian island of Maui (Auwahi and Kaheawa I) examined the effectiveness of increasing cut in speed on the fatality estimates of Hawaiian hoary bats (*L. c. semotus;* Snetsinger et al. 2016*)*. At the Auwahi facility, curtailment of 5.0–5.5 m/s was used from Feb 15th to Dec 15th, 2014 and 2015. All years post implementation had mean fatality estimates within the confidence interval of at least one pre-curtailment year. The 2014 and 2015 mean fatality rate was over 50% lower than the 2012 and 2013 fatality rates, but similar to fatality rates of 2011. At the Kaheawa I Facility curtailment of 5.0 m/s was implemented year-round in 2015 and 2016. Fatality rates of all years overlapped; however, the mean fatality estimate of 2016 (under curtailment) was over twice the 2014 estimate (the highest pre-curtailment estimate). The studies on Hawaii emphasize the high degree of interannual variation in fatality rates. This fact is more pronounced on Hawaii due to an overall low fatality rate (often less than 1 bat per turbine).

Beech Ridge Wind Farm in West Virginia, USA compared the site's 2012 fatality rate to the regional average (Tidhar et al. 2013). Beech Ridge Wind Farm operated all turbines at an increased cut-in speed of 6.9 m/s. They estimated a 73% decrease in fatalities from facilities across eastern North America, a 73% decrease in fatalities in the Northeast region, and an 89% reduction from two other facilities in West Virginia. No confidence intervals for this estimate were provided and confidence intervals of fatality estimates were not used. Additionally, it is unclear how multiple years at a facility were combined. This comparison does not account for variation presented by inter-annual variation, site variability, and turbine characteristics.

In Ontario, Canada the effectiveness of a 5.5 m/s cut-in speed at individual turbines across 12 wind energy facilities was examined (Zimmerling et al. 2016). The study required fatality estimates for one-year of each treatment for turbines to be included; therefore, the interannual variation in fatality rate of each turbines could not be calculated. The study reports an average 53% reduction in fatalities across all turbines by implementing a 5.5 m/s cut-in speed. This reduction was statistically significant at 7 of the 12 wind farms; however, the mean prediction for every site was that a reduction in fatalities occurred with an increase in cut-in speed.

Factors Influential for Statistical Inference in Operational Minimization Studies

Study Design — Minimizing variation within studies improves the ability to make strong statistical conclusions and inference. Limiting variables introduced by the study design enhances ability to statistically detect a change when it exists, whereas introduction of variability through poor study design often leads to inconclusive results that fail to detect a difference, even when one exists. Studies that include multiple turbine types or search protocols should account for higher sources of variability in their analysis. Study designs that properly account for variation allows results to be compared and compiled in a synthesis or meta-analysis for inference and utility beyond the scope of the single study.

Plot Size—Effects of raising the cut-in speed may be biased to indicate greater reduction in fatalities if wind speed affects where carcasses land on the ground after a turbine strike. If carcasses land farther from the turbine as wind speed increases, including more carcasses landing beyond the search plot perimeter, then fatality reduction will be underestimated at higher wind speeds and overestimated at low wind speeds. Huso (2018) found that the proportion of carcasses that land >60 m of the turbine base increased consistently with increasing wind speed. Most curtailment studies limit search area to within 60 m, which likely results in estimating a stronger curtailment effect on reducing fatalities than what actually occurs. Schirmacher et al. (2016) tested control turbines (3.5 m/s) and curtailed turbines (5.0 m/s) with 90 m radius plots and found a non-significant effect of 0–38% reduction in bat fatalities. They had enough statistical power to detect a 50% reduction for turbines curtailed to 5.0 m/s. Future studies should account for this bias by having plots sizes >60 m to quantify the effect of curtailment on reducing bat fatality. In addition, power analysis should allow for study designs capable of estimating reductions of less than 50%.

Length of Time Implemented— Arnett et al. (2013) noted that:

> *studies that did not demonstrate statistically significant effects could be explained by lack of treatments being implemented during the study (i.e., winds were either too low or high to enable comparison of treatments)*

Arnett et al. (2010) demonstrated this point by showing the operating status of treatments at Casselman wind energy facility during a curtailment study with a control and two operational minimization treatments (Table 2.1). The two treatments (5.0 m/s and 6.5 m/s) were only operating differently when wind speed was 5.1–6.5 m/s. If these conditions did not exist frequently, then the expected reduction would decrease. This point was emphasized in Hein et al. (2014). In their study at Pinnacle Wind Facility, West Virginia, the proportion of night that the treatment was implemented was a significant parameter in explaining the number of observed fatalities during operational minimization.

Table 2.1: Possible turbine conditions ("feathered" or "rotating") under different treatments and wind conditions at the Casselman Wind Project in Somerset County, Pennsylvania. Under the treatment condition when wind is <3.5 m/s, we expected all turbines to be feathered with no rotation. (*Recreated from Arnett et al. 2010 Table 1*)

Treatment	**Wind Speed (m/s)**			
	< 3.5	**3.5–5.0**	**5.1–6.5**	**> 6.5**
5.0 m/s	Feathered/ No rotation	**Feathered/ No rotation**	No feathering/ Full rotation	No feathering/ Full rotation
6.5 m/s	Feathered/ No rotation	**Feathered/ No rotation**	**Feathered/ No rotation**	No feathering/ Full rotation
Fully Operational	Feathered/ No rotation	No feathering/ Full rotation	No feathering/ Full rotation	No feathering/ Full rotation

Statistical Power—Low effect size between treatments can be attributed to the lack of time a treatment is implemented and the number of fatalities that are observed at higher wind speed. For example, take a hypothetical study to test the efficacy of 5.0 m/s and 6.0 m/s curtailment scenarios with a control condition of 2.5 m/s. Assume an average fatality rate of 20 bats/turbine during the study period. Using the results of the meta-analysis (objective 2), we would expect a decrease in fatalities of 62% for the 5.0 m/s treatment and a reduction of 75% for the 6.0 m/s treatment (both reductions relative to the control). That would translate to expected fatalities of 7.6 and 5 for the 5.0 m/s and 6.0 m/s treatment respectively. Increasing the cut-in speed by 1.0 m/s (5.0–6.0m/s) thus decreases fatalities by just over 33% between 5.0 and 6.0 m/s treatments (7.6-(7.6*0.33)=5.09 — slight difference due to rounding). This smaller effect size (2.5 bats) is difficult to detect statistically, especially when there is high variability.

Observed bat fatalities for the studies that did not detect a significant difference were less than the hypothetical scenario above. Two studies had estimated control fatality of 10–15 bats/turbine during the study. Four other studies had control fatalities of 2–5 bats/turbine/period or an effect size of 0.36–1.15 bats/turbine/period with the same hypothetical reductions. The only studies that detected a statistical difference had either a high number of turbines (Fowler Ridge 2011, 168 turbines) or a high fatality rate in the study (Pinnacle 2013, 90 bats/turbine/study period). These results emphasize the importance of power analysis to determine the appropriate sample size of future studies. Post-hoc power analysis can be used to evaluate study designs ability to statistically detect differences and can inform interpretation of statistical results.

OBJECTIVE 3: POWER LOSS ASSOCIATED WITH CURTAILMENT

The annual energy production (AEP), or total amount of electrical energy produced over a year, is influenced by several factors, including the prescribed cut-in speed, number of nights implementing operational minimization, turbine model, and wind regime. Significant aspects of curtailment to consider, but difficult to quantify at a broad scale, are the financial (e.g., market and price structure), technological (e.g., technology replacement and maintenance), and contractual liability (e.g., power purchasing agreements) issues associated with lost generation. Therefore, the loss of AEP at one location may have limited applicability to others. Variations in these factors across jurisdictions further complicate the impact of operational minimization on the wind energy industry. Here we summarize the data reported from publicly available studies to demonstrate this variability.

Publicly Reported Power Loss

The loss in AEP while implementing operational minimization to reduce bat fatalities is limited and only publicly reported from five facilities across 11 operational minimization comparisons (Table 3.1). These studies implemented different curtailment cut-in speeds and had different turbine models. Despite the high degree of variation in treatments and locations, most studies reported less than a 1% loss in AEP based on the specific treatments and conditions at the project. The loss in AEP ranged from 0.06 to 3.20, with eight studies reporting ≤1% loss in AEP and six studies reporting ≤0.5% loss.

At the Sheffield Wind Facility in Vermont, implementation of a 6.0 m/s cut-in speed on fall nights over 50 °F reduced power 1.13% and 1.20% percent in 2012 and 2013, respectively. The addition of temperature to the operational minimization regime is estimated to have reduced lost power by 18%. At the Cassleman Wind Project in Pennsylvania, 2010 power production was reduced by 0.3% power loss when implementing a 5.0 m/s cut-in speed. The same project reported a 1% power loss when implementing a 6.5 m/s cut-in speed. Similar results were reported in Arnett et al. (2013) for an anonymous project in the Midwest. They reported a 0.2% and 1.0% annual power loss for 4.5 and 5.5 m/s cut-in speeds, respectively. The Wolf Ridge Wind Energy Facility in Texas reported the smallest loses, 0.06% and 0.2% per year in 2013 and 2014, respectively with a 5.0 m/s cut-in speed (Hale and Bennett 2014). Blue Sky Green Field in Wisconsin implemented a 'smart' curtailment system based on the acoustic detection of bats recorded in the rotor-swept area (Hayes et al. 2019). They curtailed up to 8.0 m/s when bats were detected. This curtailment reduced AEP by 3.2%. Increases in power loss with increasing cut-in speed appear to reflect the well-documented cubic relationship between power generation and wind-speed (Albadi and El-Saadany 2009, Prakash and Markfort 2020).

Three studies report the average loss in operating time of treatment turbines. Fowler Ridge Wind Farm, Indiana reported a 21% and 42.1% reduction in operating time at 5.0 and 6.5 m/s cut-in speeds, respectively. When raising the cut-in speed to 5.5 m/s for 24 hours a day, Baerwald et al. (2009) reported a 42.3% power loss for the treatment period. The Sheffield Wind Facility reported a 49% reduction in operating time each year (Martin et al. 2017), which translates to their previously referenced 1.13% and 1.2% annual power loss. The small sample size of studies reporting loss in operating time limits the ability to determine whether these facilities are representative of general patterns in power loss from operational minimization across facilities and regions.

Table 3.1: **Re**ported annual percent power loss from operational minimization.

Facility	Year	Operational minimization Conditions	Annualized Percent Lost Power
Sheffield	2012	6.0 m/s + >50F	1.13
Sheffield	2013	6.0 m/s + >50F	1.2
Wolf Ridge	2013	5.0 m/s	0.06
Wolf Ridge	2013	Wind Speed + Direction	0.28
Wolf Ridge	2014	5.0 m/s	0.2
Wolf Ridge	2014	Wind Speed + Direction	0.53
Cassleman	2008&2009	5.0 m/s	0.3
Cassleman	2008&2009	6.5 m/s	1
Anon1[1]	2010	4.5m/s	0.2
Anon1[1]	2010	5.5 m/s	0.8
Blue Sky	2015	8.0 m/s with Acoustic detection	3.20

[1]Reported in Arnett et al. 2013

Discussion

This summary demonstrates the variability in lost annual energy production among regions and operational minimization scenarios. It is beyond the scope of this paper to account for all factors, associated with loss of AEP when implementing operational minimization. Although the percent change at a site for a given scenario may not appear large, it may represent an economic barrier. Financial, technological, and legal considerations (e.g., power purchasing agreements) across jurisdictions complicate the impact of operational minimization on the wind energy industry. Operational minimization is shown to significantly reduce bat mortality at wind turbines, but to be considered as a practicable option for implementation it is important to also weigh the impacts on the wind energy facility.

CONCLUSION

We estimate that total fatalities are reduced by an average of 33% with every 1.0 m/s increase in cut-in speed. Estimates of the efficacy of a 1.0 m/s increase on the three migratory tree-roosting species in North America are similar (28% for hoary bats, 32% for eastern red bats, and 32% for silver-haired bats). Extrapolating these data across multiple facilities and time periods, a 5.0 m/s cut-in speed is estimated to reduce total bat fatalities by an average of 62% (95% CI: 54–69%). We estimate total bat fatality reductions at individual facilities in any given year to fall between 33%–79% (95% prediction interval). For individual species, average fatality reduction at 5.0 m/s cut-in speed was estimated as 48% (95% CI: 24%–64%) for hoary bats, 61% (95% CI: 42–74%) for eastern red bats, and 52% (95% CI: 30%–66%) for silver haired bats. Geographic variation in efficacy is overshadowed by interannual variation at each facility.

Other strategies that seek to refine operational minimization are poorly studied. The use of temperature and wind direction to make operational minimization decisions were only evaluated in 1 study each. Feathering blades below cut-in speed was only studied at one site. Using bat activity to make operational minimization decisions seems effective but has only been evaluated once. Many studies are plagued by a low effect size introduced by the small difference in treatment implementation that minimizes the ability to detect a statistical difference between treatments. Additional studies that compare fatality rates between years and treatments are unreliable due to the interannual variability in fatality rates and operational minimization efficacy.

Operational minimization poses a tradeoff between power generation and bat conservation goals. The reported annual power loss across 5 projects and 11 treatments ranged from 0.06 to 3.2%. Eight comparisons report ≤1% lost power production per year. However, to fully evaluate the viability of operational minimization at individual facilities, additional financial, technological, and legal implications should be considered. If operational minimization is not practicable for a site, other strategies can be considered and compared to the efficacy of operational minimization.

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APPENDIX I
DEFINITIONS

For the purposes of this review, we used the following terminology and definitions, which are consistent with those used by Arnett (2013) and U.S. Fish and Wildlife Service Land-based Wind Energy Guidelines (2012):

Curtailment— The act of limiting the supply of electricity to the grid during conditions when it would normally be supplied. This is usually accomplished by cutting-out the generator from the grid and/or feathering the turbine blades.

Cut-in speed— The wind speed at which the generator is connected to the grid and producing electricity. The manufacturer's set cut-in speed for most contemporary turbines is between 3.0 and 4.0 m/s. For some turbines, their blades will spin at full or partial RPMs below cut-in speed when no electricity is being produced.

Feathering or Feathered— Adjusting the angle of the rotor blade parallel to the wind, or turning the whole unit out of the wind, to slow or stop blade rotation. Normally operating turbine blades are angled perpendicular to the wind at all times.

Free-wheeling— Blades that are allowed to slowly rotate even when fully feathered and parallel to the wind. In contrast, blades can be "locked" and cannot rotate, which is a mandatory situation when turbines are being accessed by operations personnel.

Increasing cut-in speed— The turbine's computer system (referred to as the Supervisory Control and Data Acquisitions or SCADA system) is programmed to a cut-in speed higher than the manufacturer's set speed, and turbines are programmed to stay feathered at 90° until the increased cut-in speed is reached over some average number of minutes (usually 5–10 min), thus triggering the turbine blades to pitch back "into the wind" and begin to spin normally.

APPENDIX II

ABSTRACTS
FROM
OPERATIONAL MINIMIZATION
STUDIES

Anonymous 1

Arnett, E. B., G. D. Johnson, W. P. Erickson, and 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.

Summary from Arnett et al. 2013

This wind energy facility (AN01) is located in USFWS Region 3 (Midwest Region that includes Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin). Although the developer of this project allowed use of the data, they stipulated that the name and location of the project should not be disclosed. This wind energy facility is composed of 240 1.65-MW turbines which have an 80-m hub height and an 82-m rotor diameter. The standard cut-in speed for these turbines was 3.5 m/sec. Based on land cover classifications, most (over 90%) of the wind resource area was composed of tilled agriculture, with corn (Zea mays) and soybeans (Gylcine max) being the predominant crops Fatalities at this facility were dominated by eastern red bats, hoary bats, and silver-haired bats.

This study was conducted from 1 August–1 October, 2010, a time period selected to cover the period when 82–97.4% of bat fatalities occurred during previous studies of the facility in 2007, 2008 and 2009. Twelve turbines were selected for the study using a systematic design with a random start. Each of the study turbines had a search plot of 80 X 80 m cleared around the turbine by mowing standing crops using a brush mower pulled by a small tractor. This allowed for all areas within 40 m of a turbine to be searched. This distance was based on previous studies at the facility, where 83% of all bat carcasses were found within 40 m of a turbine. Eleven of the turbines were in either corn or soybean fields and the remaining turbine was in an alfalfa (Medicago sativa) field.

Treatments for cut-in speeds were rotated between the twelve turbines on a weekly basis using a Latin square design, with four turbines having cut-in speeds raised to 4.5 m/s, four turbines having cut-in speeds raised to 5.5 m/s, and four turbines having a normal (control) operational cut-in speed of 3.5 m/s during each week. The Latin square design ensured that each turbine received the same number of days under each cut-in speed treatment. The study lasted nine weeks; therefore, each of the 12 turbines operated for three weeks over the course of the study at each cut-in speed. Cut-in speed treatments were set to begin approximately one hour before sunset and to end approximately one hour after sunrise.

Daily searches were conducted on all 12 turbines. The estimated time since death for each bat carcass found was evaluated to determine which bats should be excluded from the analysis or were likely killed the previous week. This resulted in removal from the analysis of 10 bats found during the first week of the study which were presumed to have been killed prior to study initiation. Another two bats were removed from the analysis because it was not possible to determine which study week they were killed, including one bat in week 2 and one bat in week 5 of the study. Five bats were assumed to have been killed the week before they were found and were assigned to that time period for analysis. Overall, 88.6% of bats found during the study were included in the analysis to determine effects on mortality of raising cut-in speeds on wind turbines.

Differences in cut-in speed were examined by building a Poisson model to determine the relative difference in counts based on cut-in speed. A Poisson model was considered appropriate in this case, since the response variable is a count of bat fatalities. From this model, the magnitude of differences and significance of variables in the model was determined.

A total of 93 bats found during the study were used for the cut-in speed analysis as they could be confidently assigned to a treatment based on the estimated time of death in relation to when the cut-in speeds were changed. Fifty-three bat carcasses were found at turbines with normal operational cut-in speeds of 3.5 m/s (control). This compared to 25 and 14 bat carcasses found at turbines with cut-in speeds raised to 4.5 m/s and 5.5 m/s, respectively.

A Poisson model was built considering cut-in speed and week as fixed effects and the turbine as a random effect. Although blocking by week can potentially eliminate temporal effects, a definite trend was observed by week. Therefore, week was considered as a fixed effect in the model. In the Poisson model, a cut-in speed of 4.5 m/s had a parameter estimate of -0.64, which corresponds to an approximate 47% decrease in the odds of a fatality with this cut-in speed when all other variables are equal. This cut-in speed was significant in the model ($z=-2.57$, $p=0.01$). The cut-in speed of 5.5 m/s had a parameter estimate of -1.26 in the model. This corresponds to an approximate 72% decrease in odds of a bat fatality occurring at a turbine with a cut-in speed of 5.5 m/s when all other variables are equal ($z=-4.13$, $p<0.001$).

Based on data obtained from the turbine SCADA system, the average wind speed at the facility during the 1 August–30 September study period was 5.9 m/s. During the study period, wind speeds at the facility were below 4.5 m/s approximately 29% of the time, and were below 5.5 m/s approximately 48% of the time. It was not possible to know exactly when each bat fatality occurred during a night, so it could not be determined whether the cut-in speed restrictions were active at a particular turbine when the fatality occurred.

This was the first study to demonstrate that cut-in speeds raised to 4.5 m/s reduce bat fatalities substantially, albeit not to the same level obtained with a cut-in speed of 5.5 m/s. This also was the second study to evaluate raising cut-in speeds at a wind energy facility located in a corn and soybean agro-ecosystem in the Midwestern U.S., (see Fowler Ridge, Indiana summary).

Anonymous 2

Arnett, E. B., G. D. Johnson, W. P. Erickson, and 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.

Summary from Arnett et al. 2013

This wind energy facility (AN02) is located in USFWS Region 8 (Pacific Southwest Region which includes California and Nevada). Although the developer of this project allowed use of the data, they stipulated that the name and location of the project should not be used. The facility consists of 40 2.3-MW wind turbines (manufacturer not disclosed) situated on 80-m towers with rotor blades 101 m in diameter. The nominal cut-in speed of the turbines is 3.0 m/s. This facility lies within a basin on relatively flat terrain; and the predominant land cover is desert scrub, big sagebrush (*Artemisia tridentata*) shrubland and xeric mixed sagebrush shrubland. Brazilian free-tailed bats (Tadarida brasiliensis) dominated fatalities at this facility (73.5%).

The study was conducted from 2 August–30 September 2012. Daily searches were conducted at 40 study turbines. Searchers walked along transect lines spaced 5 m apart within a 126 X126 plot under each study turbine. Treatment turbines were stratified into 4 groups based on their distance from a point source for bats. Treatment turbines were assigned one of 4 cut-in speeds (3.0 m/s [turbine manufacturer's cut-in speed], 4.0 m/s, 5.0 m/s, and 6.0 m/s) for 4 hours (sunset to 4 hours past sunset) during each night of the study. A fifth treatment (5.0 m/s for the entire night [5.0 m/s AN]) also was included to test the effectiveness of curtailing for a greater duration of the night. Nightly cut-in speed treatments were assigned using a randomized block design, with the turbine as the blocking factor and turbine-night as the sampling unit. However, randomization was constrained to ensure that 1) each turbine received each treatment the same number of times over the course of the study, and 2) each treatment was applied to two turbines within each group on each night of the study. As there were 5 treatments, full design balance was achieved every 5 nights. The process was repeated 12 times to generate cut-in speed assignments for a 60-night study period.

A total of 136 bat fatalities were found during the study. Unlike other curtailment studies reviewed in this paper, most (73.5%) of the bat fatalities were Brazilian free-tailed bats (*Tadarida brasiliensis*), with smaller numbers of hoary bats (22.8%) and silver-haired bats (3.7%). Compared to the control turbines set to a cut-in speed of 3.0 m/s, the following reductions in bat fatality were obtained in each treatment: 20.1% at 4.0 m/s, 34.5% at 5.0 m/s, and 38.1% at 6.0 m/s during the first four hours after dark, and 32.6% for turbines raised to 5.0 m/s all night long. None of the reductions in fatality were considered statistically significant (chi-square test $p>0.05$) between turbines with cut-in speeds raised to 5.0 or 6.0 m/s, regardless if the treatment occurred only during the first four hours after dark (5.0 and 6.0 m/s) or was left in place all night long (5.0 m/s). The lack of significance was likely due to low statistical power, since the number of fatalities observed was relatively low.

Alberta, Canada

Baerwald, E. F., J. Edworthy, M. Holder, and R. M. R. Barclay. 2009. A large-scale mitigation experiment to reduce bat fatalities at wind energy facilities. Journal of Wildlife Management 73: 1077–1081. Available Here

Abstract (Baerwald et al. 2009)

Until large numbers of bat fatalities began to be reported at certain North American wind energy facilities, wildlife concerns regarding wind energy focused primarily on bird fatalities. Due in part to mitigation to reduce bird fatalities, bat fatalities now outnumber those of birds. To test one mitigation option aimed at reducing bat fatalities at wind energy facilities, we altered the operational parameters of 21turbines at a site with high bat fatalities in southwestern Alberta, Canada, during the peak fatality period. By altering when turbine rotors begin turning in low winds, either by changing the wind-speed trigger at which the turbine rotors are allowed to begin turning or by altering blade angles to reduce rotor speed, blades were near motionless in low wind speeds, which resulted in a significant reduction in bat fatalities (by 60.0% or 57.5%, respectively). Although these are promising mitigation techniques, further experiments are needed to assess costs and benefits at other locations.

Beech Ridge Wind Farm, West Virginia

Tidhar, D., M. Sonnenberg, and D. Young. 2013. 2012 post-construction carcass monitoring study for the Beech Ridge Wind Farm, Greenbrier County, West Virginia. Unpublished report prepared for Beech Ridge Wind Farm and Beech Ridge Energy, LLC, Chicago, IL. Prepared by WEST, Inc, Waterbury Vermont. Available Here

Summary from Arnett et al. 2013

This project is located in Greenbrier and Nicholas counties, West Virginia, and is located along Beech Ridge on a 63,000-acre tract of forestlands managed for commercial timber harvesting (Tidhar et al. 2013). The Project has 67 GE 1.5-MW wind turbines with 80-m hubs and 77-m diameter blades; the nominal cut-in speed is 3.5 m/s. The facility lies within the Central Appalachian Broadleaf Forest Ecological Subregion within the southern portion of the Allegheny Mountains ecological section. This ecological section is characterized by a dissected plateau of high ridges, low mountains, and narrow valleys. Beech Ridge is largely forested, and the landscape is a mosaic of deciduous forest in various stages of growth interspersed with areas cleared for roads, timber harvest activities, and historic mining activities. Eastern red bats were most commonly found at this facility, and other species included hoary, silver-haired, and tri-colored (*Perimyotis subflavus*) bats.

The cut-in speed for all turbines was raised to 6.9 m/s all night long throughout the entire study period. Turbines were feathered so that they did not rotate at wind speeds below 6.9 m/s. This Project was required to implement turbine curtailment at all 67 turbines; therefore, no control turbines were available to compare bat mortality at curtailed turbines to. To assess efficacy of the curtailment for reducing bat fatality, bat fatality rates for the study period were qualitatively compared to measured bat fatality rates at other regional wind energy facilities. Three spatial scales for meta-analysis were used for comparison: a) eastern North America which included all wind energy facilities in the Northeast, Southeast, Southern Plains and Midwest regions; b) Northeastern region which included all wind energy facilities in Maine, New Hampshire, New York, Pennsylvania, West Virginia, and Ontario, Canada; and c) other wind energy facilities in West Virginia.

At all spatial scales used for comparison the bat fatality rate observed at Beech Ridge was below the median and mean of the range of bat fatality rates observed at these other facilities. At the Eastern North America scale, the estimated bat fatality rate at the Project (2.03 fatalities/MW/year) was approximately 73% less than the average for other annualized estimates, which was approximately 7.40 bat fatalities/MW/year. The observed bat fatality estimate at the Project also was approximately 73% less than the average for other annualized projects located just within the Northeastern region. Only two facilities in West Virginia have published comparable, publicly-available fatality studies: Mount Storm and Mountaineer. Bat fatality rates at Mount Storm ranged from 6.62–24.32 bat fatalities/MW/year, while rates at Mountaineer were 25.17 and 31.69 fatalities/MW/year. The bat fatality rate at the Project was approximately 89% less than the average for other annualized West Virginia projects.

Blue Creek Wind Energy Facility, Ohio USA

Schirmacher, M. 2020. Evaluating the Effectiveness of an Ultrasonic Acoustic Deterrent in Reducing Bat Fatalities at Wind Energy Facilities - Final Technical Report (Report No. DOE-BCI-0007036). Report by Bat Conservation International. Report for US Department of Energy (DOE). Available Here

Executive summary (selected portions from Schirmacher 2020)

This project was designed to use thermal video cameras and fatality monitoring to evaluate the effectiveness of an ultrasonic acoustic deterrent (UAD) on bat activity and mortality, respectively. Our goals were to redesign the UAD device and installation infrastructure, determine the placement on wind turbines to optimize safety, compatibility and functionality, and to compare the mortality among the following conditions: Control (deterrents off and turbines feathered up to the manufacturer's cut-in speed of 3.5 m/s), Deterrent (deterrents on and turbines feathered up to the manufacturer's cut-in speed of 3.5 m/s), Curtailment (deterrents off and turbines feathered up to 5/ m/s), and combination (deterrents on and turbines feathered up to 5 m/s)… We searched the area within 90 m of each turbine daily to recover the highest number of fresh fatalities possible. We were unable to detect a clear reduction in mortality from deterrents alone for any individual species. Surprisingly, mortality rate of the eastern red bat (*Lasiurus borealis*) was estimated to be 1.3–4.2 times as much when turbines were operating normally and UADs were on than when UADs were off. Reduction in mortality of all bat species combined due to curtailment of turbines was estimated to be between 0%–38%. This effect was nullified when, in addition to curtailment, UADs were on, with 95% confidence interval ranging from a 45% reduction to a 36% increase in mortality. This was likely due to the large proportion of eastern red bats in the total carcass population. Mortality of all low-frequency echolocating bats combined (i.e., hoary bat [*L. cinereus*], big brown bat [*Eptesicus fuscus*], silver-haired bat [*Lasionycteris noctivagans*]) relative to control was lower when curtailed (95% CI: 0%–74%), but the addition of UADs had no detectable effect (95%CI: 13%–79%). The combined treatment reduced mortality in silver-haired bats relative to control by 11%–99%, compared to curtailment (81% reduction–67% increase) or deterrent (82% reduction–67% increase) alone. Because silver-haired bats comprised a large proportion of low-frequency calling bats found during this study, a similar effect was seen for that group. The higher mortality observed for eastern red bats at UAD compared to control could have been caused by several factors, such as the effective range of the UAD, particularly at higher frequencies, behavior, positioning of the devices on the nacelle, or a combination of these.

Blue Sky Green Field, Wisconsin, USA

Hayes, M. A., Lauren A. Hooton, Karen L. Gilland, Chuck Grandgent, Robin L. Smith, Stephen R. Lindsay, Jason D. Collins, Susan M. Schumacher, Paul A. Rabie, Jeffrey C. Gruver, and John Goodrich-Mahoney. 2019. A smart curtailment approach for reducing bat fatalities and curtailment time at wind energy facilities. Ecological Applications 29:e01881. Available Here

Electric Power Research Institute. 2017. Bat Detection and Shutdown System for Utility-Scale Wind Turbines. Palo Alto, CA. Available Here

Abstract (Hayes et al. 2019)

The development and expansion of wind energy is considered a key global threat to bat populations. Bat carcasses are being found underneath wind turbines across North and South America, Eurasia, Africa, and the Austro-Pacific. However, relatively little is known about the comparative impacts of techniques designed to modify turbine operations in ways that reduce bat fatalities associated with wind energy facilities. This study tests a novel approach for reducing bat fatalities and curtailment time at a wind energy facility in the United States, then compares these results to operational mitigation techniques used at other study sites in North America and Europe. The study was conducted in Wisconsin during 2015 using a new system of tools for analyzing bat activity and wind speed data to make near real-time curtailment decisions when bats are detected in the area at control turbines (N = 10) vs. treatment turbines (N = 10). The results show that this smart curtailment approach (referred to as Turbine Integrated Mortality Reduction, TIMR) significantly reduced fatality estimates for treatment turbines relative to control turbines for pooled species data, and for each of five species observed at the study site: pooled data (–84.5%); eastern red bat (Lasiurus borealis, –82.5%); hoary bat (Lasiurus cinereus, –81.4%); silver-haired bat (Lasionycteris noctivagans, –90.9%); big brown bat (Eptesicus fuscus, –74.2%); and little brown bat (Myotis lucifugus, –91.4%). The approach reduced power generation and estimated annual revenue at the wind energy facility by ≤ 3.2% for treatment turbines relative to control turbines, and we estimate that the approach would have reduced curtailment time by 48% relative to turbines operated under a standard curtailment rule used in North America. This approach significantly reduced fatalities associated with all species evaluated, each of which has broad distributions in North America and different ecological affinities, several of which represent species most affected by wind development in North America. While we recognize that this approach needs to be validated in other areas experiencing rapid wind energy development, we anticipate that this approach has the potential to significantly reduce bat fatalities in other ecoregions and with other bat species assemblages in North America and beyond.

Casselman Wind Project, Pennsylvania, USA

Arnett, E. B., M. M. P. Huso, M. R. Schirmacher, and J. P. Hayes. 2011. Altering turbine speed reduces bat fatalities at wind-energy facilities. Frontiers in Ecology and the Environment 9: 209–214; doi:10.1890/100103. Available Here

Arnett, E. B., M. Schirmacher, M. M. P. Huso, and J. P. Hayes. 2009. Effectiveness of changing wind turbine cut-in speed to reduce bat fatalities at wind facilities. An annual report submitted to the Bats and Wind Energy Cooperative. Bat Conservation International. Austin, Texas, USA. Available Here

Arnett, E. B., M. M. P. Huso, J. P. Hayes, and M. Schirmacher. 2010. Effectiveness of changing wind turbine cut-in speed to reduce bat fatalities at wind facilities. A final report submitted to the Bats and Wind Energy Cooperative. Bat Conservation International. Austin, Texas, USA. Available Here

Abstract (Arnett et al. 2011)

Wind-turbine operations are associated with bat mortality worldwide; minimizing these fatalities is critically important to both bat conservation and public acceptance of wind-energy development. We tested the effectiveness of raising wind-turbine cut-in speed – defined as the lowest wind speed at which turbines generate power to the utility system, thereby reducing turbine operation during periods of low wind speeds – to decrease bat mortality at the Casselman Wind Project in Somerset County, Pennsylvania, over a 2-year period. Observed bat mortality at fully operational turbines was, on average, 5.4 and 3.6 times greater than mortality associated with curtailed (i.e., non-operating) turbines in 2008 and 2009, respectively. Relatively small changes to wind-turbine operation resulted in nightly reductions in bat mortality, ranging from 44% to 93%, with marginal annual power loss (< 1% of total annual output). Our findings suggest that increasing turbine cut-in speeds at wind facilities in areas of conservation concern during times when active bats may be at particular risk from turbines could mitigate this detrimental aspect of wind-energy generation.

Criterion Wind Project, Maryland

Young, D., C. Nations, M. Lout, and K. Bay. 2013. 2012 post-construction monitoring study, Criterion Wind Project, Garrett County, Maryland. An unpublished report submitted to Criterion Power Partners, LLC, Maryland by Western EcoSystems Technology, Inc., Wyoming.

Summary from Arnett et al. 2013

This project is located along a 5-mile section of Backbone Mountain in Garrett County, Maryland (Young et al. 2013). The Project has 28 Clipper 2.5-MW wind turbines with 80-m hubs and 93-m diameter blades; the nominal cut-in speed is 4.0 m/s. The topography of the Project area is steeply sloping on the western side of the ridge and relatively gently sloping on the eastern side; and the ridgeline maintains an elevation of approximately 975 m above mean sea level. The facility falls within the Ridge and Valley province of the Central Appalachian Ecoregion, characterized by heavily forested, steep ridges that alternate with folded sandstone crests and limestone plateaus. The Project is situated on largely undeveloped, previously logged forestland interspersed with some open farmland and consists of rugged terrain traversed with old logging roads. Land use in the vicinity of the Project is dominated by forest and hay fields. Bat species found as fatalities included eastern red bat (53.7%), hoary bat (32.9%), silver-haired bat (7.3%), big brown bat (3.7%), tri-colored bat (1.2%) and unidentified bat (1.2%).

During the period 15 July–15 October 2012, the turbine blades were feathered to minimize rotation to less than 2 RPMs during periods when wind speeds were equal to or less than 5.0 m/s at night. Half of the 28 turbines (n = 14) were randomly selected for fatality monitoring, and each turbine was searched once per week using cleared plots within a 40-m radius of the turbine. Since no control turbines were used during the study, effectiveness of curtailment treatments was determined by comparing bat fatality rates for the study period while operational curtailment was in place in 2012 with those at the same facility over the same time period in 2011 when no operational curtailment was in place.

The estimated bat fatality rate in 2012, when turbines were curtailed, was 10.97 bats/turbine (90% CI = 4.81–20.19), whereas the estimated fatality rate in 2011 was 28.78 bats/turbine (90% CI = 24.09–35.17). These results indicate a reduction in bat fatality of approximately 62% when the turbines were feathered below 5 m/s, but this analysis assumes that other factors affecting levels of bat fatality were similar between 2011 and 2012, which may not have been true.

Fowler Ridge Wind Farm, Indiana, USA

Study Year 2010

Good, R., W. Erickson, A. Merrill, S. Simon, K. Murray, K. Bay, and C. Fritchman. 2011. Bat monitoring studies at the Fowler Ridge Wind Energy Facility Benton County, Indiana. A report prepared for Fowler Ridge Wind Farm. Western EcoSystems Technology, Inc., 2003 Central Avenue, Cheyenne, Wyoming 82001. Available Here

Summary from Arnett et al. 2013

The Fowler Ridge Wind Farm (FRWF) is located in Benton County, Indiana, and consists of 355 wind turbines in three operating phases with a total capacity of 600 MW. Phase I had 122 Vestas V82 1.65-MW turbines and 40 Clipper C96 2.5-MW turbines, Phase II had 133 1.5-MW General Electric (GE) SLE turbines, and Phase III had 60 Vestas V82 1.65-MW turbines. All three turbine models were located on 80-m towers, while rotor diameters were 77 m for the GE turbines, 82 m for the Vestas V82 turbine, and 96 m for the Clipper C96 turbine. The standard cut-in speed for all three turbines was 3.5 m/sec. Of the roughly 59,000 acres within one half-mile (0.80 km) of turbine locations, row crops, primarily corn and soybeans, comprised about 93% of the land cover. As with most sites in the East and much of the Midwest, eastern red bats, hoary bats, and silver-haired bats made up the greatest proportion of fatalities at this facility in both years of the study.

Experiments were conducted in 2010 and 2011 using different methods. In 2010, bat fatality rates were measured at two different cut-in speed adjustments or treatments and two sets of control turbines with no cut-in speed adjustment (Good et al. 2011). Nine turbines were randomly selected from the sample of 36 turbines being searched daily for use as a reference sample for the duration of the study. Treatments for cut-in speed adjustment and a second set of reference turbines were rotated on a weekly basis among the remaining 27 daily search turbines, with nine turbines assigned to each group. The treatments included turbines with cut-in speeds raised to 5 and 6.5 m/s. Turbines were randomly assigned to control and treatment groups among the 27 turbines, and treatments were distributed temporally to ensure each turbine received 3–4 weeks of treatment or control cut-in speeds. Square 80 x 80 m plots at the 36 turbines were maintained relatively free of vegetation through use of mowing and herbicides.

Fatality rates for each cut-in speed were calculated along with corresponding 90% bootstrap confidence intervals. Estimates without overlapping confidence intervals were considered significantly different. In addition, differences in bat fatality between cut-in speed treatments were examined by building a Poisson model to determine the relative difference in fatality rates based on cut-in speed. The magnitude of model coefficients represents the relative ratio of fatality rates between curtailed turbines and those with no cut-in speed adjustment. Tests for variable selection were used to assess the statistical significance of the cut-in speed covariates. The estimated time since death for each bat carcass was evaluated to determine which curtailment condition the bat fatality occurred during. Carcasses of bats that were estimated to have died prior to the start of the study and carcasses where the length of time since death could not accurately be determined were not included in the analysis. Data on estimated time of death were used to determine the curtailment condition that the fatality most likely occurred during. Two hundred fifty-two bat carcasses were determined to have occurred at turbines while under normal operational cut-in speeds of 3.5 m/s (control). This compares to 63 dead bats at turbines with cut-in speeds raised to 5.0 m/s and 27 dead bats found at turbines with cut-in speeds raised to 6.5 m/s. Bat fatalities were primarily eastern red bats (71.6%), followed by silver-haired bats (18.7%), hoary bats (15.5%), big brown bats (2.3%), tri-colored bats (0.3%) and Indiana bats (Myotis sodalis; 0.3%).

The observed fatality rates and corresponding 90% bootstrap confidence intervals were 14.0 (11.6–16.5), 7.0 (7.0–9.1), and 3.0 (1.8–4.2) bats/turbine for control, 5.0 m/s, and 6.5 m/s treatment conditions, respectively. Non-overlapping confidence intervals for observed fatality rates under each cut-in speed condition indicate a significant difference between treatments. An approximate 50% reduction in overall bat mortality was observer by raising the cut-in speed from 3.5–5.0 m/s, while an approximate 78% reduction in overall bat mortality was realized by raising the cut-in speed from 3.5–6.5 m/s.

Poisson modeling of observed fatality rates resulted in significant cut-in speed covariates and week effect covariate. Although blocking by week can potentially eliminate temporal effects, a definite trend was observed by week and therefore week was left as a fixed effect in the model to account for this variation. The parameter estimate for the 5.0 m/s cut-in speed was -0.69, which corresponds to a 0.5 = exp (-0.69) incident rate ratio (i.e., the ratio of the fatality rate occurring at turbines with cut in speeds of 5.0 m/s to the fatality rate occurring at turbines with cut-in speeds of 3.5 m/s) supporting a conclusion of a 50.0% reduction in fatality rates when turbines have a cut-in speed of 5.0 m/s having adjusted for all other model variables. The corresponding 90% confidence interval for the 5.0 m/s incident rate ratio implies a reduction in fatality rates of between 37.3% and 60.6%. The parameter estimates for the 6.5 m/s cut in speed treatment also were significant with a value of -1.54, which corresponds to a 0.2 incident rate ratio. This implies a reduction of 78.6% in fatality rates for turbines curtailed below wind speeds of 6.5 m/s with a 90% confidence interval of 70.5–84.9%. Non-overlapping confidence intervals between cut-in speeds of 5.0 and 6.5 m/s suggest a significant difference in fatality rates between these two treatments. The incident rate ratio between treatment types is 0.4 which corresponds to a 57.3% reduction in fatalities at 6.5 m/s cut-in speeds when compared to 5.0 m/s cut-in speeds.

Based on weather data collected at study turbines and an on-site meteorological tower, the average nightly wind speed (between 7:00 pm and 7:00 am) at the Fowler Ridge facility was 5.70 m/s during the study period. Nightly wind speeds were below 5.0 m/s approximately 43.4% of the time, and were below 6.5 m/s approximately 63.7% of the time. It was not possible to know exactly when each bat fatality occurred during a night, so it could not be determined whether the cut-in speed restrictions were active at a particular turbine when the fatality occurred. However, compared to turbines with no cut-in speed adjustments, the turbines were estimated to be operating approximately 21.6% less at the 5.0 m/s and 42.1% less at the 6.5 m/s cut-in speed treatments.

Study Year 2011

Good, R. E., A. Merrill, S. Simon, K. Murray, and K. Bay. 2012. Bat monitoring studies at the Fowler Ridge Wind Farm, Benton County, Indiana. An unpublished report submitted to the Fowler Ridge Wind Farm by Western EcoSystems Technology, Inc., 408 West 6th Street, Bloomington, IN 47403. Available Here

Summary from Arnett et al. 2013

The effectiveness of feathering turbine blades below multiple cut-in speeds for reducing bat fatality rates was evaluated at Fowler Ridge during the fall of 2011 (Good et al. 2012). Bat fatality rates were measured at three different speed adjustments, or "treatments", and two sets of "control" turbines with no cut-in speed adjustment. Nine turbines were randomly selected from the sample of 36 turbines with cleared plots searched in 2010, and were considered a "control" sample, operating normally for the duration of the study. The control group comprised three GE SLE 1.5-MW turbines, three Clipper C96 2.5-MW turbines, and three Vestas V82 1.65-MW turbines. Treatments for blade feathering and a second set of "control" turbines were rotated on a nightly basis between the remaining 168 turbines, with 42 turbines assigned to each group. The treatments included turbines with blades feathered below 3.5 m/s, below 4.5 m/s, and a control group with no feathering. Turbines were assigned to control and treatment groups among the 168 turbines on a nightly basis using a balanced block design to ensure that equal numbers of each turbine type were assigned to each treatment.

Fatality rates at turbines with normal operation parameters and those at turbines feathered below 3.5 m/s, 4.5 m/s, and 5.5 m/s were compared using a chi-square test of proportions to determine if significantly fewer fatalities were found under feathered turbine operation than under normal turbine operation. In addition to a chi-square test of proportions, differences in observed fatality rates by feathering condition were examined by building a negative binomial model to determine the relative difference in fatality rates. The magnitude of model coefficients represented the relative ratio of fatality rates between feathered operation at a given cut-in speed and those with no feathering. Tests for variable selection were used to assess the statistical significance of the f covariates corresponding to the levels of feathered operation. Since feathering condition was rotated nightly among turbines, only carcasses of bats that were estimated to have died the night prior to searches were included in the analysis.

A total of 105 bat carcasses were determined to have occurred at turbines while operating under normal operational cut-in speeds of 3.5 m/s (control) throughout the fatality searches. This compares to 66, 42, and 25 bat carcasses found at turbines where blades were feathered below 3.5 m/s, 4.5 m/s, and 5.5 m/s, respectively. Bat fatalities were composed of 57.1% eastern red bats, 23.5% hoary bats, 12.2% silver-haired bats, 5.0% big brown bats, 1.3% tri-colored bats, 0.4% Seminole bats, and 0.4% little brown bats.

Chi-square tests of proportions show that decreases in observed bat fatality rates between control turbines with no feathering compared to feathered turbines were statistically significant. Chi-square tests of proportions between successive treatment levels also showed significant decreases in fatality counts: (3.5 m/s feathered versus 4.5 m/s feathered; chi-square=5.1, df=1, p-value=0.02; 4.5m/s feathered versus 5.5 m/s feathered; chi-square=4.2, df=2, p=0.04).

Negative binomial modeling of observed fatality rates resulted in significant blade feathering covariates. The parameter estimate for feathering below a 3.5 m/s cut-in speed corresponded to a 36.3% reduction in fatality rates, with a corresponding 90% confidence interval (90% CI) of 12.4–53.8%. Feathering below a 4.5 m/s cut-in speed resulted in a parameter estimate of 56.7% (90% CI: 5–69.8%). A parameter estimate corresponding to a 73.3% (90% CI: 60.0–82.5%) reduction in fatality rates was estimated when the turbines were feathered below a 5.5 m/s cut-in speed.

Summary 2010-2017

Good. R. E., G. Iskali, K. Nasman, and A. Ciecka. 2017. Bat Evaluation Monitoring Studies at the Fowler Ridge Wind Farm, Benton County, Indiana: August 1 – October 15, 2017. Prepared for Fowler Ridge Wind Farm, Fowler, Indiana. Prepared by Western EcoSystems Technology, Inc. Bloomington, Indiana. January 29, 2018.

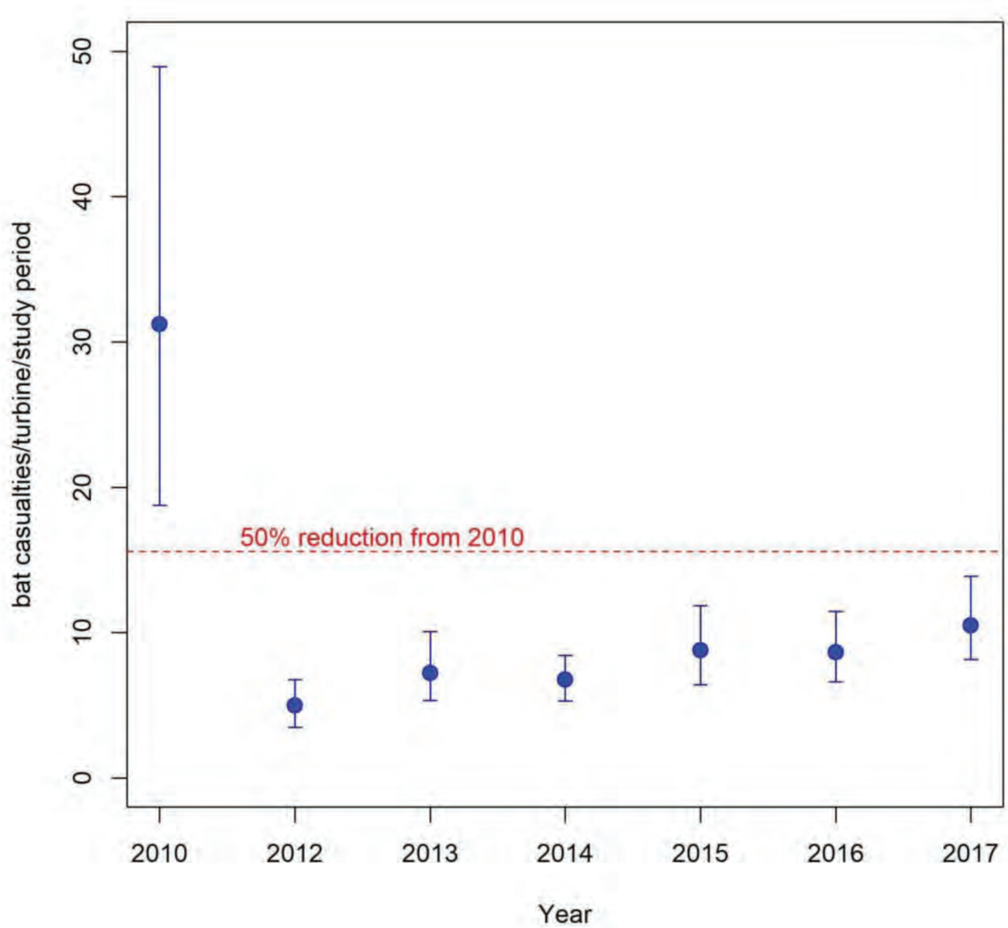
Executive Summary

The Fowler Ridge Wind Farm (FRWF) collectively includes Fowler Ridge Wind Farm LLC, Fowler Ridge II Wind Farm LLC, Fowler Ridge III Wind Farm LLC, and Fowler Ridge IV Wind Farm LLC. The FRWF consists of 420 wind turbines in four phases in Benton County, Indiana. A post-construction casualty study of bats was conducted by Western EcoSystems Technology, Inc. (WEST) within Phases I and III in 2009, during which an Indiana bat carcass was found. The FRWF worked with the US Fish and Wildlife Service and developed a Habitat Conservation Plan for the Indiana bat designed to minimize Indiana bat casualties. FRWF received an Incidental Take Permit for Indiana bats in August of 2014 (TE95012A-0). Monitoring the effectiveness of minimization measures is required by both the Habitat Conservation Plan and the Incidental Take Permit. Two years of more intensive evaluation phase monitoring, utilizing a larger sample of turbines to test effectiveness of applied minimization procedures, was completed for FRWF Phases I, II and III in 2014 and 2015. Because Indiana bat mortality was below adaptive management thresholds, less intensive implementation phase monitoring was applied for FRWF Phases I, II and III in 2016 and 2017, and will continue unless adaptive management thresholds are exceeded in the future. The second year of evaluation phase monitoring, requiring a minimum of 33% of turbines to be searched, was completed at FRWF Phase IV in 2017.

The 2017 casualty study occurred during the fall (August 1 – October 15) migration period for Indiana bats. Casualty searches were completed once per week on roads and gravel pads of 140 turbines from August 1 – October 11, 2017. Personnel trained in proper search techniques conducted the carcass searches. Searcher efficiency and carcass persistence trials were conducted to adjust for removal bias and searcher efficiency.

A total of 130 bat carcasses were found in 2017 during carcass searches and incidentally. Similar to previous years of monitoring, the most commonly found bat species were eastern red bats, silver-haired bats, and hoary bats. Eight big brown bats, one Seminole bat and one evening bat (state-listed as endangered) were also found. No Indiana bat, northern long-eared bat or any other *Myotis* spp. carcasses were found.

Bat casualty rates were calculated based on the number of carcasses found, the results of bias trials, and adjustments for bats that did not fall on roads and pads. Bat casualty rates in 2017 were estimated to be 5.24 bat casualties/MW/study period (90% confidence interval: 4.09 – 6.90), which was 66.3% lower than casualty estimates at turbines operating normally in 2010. The results of monitoring during 2017 provide evidence that operational strategies exceeded the objective of reducing bat casualty rates by 50%, compared to casualty estimates from turbines operating normally in 2010. Within-season adjustments of minimization strategies were not required in 2017 because bat casualty rates were well below adaptive management thresholds.


50
40
30
20
10
0
bat casualties/turbine/study period
50% reduction from 2010
2010
2012
2013
2014
2015
2016
2017
Year

Hawaii, USA - Kaheawa and Auwahi

Snetsinger, Thomas, Jonathan Plissner, Brita Woeck, Alicia Oller, Marie VanZandt. Challenges in Estimating the Effectiveness of Low Wind Speed Curtailment to Reduce Take of Bats in Hawaii. 2016. Poster at Wind Wildlife Research Meeting XI. Broomfield, Colorado, USA. Available Here

Abstract

Low wind speed curtailment (LWSC) has been demonstrated as an effective operational measure to reduce fatalities of migratory tree roosting bat species, including the hoary bat, on the U.S. mainland and Canada at wind farms. On this basis, state and federal wildlife agencies recommend LWSC be implemented at wind farms in Hawaii and incorporated in project Habitat Conservation Plans as a minimization measure to reduce fatalities of the endangered Hawaiian hoary bat. Accurate analysis of post-construction monitoring data requires an understanding of the effectiveness of operational changes that alter fatality risk; however, because bat fatalities in Hawaii are rare events, evaluating the potential benefits of this measure is challenging. Data from the only two commercial wind farms in Hawaii with both pre- and post-LWSC data are used to investigate evidence for the potential effectiveness of LWSC in Hawaii and to explore challenges to this goal in a data-poor environment.

We evaluated post-construction mortality monitoring data at the Kaheawa I and Auwahi wind Projects on Maui for 2-3 years prior to the implementation of LWSC and 1–2 year post-implementation of LWSC to examine evidence for the effectiveness of curtailment. The implementation approach at the two facilities differed, with a seasonal implementation (February 15 – December 15) of 5 – 5.5 meters/second curtailment at the Kaheawa I Wind Project and year-round curtailment at 5 meters/second at the Auwahi Wind Project. We used Dalthorp and Huso's Evidence of Absence analysis tool to estimate the annual rate of take and its 95 percent confidence interval for the LWSC and non-LWSC periods. Within project results show broad overlap of the confidence intervals among years. Annual pre-LWSC estimates at Kaheawa I were 1.76 (0.00 – 9.03), 7.8 (1.23 – 21.1), and 11.44 (3.37 – 24.7) bats/year. The post-LWSC estimate was 2.53 (0.00 – 12.9) bats/year. At the Auwahi Project, pre-LWSC estimates were 5.83 (0.41 – 18.5) and 9.01 (2.65 – 19.40) bats/year. The Auwahi Wind Project post-LWSC estimates were 3.79 (0.27 – 11.90) and 19.5 (7.98 – 36.5) bats/year. The apparent spike in fatalities in the second year of LWSC at the Auwahi Wind Project suggests that other factors could mask benefits of LWSC and that additional information and greater sample sizes are necessary to understand the potential benefit of LWSC. We address how the occurrence of anomalous fatality events, temporal changes in fatality risk, differences between the projects (e.g., bat population, wind intensity, weather patterns), and the inter-annual variability of data may affect approaches to the analysis of curtailment effectiveness.

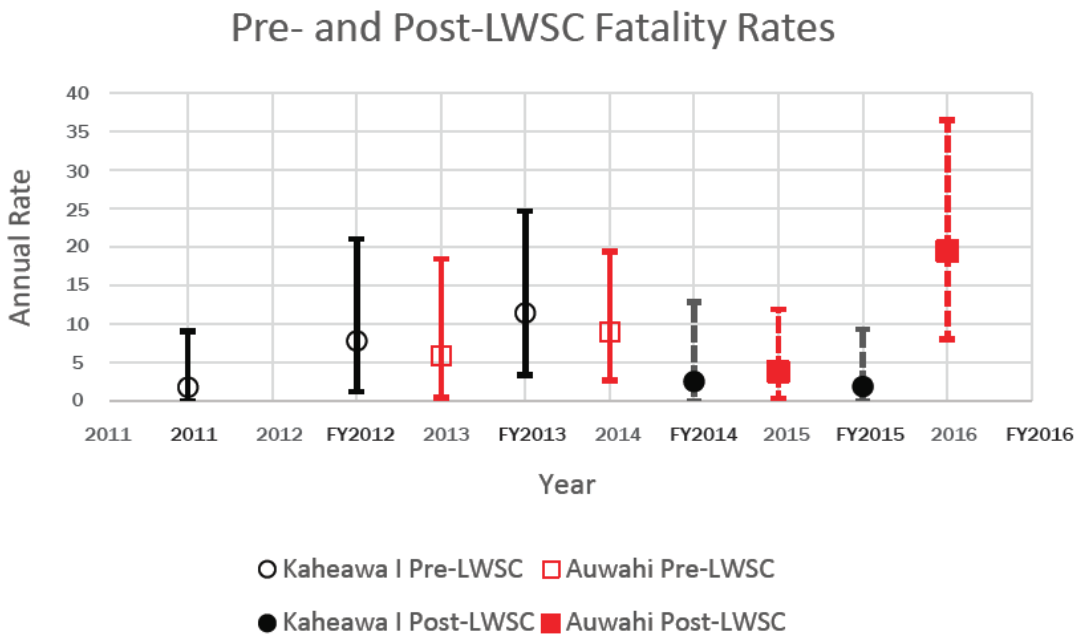


Figure 2: Pre and post Low wind speed curtailment (LWSC) fatality estimates at Kaheawa I and Auwahi Wind farm, Hawaii, USA (copied from source)

Mount Storm, West Virginia, USA

Study Year 2010

Young, D. P. Jr., S. Nomani, W. L. Tidhar, and K. Bay. 2011. NedPower Mount Storm Wind Energy Faciligy post-construction avian and bat monitoring, July–October 2010. Unpublished report prepared for NedPower Mount Storm, LLC, Houston, Texas. Prepared by Western EcoSystems Technology, Inc., Cheyenne, WY, USA. Available Here.

Summary from Arnett et al. 2013

Young et al. (2011) conducted an operational mitigation study at NedPower's Mount Storm Wind Energy Facility located in Grant County, in northeast West Virginia. This facility has 132 Gamesa G80 2-MW wind turbines mounted on 78-m hub height with a maximum height above ground of 118 m and an 80-m rotor-swept area. These turbines have a manufacturer's cut-in speed of 4.0 m/s, are variable speed and blades spin at approximately 9.1–19.0 rpm. The Project is located on the primary ridgeline of the Allegheny Mountains known as the Allegheny Front. Hardwood forest on the site consists primarily of oaks, maples, hickories, black cherry, black and yellow birch, and beech trees, while the spruce and conifer type consists of red spruce, hemlock, and a variety of pines, including red, pitch, and Virginia, used for reclamation of abandoned surface mines. Much of the site was previously strip mined for coal and consists of reclaimed areas. This facility is approximately 19 km long from north to south and turbines are generally positioned in rows of variable length oriented along a northeast to southwest axis (parallel to the primary ridgeline of the Allegheny Front). Eastern red bats, hoary bats, and silver-haired bats were killed most frequently at this facility in both years of the study.

The study included a design that incorporated weather forecasting to predict when bat mortality would be high based on wind speed. The risk to bats associated with freewheeling turbines (those spinning below the normal cut-in speed when they are not producing electricity) was evaluated as part of this study. The study also was designed to investigate whether limiting blade rotation of the turbines for first half of the night (approximately sunset plus 5 hrs) or the second half of the night (sunrise minus 5 hrs) was more effective. For nights when wind speeds were predicted to be below the normal turbine cut-in speed (4 m/s), turbine rotation was limited by feathering the turbine blades (pitching them more parallel to the wind) so there was only minimal rotation (<1 rpm). Normally, the turbines freewheel or spin at up to 9 rpm in winds under the cut-in speed of 4 m/s. The effect of restricting turbine rotation up to the cut-in speed for the first half of the night was compared to restricting turbine rotation during the second half of the night. Both of these treatment groups of turbines were compared to turbines that were allowed to operate under normal conditions to help evaluate when during a night bats are at greatest risk.

The study was conducted from 15 July–13 October 2010. Daily searches were employed at 24 turbines that were randomly assigned to 3 groups of 8 turbines each. Each turbine group was rotated weekly between the following treatments (I, II, III), such that each group received each treatment for 4 weeks over the duration of the late summer-fall study period, and groups were rotated weekly:

I. Turbine rotation restricted for first half of the night (approximately 5 hrs after sunset).
II. Turbine rotation restricted for second half of the night (approximately 5 hrs prior to sunrise).
III. Control group; no change to normal turbine operations.

Since treatments were cancelled on many nights during the study, only fatalities assumed to have occurred the previous night were used in the analysis. Fatality rates for each treatment were calculated along with corresponding 90% bootstrapped confidence intervals. Estimates without overlapping confidence intervals were considered significantly different. In addition to using fatality estimates, differences in treatments were examined by building a Poisson model to determine the relative difference in fatality rates based on the type of treatment. The magnitude of model coefficients represents the relative ratio of fatality rates between turbines subject to the treatments and those with no treatment (i.e., normal operations). Tests for variable selection were used to assess the statistical significance of the treatment covariates. The analysis for the turbine operations study considered two different data sets: those including nights when the treatments were cancelled because the weather forecast was for wind speeds greater than 4.0 m/s, and those excluding nights when treatments were cancelled (i.e., only those nights when turbine rotation was restricted).

When nights with cancelled treatments were included, 256 bat casualties were found during the study period (15 July–13 October) and were included in the turbine operations analysis that included nights with cancelled treatments. One-hundred eleven bat carcasses were found at control turbines compared to 59 bat carcasses found at turbines with rotation restricted during the first half of the night (treatment I) and 86 bat carcasses found at turbines with rotation restricted during the second half of the night (treatment II). This resulted in observed daily fatality rates and corresponding 90% bootstrap confidence intervals of 0.151 (0.114–0.187), 0.080 (0.052–0.109), and 0.117 (0.093–0.141) bats/turbine/study period for control, treatment I, and treatment II, respectively. Lack of overlap between confidence intervals for observed fatality rates under treatment I and control suggest a significant difference between casualties at turbines with rotation restricted during the first part of the night versus control turbines ($\alpha = 0.10$). Overlapping confidence intervals for observed fatality rates under treatment II and control and between treatments I and II suggest that there was no difference between bat fatalities at turbines with rotation restricted during the second part of the night versus control turbines or treatment I turbines ($\alpha = 0.10$).

Poisson modeling of observed fatality rates resulted in significant treatment covariates. The parameter estimate for treatment I was -0.63, which implies that the odds of a fatality occurring when turbine rotation is restricted during the first part of the night are 1.88 times less likely than with normal operations, with all other variables being equal. Variable selection tests for this covariate were significant ($z = -3.92$, $p < 0.01$), suggesting that restricting turbine rotation during the first part of the night has a significant effect in explaining differences in observed fatality rates among treatment I and control turbines. Parameter estimates for restricted turbine rotation during the second part of the night also were significant in the model ($z = -1.78$, $p = 0.08$) with a value of -0.26. This corresponds to approximately 1.29 times the odds of a fatality occurring with normal operations than when turbine rotation is restricted during the second part of the night, all other variables being equal. A nightly paired t-test comparison between the two treatments (first part of night, and second part of night) showed that the difference between them was significant at $\alpha = 0.10$ ($t = -1.84$, $p = 0.068$).

When nights with cancelled treatments were excluded, 104 bat carcasses were found during the study period (15 July–13 October) on nights when the two treatments were in place. Fifty-nine of these carcasses were found at control turbines during treatment nights, compared to 16 bat carcasses found at turbines with rotation restricted during the first half of the night (treatment I) and 29 bat carcasses found at turbines with rotation restricted during second half of the night (treatment II). This resulted in observed daily fatality rates and corresponding 90% bootstrap confidence intervals of 0.18 (0.13–0.22), 0.05 (0.03–0.07), and 0.09 (0.06–0.12) bats/turbine/study period for control, treatment I, and treatment II conditions, respectively. Non-overlapping confidence intervals for observed fatality rates under each treatment suggest that fatality rates at turbines with rotation restricted is lower than rates at control turbines ($\alpha = 0.10$).

Poisson modeling of observed fatality rates resulted in significant treatment covariates. The parameter estimate for the treatment I was -1.3, which implies that the odds of a fatality occurring when turbine rotation is restricted during the first part of the night are 3.69 times less likely than with normal operations, with all other variables being equal. Variable selection tests for this covariate were significant ($z = -4.63$, $p < 0.01$), supporting the conclusion that restricting turbine rotation during the first part of the night explained differences in observed fatality rates. Parameter estimates for restricted turbine rotation during the second part of the night also were significant in the model ($z = -3.13$, $p < 0.01$) with a value of -0.71. This corresponds to approximately 2 times the odds of a fatality being recorded with normal operations than when turbine rotation is restricted during the second part of the night, all other variables being equal. A nightly paired t-test comparison between the two treatments (first part of night, and second part of night) showed that the difference between them was not significant ($t = -1.57$, $p = 0.124$).

For both analyses, restricting turbine rotation during the first half of the night reduced bat mortality by 47% and 72%, respectively, which were substantially lower than the control group. For the second half of the night, the reduction in bat mortality was not as substantial, but still resulted in 22% and 50% reduction for the two analyses, respectively.

Study Year 2011

Young, D., S. Nomani, Z. Courage, and K. Bay. 2012. NedPower Mount Storm Wind Energy Facility post-construction avian and bat monitoring, July–October 2011. Unpublished report prepared for NedPower Mount Storm, LLC, Houston, TX. Prepared by WEST, Inc., Cheyenne, WY. Available Here

Summary from Arnett et al. 2013

This study conducted by Young et al. (2012) was based on results from the previous year that showed a reduction in bat mortality resulted from feathering turbine blades below the 4.0 m/s cut-in wind speed on nights when the wind was predicted to be low. For the 2011 study, the turbine blade feathering was automated so that the turbines would self-regulate as wind speeds changed. The general process for turbine operations was that if wind speeds dropped below the normal cut-in speed of 4.0 m/s at the turbine for a period of 6 min, a pause command was sent to the turbine which initiated blade feathering. Conversely, if the wind speed rose above 4.0 m/s for a period of 6 min the turbine was programmed to run normally.

To evaluate the effects of this treatment on bat mortality, the 24 turbines in the study were assigned to two groups of 12 turbines each for the duration of the late-summer and fall monitoring (16 July 16–15 October). Each turbine group was rotated weekly between the following two treatments (I and II), such that each group of turbines would receive each treatment for six weeks over a 12-week study period:

I. Blades feathered automatically.
II. Control group; allowed to operate normally with no automated blade feathering.

Groups were rotated weekly (i.e., repeated six times over 12 weeks). The analysis for the turbine operations study compared the bat mortality rate between the two treatment groups and looked at the correlation between bat mortality rate and percent of the night that turbines were feathered for the group for which the blades were feathered automatically in response to changes in wind speed.

During the study 39 fresh bat carcasses were found at turbines that had the automatic blade feathering and 43 fresh bat carcasses were found at control turbines. In general, the number of bat carcasses found each week by group was similar throughout the study. A Chi-square test for comparison of fatality counts was $\chi2 = 0.2459$, $df = 1$, $p = 0.62$. The chi-square test indicated no significant difference ($p > 0.1$) in fatality counts (weighted by effort) between control and feathered turbines. Bat fatality estimates for the study period were 6.45 and 7.35 bats/turbine for the feathered and control turbines, respectively.

Turbine data from the project for the period 16 July through 13 October were used to estimate proportion of night that feathering was in place and was correlated with nightly bat fatality rates for Group I and Group II turbines. There was an increase in nightly bat fatality when the proportion of night when feathering was taking place increased for Group I turbines. Feathering at Group I turbines reduced bat mortality when all study dates were considered (r = 0.225, p = 0.052), and when only planned feathering dates were considered (r = 0.365, p = 0.037). Feathering at Group II turbines did not reduce bat mortality when all study dates were considered (r = 0.079, p = 0.498), and when only planned feathering dates were considered (r = 0.074, p = 0.640). More than 60% of the weather data readings collected did not have rpm readings, which did not allow for effectively determining when blade feathering was active during the study.

Ontario, Canada

Zimmerling, Ryan J., Lauren A. Hooton, and Christian Roy. 2016. How Effective are Mitigation Measures in Ontario at Reducing Bat Mortality? Poster at the National Wind Coordinating Collaborative Wind Wildlife Research Meeting XI Broomfield, CO.

Hooton, Lauren. Ontario Mitigation Analysis. April 13 2016. webinar

Forcey, Greg, Lauren Hooton; Crissy Sutter. 2016. Reductions in Bat Mortality at Wind Facilities Vary Depending on Operational Curtailment Strategy. Presentation to the 23rd annual meeting of The Wildlife Society. Raleigh, NC, USA.

Abstract

The effectiveness of mitigation measures at reducing bat mortality has not been adequately assessed for most jurisdictions in Canada. In the province of Ontario, wind farms that exceed the mortality threshold of 10 bats / turbine / year must implement an increased cut-in speed of 5.5 m / sec from July 15 to September 30 for all wind turbines across the entire wind farm for the life of the project. We conducted a large-scale assessment of the effectiveness of mitigation in Ontario by comparing pre- and post-mitigation bat mortality within and among wind farms. We also compared the species-specific effectiveness of mitigation at reducing mortality. Overall, our results demonstrate that increasing the cut-in speed of wind turbines to 5.5 m / sec reduces bat mortality to varying degrees, although it is somewhat species dependent. We suggest that the effectiveness of mitigation measures in Ontario could be further increased by utilizing an adaptive management framework.

Pinnacle Wind Farm, West Virginia, USA

<u>Study Year 2012</u>

Hein, C. D., A. Prichard, T. Mabee, and M. R. Schirmacher. 2013. Effectiveness of an Operational Mitigation Experiment to Reduce Bat Fatalities at the Pinnacle Wind Farm, Mineral County, West Virginia, 2012. Bat Conservation International. Available Here

Executive Summary

In accordance with the West Virginia Public Service Commission (WVPSC) and with guidance from the Technical Advisory Committee, which included members from the WVPSC, U.S. Fish and Wildlife Service, West Virginia Division of Natural Resources, and Edison Mission Energy, we initiated a study in July 2012 to test the effectiveness of an operational mitigation experiment to reduce bat fatalities at the Pinnacle Wind Farm (PWF), Mineral County, West Virginia. Our objective was to determine the difference in bat fatalities at turbines with different operational adjustments. A post-construction fatality monitoring study was conducted at the PWF between 1 March and 30 November 2012, results of which are discussed in a separate report.

The facility lies within the Appalachian mixed mesophytic forests ecoregion composed of moist broadleaf forests, which cover the plateaus and rolling hills west of the Appalachian Mountains. The project consists of 23 Mitsubishi 2.4-MW turbines, with 95 m rotor diameter and 80 m hub height for a total height of approximately 128 m (from base of tower to highest point of the blade), and a manufacturer's cut-in speed of 3.0 m/s. Turbines are fully "feathered" below the manufacturer's cut-in speed. In this position, there is no aerodynamic lift from the blades and thus no rotor rotation. At 3.0 m/s the blades are pitched to generate lift and the rotor starts rotation. Twelve of the 23 turbines at the PWF were randomly selected for the experiment and we rotated three treatments among these turbines: 1) fully operational at 3.0 m/s cut-in speed, 2) increased cut-in speed at 5.0 m/s from sunset to sunrise, and 3) increased cut-in speed at 5.0 m/s for the first four hours past sunset. We used a completely randomized design and treatments were randomly assigned to turbines each night of the experiment, with the night when treatments were applied as the experimental unit. We conducted daily fatality searches between 15 July and 30 September 2012.

We found a total of 186 bat carcasses, of which 31, 89, and 66 were found in July, August, and September, respectively. We recovered carcasses from 6 different species, including eastern red bats (*Lasiurus borealis*), hoary bats (*Lasiurus cinereus*), silver-haired bats (*Lasionycteris noctivagans*)-listed as Imperiled (S2) by West Virginia Division of Natural Resources (WVDNR), tri-colored bats (*Perimyotis subflavus*), big brown bats (*Eptesicus fuscus*), and Seminole bats (*Lasiurus seminolus*). Migratory tree-roosting bats (hoary bats, silver-haired bats, and eastern red bats) comprised 79% (n = 147) of all fatalities, and big brown bats and tri-colored bats, two species impacted by White-nosed Syndrome (WNS), collectively represented 19% (n = 36) of carcasses found. There was no evidence of WNS on any bats recovered during the study. One Seminole bat and 2 unidentified carcasses also were found.
Of the 186 total bat carcasses found, 155 were determined to be fresh (i.e., killed the previous night). Thirty-nine fatalities occurred when turbines were operating at 5 m/s all night, 56 occurred when turbines were operating at 5 m/s during the first four hours past sunset (herein referred to as half night), and 60 occurred when turbines were fully operational. Average nightly wind speeds among turbines across the study showed that over 70% of the time wind speed was above 5 m/s. Average wind speed was only between 3 and 5 m/s (i.e., the time when treatments were implemented) for approximately 17% of the time during the study.

The most parsimonious model in our candidate model set, regardless of whether or not an outlier was included, incorporated the variables date, treatment, proportion of wind speeds between 3–

5 m/s and a wind speed by treatment interaction. The fatality rate increased with the proportion of wind speeds between 3–5 m/s for fully operational turbines, increased at a slower rate for turbines undergoing the 5 m/s half night, and did not increase for turbines that experienced the 5 m/s all night treatment, with and without the outlier. The slope for 5 m/s all night turbines was significantly different from fully operational turbines (P = 0.022), but the slope for the 5 m/s half night was not significantly different from fully operational turbines (P = 0.084).

Our success in implementing an operational mitigation strategy varied with the experimental treatment groups. We found no difference between the 5 m/s half night treatment and fully operational turbines regardless of model. We observed a 47% reduction in bat fatalities for the 5 m/s all night treatment compared to fully operational turbines, but only when we removed an outlier (i.e., a night when 7 fatalities were recovered from a 5 m/s all night treatment turbine) from the dataset. Our lack of a treatment effect likely is a result of the small proportion of time (17%) wind speeds were between 3 and 5 m/s. Based on the best model, which incorporated the proportion of the night that wind speeds were between 3 and 5 m/s, we observed a 72.2% and 81.7% reduction in bat fatalities at 5 m/s all night treatment turbines compared to fully operational turbines, with and without the outlier, respectively.

Presently, our understanding of the sustainability of wind energy impacts on bats is limited by the lack of knowledge of population size, structure and dynamics. Until we have a better understanding of bat populations, our ability to determine whether the reduction in bat fatalities, from operational mitigation measures, is adequate to mitigate the adverse effects of wind energy development remains unknown. Although gathering data to address this issue is a priority, data are not expected to be available in the near future. Given the magnitude and extent of bat fatalities throughout North America, we believe that wind operators should implement operational mitigation strategies, even in the absence of population data.

Study Year 2013

Hein, C. D., A. Prichard, T. Mabee, and M. R. Schirmacher. 2014. Efficacy of an operational minimization experiment to reduce bat fatalities at the Pinnacle Wind Farm, Mineral County, West Virginia, 2013. An annual report submitted to Edison Mission Energy and the Bats and Wind Energy Cooperative. Bat Conservation International. Austin, Texas, USA. Available Here

Executive Summary

In accordance with the guidance of the West Virginia Public Service Commission (WVPSC) and with recommendations from the Pinnacle Technical Advisory Committee, which included members from the WVPSC, U.S. Fish and Wildlife Service (USFWS), West Virginia Division of Natural Resources (WVDNR), and Edison Mission Energy, we initiated a study in July 2013 to test the effectiveness of an operational minimization experiment to reduce bat fatalities at Pinnacle Wind, LLC (PWF), Mineral County, West Virginia. Our objective was to determine the difference in bat fatalities at turbines with different operational adjustments.

The PWF lies within the Appalachian mixed mesophytic forests ecoregion composed of moist broadleaf forests, which cover the plateaus and rolling hills west of the Appalachian Mountains. The project consists of 23 Mitsubishi 2.4 megawatt (MW) turbines, with 95 m rotor diameter and 80 m hub height for a total height of approximately 128 m (from base of tower to highest point of the blade), and a manufacturer's cut-in speed of 3.0 m/s. Turbines are fully "feathered" below the manufacturer's cut-in speed. In this position, there is no aerodynamic lift from the blades and thus no rotor rotation. At 3.0 m/s the blades are pitched to generate lift and the rotor starts rotation. We randomly selected 12 of the 23 turbines at the PWF for the experiment and we alternated 3 treatments among these turbines from sunset to sunrise: 1) fully operational at 3.0 m/s cut-in speed, 2) increased cut-in speed and fully feathered until wind speed reached 5.0 m/s, and 3) increased cut-in speed and fully feathered until wind speed reached 6.5 m/s. We used a completely randomized design and treatments were randomly assigned to turbines each night of the experiment, with the night when treatments were applied as the experimental unit. We conducted daily fatality searches between 15 July and 30 September 2013, which represents the expected peak fatality period for this region.

We found a total of 107 fresh bat carcasses, of which 16, 36, and 55 were found in July, August, and September, respectively. We recovered carcasses from 5 different species, including eastern red bats (*Lasiurus borealis*), hoary bats (*Lasiurus cinereus*), silver-haired bats (*Lasionycteris noctivagans*), tri-colored bats (*Perimyotis subflavus*), and big brown bats (*Eptesicus fuscus*). Migratory tree-roosting bats (i.e., eastern red bats, hoary bats, and silver-haired bats) comprised 85% (n = 91) of fatalities. Of these, 42 fatalities were of silver-haired bats, a state imperiled (S2) species (i.e., imperiled in the state because of rarity or because of some factors(s) making it very vulnerable to extirpation from the state). Big brown bats and tri-colored bats, two species impacted by WNS, collectively represented 15% (n = 16) of carcasses found. We found no evidence of WNS on any bat recovered during the study.

Of the 107 fresh bat carcasses recovered, we found 63 under fully operational turbines, 29 under 5.0 m/s treatment turbines, and 15 under 6.5 m/s treatment turbines. The estimated fatality rate over all 12 turbines during the 72-night period was 0.705 bats/turbine/night (95% CI: 0.513–1.066). The estimated fatality rate was 1.263 bats/turbine/night (95% CI: 0.795–2.132) for the fully operational, 0.533 bats/turbine/night (95% CI: 0.259–0.957) for the 5.0 m/s treatment, and 0.320 bats/turbine/night (95% CI: 0.157–0.637) for the 6.5 m/s treatment. The estimated fatality rate for the entire study by bats/turbine and bats/MW was 50.76 (36.9–76.8) and 21.2 (15.4–32.0), respectively.

Our results showed significant differences among treatment groups. Both the 5.0 m/s treatment (P = 0.003) and the 6.5 m/s treatment (P = 0.001) had significantly lower fatality rates than the fully operational treatment. The fatality rate for the 6.5 m/s treatment was not significantly lower than the fatality rate for the 5.0 m/s treatment ($P = 0.103$), although the estimated mortality rate was lower. We observed a 54.4% (95% CI: 17.7–74.7) and 76.1% (95% CI: 49.1–88.8) reduction in bat fatalities for the 5.0 m/s and 6.5 m/s treatments, respectively.

Operational minimization studies, such as this one, consistently show significant reductions in bat fatalities when turbines are either feathered below the manufacturer's or higher cut-in speed. Our results are similar to those found in the first U.S.-based operational minimization study at the Casselman Wind Energy Facility in south-central Pennsylvania, in that we found a difference in fatalities between fully operational and treatment turbines, but not between the two treatment groups. The observed lack of significant differences in fatality rate among treatments may have been a result of the small proportion of time wind speeds were between 5 and 6.5 m/s. At the PWF, wind speeds between 5 and 6.5 m/s only occurred for 18.6% of the time, thus limiting the amount of time the treatments were in effect.

Presently, our understanding of the sustainability of wind energy impacts on bats is limited by the lack of knowledge of population size, structure and dynamics. Until we have a better understanding of bat populations, our ability to determine whether the reduction in bat fatalities, from operational minimization measures, is limited. Although gathering data to address this issue is a priority, population data are not expected to be available in the near future. Yet, our current understanding of operational minimization indicates that bat fatalities at wind turbines can be significantly reduced when the manufacturer's cut-in speed is raised between 2.0–3.0 m/s. Given the magnitude and extent of bat fatalities throughout North America, we believe that minimization strategies, such as operational minimization, should be considered at operating wind energy facilities to reduce the direct impact to bats, even in the absence of population data.

Study Year 2015

Schirmacher, M. R., A. Prichard, T. Mabee, and C. D. Hein. 2016. Evaluating a Novel Approach to Optimize Operational Minimization to Reduce Bat Fatalities at the Pinnacle Wind Farm, Mineral County, West Virginia, 2015. An annual report submitted to NRG Energy and the Bats and Wind Energy Cooperative. Bat Conservation International, Austin, Texas, USA. Available Here

Executive Summary

In accordance with the guidance of the West Virginia Public Service Commission (WVPSC) and with recommendations from the Pinnacle Technical Advisory Committee, which included members from the WVPSC, U.S. Fish and Wildlife Service (USFWS), West Virginia Division of Natural Resources (WVDNR), and NRG Energy, we initiated a study in July 2015 to test alternative wind turbine operational strategies to reduce bat fatalities at the Pinnacle Wind, LLC (PWF), Mineral County, West Virginia. Our primary objective was to test the effectiveness of a novel operational minimization strategy to reduce bat fatalities at Pinnacle Wind Farm, LLC (PWF). A secondary objective was to examine potential mechanisms that effect fatality risk to bats.

We randomly selected 15 of the 23 turbines at the PWF for the experiment to evaluate 3 operational minimization strategies. We used a completely randomized block design and treatments were randomly assigned to turbines each night of the experiment, with the night when treatments were applied as the experimental unit. We conducted daily fatality searches between 15 July and 30 September 2015, which represents the expected peak fatality period of bats for this region. The following treatments involved the decision framework to initiate turbine start-up and included:

Treatment A: increased the wind speed requirement to initiate turbine start-up from 3.0 m/s and fully feathered blades until wind speed reached 5.0 m/s based on a 10-minute rolling average as measured at a nearby meteorological (met) tower anemometer at 76 m above ground level (agl). Turbine blades were fully feathered until wind speeds reached 5 m/s. This treatment is currently the standard operating procedure at the PWF from 15 July–30 September,

Treatment B: increased the wind speed requirement to initiate turbine start-up from 3.0 m/s and fully feathered blades until wind speed reached 5.0 m/s based on a 20-minute rolling average measured at the same meteorological tower as Treatment A, and

Treatment C: increased the wind speed requirement to initiate turbine start-up from 3.0 m/s and fully feathered until wind speed reached 5.0 m/s based on a 20-minute rolling average as measured from anemometers on individual turbines at 80 m agl. To reduce the effects of the turbine blades on the wind speed measured downwind on the nacelle mounted anemometer, proprietary calculations were implemented to determine the “free-stream wind speed”.

Decisions to shut-down operations, or curtail turbines, were all based on a 10-minute rolling average of wind speed <5.0 m/s as measured at the met tower for Treatments A and B and the individual turbine for Treatment C. Thus, the shutdown/start-up decision framework for Treatment A was symmetrical (10-minute average to shut-down and start-up), whereas Treatments B and C were asymmetrical (10-minute average to shut-down, 20-minute average to start-up), but with wind speed measurements based on the met tower for Treatment A and B and the individual turbine Treatment C.

During standardized searches, we found 57 fresh bat carcasses, representing 5 different species, including 31 eastern red bats (*Lasiurus borealis*), 11 hoary bats (*Lasiurus cinereus*), 10 big brown bats (*Eptesicus fuscus*), 4 silver-haired bats (*Lasionycteris noctivagans*), and 1 tri-colored bat (*Perimyotis subflavus*). No *Myotis* species were found. We found 17 bat fatalities associated with Treatment A, 12 under Treatment B, and 23 under Treatment C. We removed 5 carcasses prior to analysis because they were associated with nights that experienced treatment implementation error.

We used two methods, Poisson regression and estimated fatality, to evaluate the 3 operational minimization strategies based on fresh bat fatalities. These two methods generally supported each other, although estimated fatality, corrected for detection bias, was the only one that showed a significant difference and only between Treatments B and C. The best Poisson Regression model explaining the number of bat fatalities found under turbines only included turbine differences, but the models with mean hours on and treatment were within 1 Deviance Information Criterion (DIC) unit. In general, Treatment C had higher bat fatalities, significantly higher than Treatment B, and turbines in that treatment were operational for significantly longer periods compared to Treatments A and B. The turbine anemometer had an average 1.03 m/s higher wind speed value compared to the met tower, which likely caused turbines under Treatment C to start-up earlier and shut-down later increasing the operating time. Operating time was not significant and therefore was not solely determined to be the reason for higher bat fatalities based on our Poisson regression models.

As a secondary objective, we examined potential mechanisms that influenced fatality only on nights when turbines were operating regardless of treatment. The best logistic regression mixed model of bat fatalities found per hour the turbine was spinning included number of stops. However, stops/starts and starts were within one AIC unit. This suggested that bats may be at risk during operational transitions (i.e. during turbine start-up or shut-down), specifically the probability of finding a fatality increased significantly with an increasing number of stops. Alternatively, since all treatments were based on a wind speed of 5 m/s it is difficult to separate risk to bats when turbine operations were in transition compared to risk at relatively low wind speeds (e.g. ~ 5 m/s), which might influence changes in turbine operation.

The results of this study suggest that fewer bat fatalities occurred when turbine operations were based on the meteorological tower (Treatment A and B) rather than the individual turbine (Treatment C). This is likely associated with the amount of time turbines were in operation each night, which was longer for Treatment C, although our models suggested other factors may also influence fatality. Furthermore, extending the decision time, from 10 minutes (Treatment A) to 20 minutes (Treatment B), to begin operating turbines when wind speeds exceed the cut-in speed, also may reduce fatalities by reducing the number of transitions (i.e., turbine start-ups and shut-downs). Minimizing the number of start-ups/shut-downs may assist in reducing wear-and-tear on turbines and, at least in this study, may also reduce the power loss related to this reduction strategy. Thus, Treatment B represents a decision framework with fewer fatalities, significantly fewer than Treatment C, and compared to Treatment A had less wear-and-tear on turbines (i.e. start-up and shut-downs) with no additional loss in power, and may be the most cost effective option of the 3 treatments studied in this experiment.

The relationship between turbine transitions and bat fatalities is unclear and additional research is needed at other wind energy facilities to better understand bat/wind turbine interactions during start-ups and shut-downs. Until more data are gathered, implementing strategies that limit operational transition of turbines at low wind speeds, such as extending the average decision time period (e.g., from 10 to 20 minutes) to inform turbine operation, may further reduce bat fatalities at the same cut-in speed. Limiting the number of times turbines start-up and shut-down may reduce turbine wear-and-tear and thereby power loss, which provide benefits for wind facility operators. Future research across a variety of facilities, turbine types and species should consider comparing differences between a longer decision framework and higher cut-in speeds or combine different decision frameworks with additional weather variables to assess the most cost-effective strategy to reduce bat fatalities at wind turbines.

Sheffield Wind Facility, Vermont, USA

Martin, C. M., E. B. Arnett, R. D. Stevens, and M. C. Wallace. 2017. Reducing bat fatalities at wind facilities while improving the economic efficiency of operational mitigation. Journal of Mammalogy 98:378–385. Available Here

Martin, C. 2015. Effectiveness of Operational Mitigation in Reducing Bat. Texas Tech University. Available Here

Abstract

Concerns about cumulative population-level effects of bat fatalities at wind facilities have led to mitigation strategies to reduce turbine-related bat mortality. Operational mitigation that limits operation may reduce fatalities but also limits energy production. We incorporated both temperature and wind speed into an operational mitigation design fine-tuned to conditions when bats are most active in order to improve economic efficiency of mitigation. We conducted a 2-year study at the Sheffield Wind Facility in Sheffield, Vermont. Activity of bats is highest when winds speeds are low (< 6.0 m/s) and, in our region, when temperatures are above 9.5°C. We tested for a reduction in bat mortality when cut-in speed at treatment turbines was raised from 4.0 to 6.0 m/s whenever nightly wind speeds were < 6.0 m/s and temperatures were > 9.5°C. Mortalities at fully operational turbines were 1.52–4.45 times higher than at treatment turbines. During late spring and early fall, when overnight temperatures generally fell below 9.5°C, incorporating temperature into the operational mitigation design decreased energy losses by 18%. Energy lost from implementation of our design was < 3% for the study season and approximately 1% for the entire year. We recommend that operational mitigation be implemented during high-risk periods to minimize bat fatalities and reduce the probability of long-term population-level effects on bats.

Wildcat Wind Farm, Indiana, USA

Stantec Consulting Services, Inc. 2018. 2017 Post-Construction Bat Mortality Monitoring Report Wildcat Wind Farm Madison and Tipton Counties, Indiana. Independence, Iowa.

Introduction and Background from Report

The Wildcat Wind Farm (Project or Wildcat) developed by Wildcat Wind Farm I, LLC (WWF) is located in Madison and Tipton counties, immediately north of the town of Elwood, Indiana. The Project consists of 125 GE 1.6 megawatt (MW) wind turbine generators and associated access roads and collector line system for a total capacity of 200 MW (Figure 1). The Project is located on lands leased from private landowners who continue their existing use of the land. Land use in the area is predominantly agricultural.

Wildcat is located within the range of both the federally endangered Indiana bat (Myotis sodalis) and federally threatened northern long-eared bat (Myotis septentrionalis). A Post-Construction Mortality Minimization and Monitoring Proposal (MMMP) was developed in June 2012 and revised in June 2015, and is consistent with methods and the recommendations of the U.S. Fish and Wildlife Service (USFWS) Land-Based Wind Energy Guidelines (USFWS 2012). From 2013 through June 2015, the Project operated under the terms of a Technical Assistance Letter (TAL) dated 18 June 2012, that established an operational scenario under which no take of Indiana bats was expected to occur (i.e. 6.9 meters per second [m/s] cut-in speed during the fall migration period [1 August – 15 October]).

From July 2015 through 18 August 2016 the Project operated under the terms of a second TAL secured on 2 July 2015 that established a revised operational scenario under which no take of Indiana bats or northern long-eared bats is expected to occur. This second TAL required curtailment to 6.9 m/s during the fall migration period (1 August – 15 October) and 5.0 m/s during the spring migration period (15 March – 15 May). On 19 August 2016, the Project obtained an Incidental Take Permit (ITP) from the USFWS, allowing operations under the terms of the Project’s Habitat Conservation Plan (HCP), which covers the Indiana bat and northern long-eared bat (or covered species), requires curtailing to 5.0 m/s during the fall migration period (1 August – 15 October), and outlines the requirements for post-construction monitoring to ensure permit compliance. The ITP authorizes the take of 162 Indiana bats and 81 northern long-eared bats over the 27 years of project operations, or an average of 6 Indiana bats and 3 northern long-eared bats per year.

Wolfe Island, Ontario, Canada

Stantec Consulting Ltd. 2012. Wolfe Island Wind Plant post-construction follow-up plan bird and bat resources, monitoring report No. 6, July–December 2011. Unpublished report prepared for TransAlta Corporation wholly owned subsidiary of Canadian Renewable Energy Corporation. Prepared by Stantec Consulting, Ltd., Guelph, ON.

Summary from Arnett et al. 2013

The Wolfe Island Wind Farm (WIWF) is located on Wolfe Island on Lake Ontario. The facility has 86 2.3-MW Siemens Mark II wind turbines with an 80-m hub height, 93-m rotor diameter and standard cut-in speed of 4.0 m/s. Dominant land cover types include row-crop agriculture, hay fields and pasture. Fatalities at this facility were dominated by hoary bats (50%) with similar numbers of eastern red bats (17.3%), silver-haired bats (15.4%) and big brown bats (*Eptesicus fuscus*; 15.4%; Stantec Consulting, Ltd. 2012).

From July 2010 through June 2011, the estimated annual bat mortality rate was 9.71 bats/MW, which is below the adaptive management threshold of 12.5 bats per MW as set forth by the Provincial government. The operator (TransAlta) proactively developed and implemented a research program to evaluate practical measures to reduce the effects of operating WTGs on bats at Wolfe Island. Fourteen turbines in each of 3 treatments (control, cut-in speed raised to 4.5 and 5.5 m/s) were randomly selected and were searched twice/week from 15 July to 30 September 2011. Searches were conducted using transects with 7-m spacing within a 50-m radius of the turbine. The experimental treatments were fixed for the entire study period and were implemented from sunset to sunrise.

Estimated bat fatality rates, adjusted for searcher efficiency and scavenging, were 2.28 bats/MW (control), 1.19 bats/MW (4.5 m/s), and 0.91 bats/MW (5.5 m/s), indicating a reduction in mortality of approximately 48–60% for turbines with cut-in speeds raised to 4.5 m/s and 5.5 m/s, respectively. However, because the number of actual bat fatalities used to make these estimates was low (7, 8, and 5 fatalities found at control, 4.5 and 5.5 m/s turbine groups, respectively), the authors did not believe statistical analysis was appropriate (Stantec Consulting Ltd. 2012) and results should be interpreted with caution.

Wolf Ridge, Texas, USA

Hale, Amanda M and Victoria J Bennett. 2014. Investigating the benefits of fine-tuning curtailment strategies at operational wind facilities. Presentation to the National Wind Coordinating Collaborative Wind Wildlife Research Meeting X. Broomfield, CO.

Abstract

We estimate that total fatalities are reduced by an average of 33% with every 1.0 m/s increase in cut-in speed. Estimates of the efficacy of 5.0 m/s operational minimization on the three migratory tree-roosting species in North America are similar (28% for hoary bats [*Lasiurus cinereus*], 32% for eastern red bats [*L. borealis*], and 32% for silver-haired bats [*Lasionycteris noctivagans*]). Extrapolating these data across multiple facilities and time periods, a 5.0 m/s cut-in speed is estimated to reduce total bat fatalities by an average of 62% (95% CI 54–69%). We estimate total bat fatality reductions at individual facilities in any given year to fall between 33%–79% (95% prediction interval). For individual species, average fatality reduction at 5.0 m/s cut-in speed was estimated as 48% (95%CI 24%–64%) for hoary bats, 61% (95%CI 42–74%) for eastern red bats, and 52% (95%CI 30%–66%) for silver haired bats. These reductions do not appear to vary geographically, however interannual variation at each facility is expected to be high.

Other strategies that seek to refine operational minimization are poorly studied. The use of temperature and wind direction to make curtailment decisions were only evaluated in 1 study each. Feathering blades below cut-in speed was only studied at one site. Using bat activity to make curtailment decisions seems effective but has only been evaluated once. Many studies are plaqued by a low effect size introduced by the small difference in treatment implementation that minimizes the ability to detect a statistical difference between treatments. Additional studies that compare fatality rates between years and treatments are unreliable due to the interannual variability in fatality rates and curtailment efficacy.

Average reported annual power loss across 11 treatments with 7 different minimization techniques was 0.51% (range 0.06 to 3.2%). Eight comparisons (73%) report ≤1% lost power production per year. However, to fully evaluate the viability of operational minimization at individual facilities, additional financial considerations, legal implications should be considered.

Taken together the three sections of our report demonstrate that a 5.0 m/s cut-in speed reduces total bat fatalities on average by 62% at a cost of <1% of annual energy production. While power loss varies regionally and according to specific operational minimization strategy employed, average fatality reductions (as a percent of original fatalities) is expected to remain constant both across space and as cut-in speed increases.

North American Values Comparison

Gruver, Jeff, Tim Sichmeller, Wally Erickson, Karen Tyrell, David Young. 2016. Curtailment for Bats: A Synthesis of Available Studies. Poster at the National Wind Coordinating Collaborative Wind Wildlife Research Meeting XI Broomfield, CO.

Abstract

Bat fatalities at wind energy facilities have been widely known since 2003. To reduce bat fatalities operational minimization strategies have been developed and implemented with successful results. In 2015, voluntary operational practices aimed at reducing bat fatalities from wind turbines by up to 30 percent were established by the wind power industry. These strategies will adjust the operation of wind turbines during the fall migration season when bats are at the highest risk of collision with moving turbine blades. Adjusting turbine blade rotation by changing cut-in speed ("turbine curtailment") does potentially reduce energy generation and therefore leads to monetary losses to wind energy companies, as well as losses in generated renewable energy which must then be generated by other means.

Here we provide an updated synthesis of results from publicly available turbine curtailment studies designed to reduce bat fatalities at wind energy facilities since 2009. Summaries and evaluations of the studies are provided. A synthesis of the results shows strong correlation between all bat fatality reductions with increasing cut-in speeds at operational facilities in North America. Additionally, studies that include feathering of turbine blades below the normal cut-in wind speed are evaluated and summarized. We provide examples of different curtailment strategies employed at different wind energy facilities and a summary of lessons.

APPENDIX III: CACLULATION OF FATALITY RATE FROM RAW DATA

We calculated fatality rates when the treatment specific fatality rate for individual species or total bat fatalities was not provided in the report, but raw data was available. All studies where fatality rates needed to be calculated were conducting using a form of randomized block design, allowing us to use a generalized linear mixed model to predict the number of found fatalities per treatment at each turbine.

We modeled the total fatalities per treatment at each turbine as a poisson random variable on a log link. Treatment was the only predictor considered. Where possible, the log number of days searched was used as an offset. A random effect of turbine allowed the intercept to vary for each turbine. We fit models using the glmmTMB package (version 1.0; Brooks et al. 2017) in program R.
Individual considerations and predicted fatality levels for each study are described below.

Blue Creek, Ohio 2017

Bat Conservation International conducted the study evaluating the efficacy of operational minimization and deterrents at Blue Creek wind facility. Available data included turbine level fatality information for a control and three treatments: Curtailment Only, Deterrent Only, and Deterrent and Curtailment. The search schedule provided information on all searches conducted and was matched with treatment to produce the number of times an individual turbine was searched under each treatment. We built models that included all treatments to better estimate the variance between turbines (Table A1). However, we only predicted fatality rates for control and curtailment treatments (Table A2). Results closely correspond with reported ratios and percent decreases.

Fowler Ridge, Indiana 2010

Raw data for the 2010 operational minimization study at Fowler Ridge wind farm in Indiana was available in Appendix E of Good et. al. (2011). This information contained the turbine number, treatment, date, and species of each fatality. Turbine model and search frequency of each turbine number was manually extracted from Figure 2 and 3 in the report.
Fatality from fixed treatment control turbines were removed from analysis. These turbines had full plots that were searched daily or were on a weekly road and pad search schedule. Only fatalities from the twenty-seven turbines with treatment rotated on a weekly basis were included in the analysis. Data on the successful search schedule/effort for each turbine were not available and therefore an offset was not included in the model. Without an offset for search effort, using the fixed control turbines would adversely affect the analysis. Fixed treatments with the same search schedule are implemented 3 times the length of time as rotated treatments. Fixed treatments with weekly road and pad searches have a smaller search area and found fatality rate. Uncorrected, this biases the fatality rate of control turbines. For Fowler Ridge, we added a fixed effect for turbine model. Good et. al. (2011) and Good et al. (2012) note that fatality rates differ among turbine types. Additionally, figure 27 of Good et. al. (2012) shows that these three turbines have vastly different start-up profiles under the same control scenario and we wanted to be able to account for this in the meta-analysis.

Temporal balance of treatments at a turbine was not ideal since treatments were rotated on a weekly basis. Therefore, we would have preferred to add a temporal fixed effect to the model; however, data on when the treatments were implemented was not available.

Our methods differed greatly from Good et. al. used in the report. In the report simple boostrapped confidence intervals of the found fatalities were used to determine if differences between treatments existed. The percent decrease in fatalities was calculated as a simple ratio of the raw means. This fails to account for the treatment effect within a turbine. They conclude that a total fatality reduction of 50% and 78% for 5.0m/s and 6.5m/s treatments. A simple model only including total fatalities and within turbine random effect reports a 64% (95%CI 52–73%) and 85% reduction (95%CI 77–90%). The fitted model for red, hoary, and silver-haired bats is shown in Table A3. Predicted fatality rates are shown in Table A4.

Fowler Ridge, Indiana 2011

Data for the curtailment study at Fowler Ridge wind facility is available in Appendix D of Good et al. (2012). Similar to 2010, we matched turbine numbers with makes and models using figures of the site (Figures 2 & 3). We removed data associated with fixed control treatments that were cleared and searched every other day. Data from 168 turbines with treatments assigned nightly in a balanced block design were used. We used the same model for Fowler Ridge 2011 as we did for Fowler Ridge 2010. This model included fixed effects for the interaction of treatment and turbine model (Table A5). Predictions are available in Table A6. Models for silver-haired bats did not converge and were not used in the analysis.

To assure we were using proper data, we used a simple generalized linear mixed model similar to Good et al. (2012) and compared results. This model uses turbine as a blocking factor and treatment as a fixed effect. We fit the model using a negative binomial distribution with quadratic parameterization and a log link. Our estimates were extremely similar to those predicted by Good et al. (2012). We predicted a decrease in fatalities of 36%, 59%, and 76% for feathering, 4.5 m/s, and 5.0 m/s treatments, respectively. Good et al. estimated the same effects to be 36%, 57%, and 73%.

Pinnacle, Pennsylvania 2012

Data from Pinnacle wind facility for 2012 was gathered from the Bat Conservation International data archives. We followed the analysis used in the report for hoary, red, and silver-haired bats (total was already reported). This model used the daily number of found fatalities as the response. Predictors included the treatment and second-degree polynomial of the date. This method produces expected daily fatality rates per turbine. For total bat fatalities, the model exactly matched the percent reduction reported, 46.6%. The fitted model for the three species analyzed is shown in table A7. Predictions of the fatality rates used in the meta-analysis are shown in table A8.

Table A1: Model output for effect of treatments (Curtailment Only, Deterrent Only, Curtailment and Deterrent) at reducing bat fatalities at Blue Creek wind facility, Ohio USA.

	Red bat			**Hoary bat**			**Silver-haired bat**			**Total Fatalities**		
Predictors	*Incidence Rate Ratios*	*CI*	*p*	*Incidence Rate Ratios*	*CI*	*p*	*Incidence Rate Ratios*	*CI*	*p*	*Incidence Rate Ratios*	*CI*	*p*
(Intercept)	0.03	0.02 – 0.06	<0.001	0.02	0.01 – 0.04	<0.001	0.02	0.01 – 0.04	<0.001	0.09	0.07 – 0.13	<0.001
Curtailment Only	0.80	0.37 – 1.70	0.559	0.66	0.24 – 1.86	0.437	0.55	0.19 – 1.65	0.288	0.61	0.37 – 1.00	0.049
Deterrent Only	2.36	1.29 – 4.31	0.006	0.89	0.34 – 2.31	0.816	0.56	0.19 – 1.67	0.296	1.27	0.85 – 1.92	0.245
Curtailment and Deterrent	1.60	0.84 – 3.05	0.153	0.77	0.29 – 2.08	0.612	0.11	0.01 – 0.87	0.037	0.85	0.54 – 1.33	0.480
RANDOM EFFECTS												
σ^2	0.00			0.00			0.00			0.00		
τ_{00}	0.13 $_{Turbine}$			0.00 $_{Turbine}$			0.00 $_{Turbine}$			0.01 $_{Turbine}$		
ICC	1.00									1.00		
N	16 $_{Turbine}$			16 $_{Turbine}$			16 $_{Turbine}$			16 $_{Turbine}$		
Observations	64			64			64			64		
Marginal R^2 / Conditional R^2	0.578 / 1.000			1.000 / NA			1.000 / NA			0.927 / 1.000		

Table A2: Model prediction for Control and Curtailment Treatment at Blue Creek wind facility. These fatality rates and CI were used in the meta-analysis

Treatment	Species	EstFat	LCI	UCI
Control	Eastern Red Bat	0.032309	0.0187	0.055823
Treatment	Eastern Red Bat	0.025772	0.014113	0.047061
Control	Hoary Bat	0.020737	0.01079	0.039855
Treatment	Hoary Bat	0.013761	0.006182	0.030631
Control	Silver-haired bat	0.020737	0.01079	0.039855
Treatment	Silver-haired bat	0.011468	0.004773	0.027552
Control	Total	0.09417	0.068981	0.128558
Treatment	Total	0.057171	0.038487	0.084927

Table A3: Model output for effect of treatments (5.0 m/s Curtailment, 6.5 m/s) within each turbine type (GE, Vestas, Clipper) at reducing bat fatalities at Fowler Ridge wind facility, Indiana USA.

	Total bat fatalities			Red bat			Hoary bat			Silver-haired bat		
Predictors	*Incidence Rate Ratios*	*CI*	*p*	*Incidence Rate Ratios*	*CI*	*p*	*Incidence Rate Ratios*	*CI*	*p*	*Incidence Rate Ratios*	*CI*	*p*
(Intercept)	7.31	3.68 – 14.54	**<0.001**	1.76	0.63 – 4.92	0.278	1.57	0.59 – 4.20	0.369	3.88	2.06 – 7.31	**<0.001**
GE	0.57	0.25 – 1.27	0.171	1.69	0.55 – 5.25	0.362	0.24	0.06 – 0.97	**0.045**	0.20	0.08 – 0.52	**0.001**
Vestas	0.90	0.42 – 1.91	0.776	2.35	0.79 – 6.99	0.126	0.77	0.26 – 2.29	0.637	0.25	0.11 – 0.57	**0.001**
5 m/s	0.36	0.17 – 0.77	**0.009**	0.33	0.07 – 1.65	0.178	0.20	0.02 – 1.71	0.142	0.33	0.11 – 1.03	0.057
6.5 m/s	0.20	0.08 – 0.52	**0.001**	0.50	0.13 – 2.00	0.327	0.00	0.00 – Inf	0.999	0.17	0.04 – 0.74	**0.019**
GE*5m/s	1.75	0.72 – 4.27	0.219	1.68	0.31 – 9.14	0.550	5.00	0.39 – 64.39	0.217	1.87	0.38 – 9.20	0.438
Vestas*5m/s	0.67	0.28 – 1.61	0.367	0.49	0.09 – 2.72	0.411	1.94	0.19 – 19.74	0.574	1.50	0.35 – 6.40	0.584
GE*6.5m/s	1.41	0.45 – 4.42	0.552	0.35	0.07 – 1.81	0.212	$1.09e^{9}$	0.00 – Inf	0.999	1.50	0.17 – 12.93	0.712
Vestas*6.5m/s	0.43	0.13 – 1.40	0.163	0.18	0.03 – 0.89	**0.036**	$9.7e^{7}$	0.00 – Inf	0.999	0.43	0.03 – 5.33	0.510
RANDOM EFFECTS												
σ^2	0.00			0.00			0.00			0.00		
τ_{00}	0.23 Turbine			0.29 Turbine			0.13 Turbine			0.05 Turbine		
ICC	1.00			1.00			1.00			1.00		
N	27 Turbine			27 Turbine			27 Turbine			27 Turbine		
Observations	81			81			81			81		
Marginal R^2 / Conditional R^2	0.753 / 1.000			0.732 / 1.000			0.991 / 1.000			0.957 / 1.000		

Table A4: Model prediction for Control and two curtailment treatments at Fowler Ridge wind facility. These fatality rates and CI were used in the meta-analysis

Species	Treatment	Turbine	Predicted Fatalities	std.error	conf.low	conf.high
all	5 m/s	Clipper	2.633	0.441	1.110	6.245
all	5 m/s	GE	2.628	0.244	1.629	4.239
all	5 m/s	Vestas	1.575	0.242	0.980	2.531
all	6.5 m/s	Clipper	1.463	0.532	0.516	4.150
all	6.5 m/s	GE	1.178	0.319	0.630	2.203
all	6.5 m/s	Vestas	0.567	0.360	0.280	1.148
all	control	Clipper	7.314	0.351	3.678	14.545
all	control	GE	4.169	0.216	2.728	6.369
all	control	Vestas	6.552	0.168	4.715	9.105
LABO	5 m/s	Clipper	0.588	0.780	0.128	2.710
LABO	5 m/s	GE	1.668	0.292	0.941	2.957
LABO	5 m/s	Vestas	0.669	0.341	0.343	1.305
LABO	6.5 m/s	Clipper	0.882	0.664	0.240	3.242
LABO	6.5 m/s	GE	0.527	0.447	0.220	1.264
LABO	6.5 m/s	Vestas	0.365	0.438	0.155	0.861
LABO	control	Clipper	1.764	0.524	0.632	4.925
LABO	control	GE	2.985	0.249	1.832	4.866
LABO	control	Vestas	4.138	0.200	2.799	6.118
LACI	5 m/s	Clipper	0.314	1.026	0.042	2.344
LACI	5 m/s	GE	0.376	0.522	0.135	1.046
LACI	5 m/s	Vestas	0.469	0.402	0.213	1.032
LACI	6.5 m/s	Clipper	0.000	$1.3e^4$	0.000	Inf
LACI	6.5 m/s	GE	0.470	0.471	0.187	1.184
LACI	6.5 m/s	Vestas	0.134	0.720	0.033	0.550
LACI	control	Clipper	1.569	0.502	0.587	4.199
LACI	control	GE	0.376	0.522	0.135	1.046
LACI	control	Vestas	1.207	0.273	0.707	2.060
LANO	5 m/s	Clipper	1.294	0.521	0.466	3.590
LANO	5 m/s	GE	0.489	0.455	0.200	1.192
LANO	5 m/s	Vestas	0.489	0.385	0.230	1.040
LANO	6.5 m/s	Clipper	0.647	0.722	0.157	2.663
LANO	6.5 m/s	GE	0.195	0.712	0.048	0.789
LANO	6.5 m/s	Vestas	0.070	1.003	0.010	0.498
LANO	control	Clipper	3.882	0.323	2.061	7.312
LANO	control	GE	0.782	0.363	0.383	1.594
LANO	control	Vestas	0.977	0.277	0.567	1.684

Table A5: Model output for effect of treatments (5.0 m/s Curtailment, 6.5 m/s) within each turbine type (GE, Vestas, Clipper) at reducing bat fatalities at Fowler Ridge wind facility, Indiana USA.

	Total Fatalities			Red bat			Hoary bat		
	Incidence Rate Ratios	*CI*	*p*	*Incidence Rate Ratios*	*CI*	*p*	*Incidence Rate Ratios*	*CI*	*p*
(Intercept)	0.60	0.34 – 1.06	0.080	0.50	0.27 – 0.93	**0.028**	0.08	0.02 – 0.36	**0.001**
GE	0.49	0.24 – 1.02	0.057	0.37	0.16 – 0.87	**0.022**	0.31	0.04 – 2.30	0.254
Vestas	1.35	0.73 – 2.49	0.339	1.02	0.51 – 2.04	0.947	1.79	0.39 – 8.13	0.450
Feathered	0.58	0.23 – 1.48	0.257	0.50	0.17 – 1.46	0.206	0.50	0.05 – 5.51	0.571
4.5	0.58	0.23 – 1.48	0.257	0.30	0.08 – 1.09	0.067	0.00	0.00 – Inf	0.998
5.5	0.33	0.11 – 1.03	0.057	0.10	0.01 – 0.78	**0.028**	0.50	0.05 – 5.51	0.571
GE* Feathered	1.08	0.33 – 3.52	0.895	1.00	0.23 – 4.28	1.000	5.00	0.27 – 91.52	0.278
Vestas* Feathered	1.11	0.41 – 3.03	0.840	1.12	0.34 – 3.65	0.856	1.87	0.15 – 22.94	0.626
GE*4.5	0.99	0.30 – 3.27	0.990	1.39	0.26 – 7.30	0.698	$1.7e^{8}$	0.00 – Inf	0.998

RANDOM EFFECTS

	Total Fatalities	Red bat	Hoary bat
σ^2	0.00	0.00	0.00
τ_{00}	0.00 Turbine	0.00 Turbine	0.40 Turbine
ICC	1.00		1.00
N	168 Turbine	168 Turbine	168 Turbine
Observations	672	672	672
Marginal R^2 / Conditional R^2	0.993 / 1.000	1.000 / NA	0.961 / 1.000

Table A6: Model prediction for Control and two curtailment treatments at Fowler Ridge wind facility. These fatality rates and CI were used in the meta-analysis

Species	Treatment	Turbine	Predicted Fatalities	std.error	conf.low	conf.high
all	4.5	Clipper	0.349	0.381	0.166	0.737
all	4.5	GE	0.172	0.305	0.094	0.312
all	4.5	Vestas	0.273	0.214	0.180	0.415
all	5.5	Clipper	0.200	0.502	0.075	0.534
all	5.5	GE	0.094	0.411	0.042	0.209
all	5.5	Vestas	0.166	0.271	0.098	0.283
all	Feathered	Clipper	0.349	0.381	0.166	0.737
all	Feathered	GE	0.187	0.292	0.106	0.332
all	Feathered	Vestas	0.523	0.158	0.384	0.712

all	Normal	Clipper	0.599	0.292	0.338	1.063
all	Normal	GE	0.296	0.234	0.187	0.469
all	Normal	Vestas	0.808	0.130	0.627	1.042
LABO	4.5	Clipper	0.150	0.577	0.048	0.465
LABO	4.5	GE	0.078	0.447	0.033	0.188
LABO	4.5	Vestas	0.143	0.289	0.081	0.252
LABO	5.5	Clipper	0.050	1.000	0.007	0.355
LABO	5.5	GE	0.047	0.577	0.015	0.145
LABO	5.5	Vestas	0.071	0.408	0.032	0.159
LABO	Feathered	Clipper	0.250	0.447	0.104	0.601
LABO	Feathered	GE	0.094	0.408	0.042	0.209
LABO	Feathered	Vestas	0.286	0.204	0.192	0.426
LABO	Normal	Clipper	0.500	0.316	0.269	0.929
LABO	Normal	GE	0.187	0.289	0.106	0.330
LABO	Normal	Vestas	0.512	0.152	0.380	0.690
LACI	4.5	Clipper	0.000	$7.6e^{4}$	0.000	Inf
LACI	4.5	GE	0.039	0.616	0.012	0.130
LACI	4.5	Vestas	0.049	0.496	0.019	0.130
LACI	5.5	Clipper	0.041	1.033	0.005	0.312
LACI	5.5	GE	0.026	0.739	0.006	0.110
LACI	5.5	Vestas	0.049	0.496	0.019	0.130
LACI	Feathered	Clipper	0.041	1.033	0.005	0.312
LACI	Feathered	GE	0.065	0.496	0.024	0.171
LACI	Feathered	Vestas	0.138	0.342	0.070	0.270
LACI	Normal	Clipper	0.082	0.753	0.019	0.361
LACI	Normal	GE	0.026	0.739	0.006	0.110
LACI	Normal	Vestas	0.148	0.335	0.077	0.285

Table A7: Model output for effect of treatments (5.0 m/s Curtailment, 5.0 m/s Curtailment for the partial night) within each turbine type at reducing bat fatalities at Pinnacle Wind Facility.

	Red bat			**Hoary bat**			**Silver-haired bat**		
Predictors	*Incidence Rate Ratios*	*CI*	*p*	*Incidence Rate Ratios*	*CI*	*p*	*Incidence Rate Ratios*	*CI*	*p*
(Intercept)	0.07	0.05 – 0.11	<0.001	0.05	0.03 – 0.08	<0.001	0.01	0.00 – 0.02	<0.001
5.0 m/s	0.46	0.23 – 0.92	0.027	0.38	0.17 – 0.86	0.020	2.34	0.60 – 9.03	0.219
Partial Night 5.0 m/s	1.04	0.61 – 1.78	0.891	0.71	0.37 – 1.38	0.312	0.67	0.11 – 3.99	0.657
Date [1st degree]	$3.7e^{4}$	$2.87 – 4.7e^{8}$	0.029	0.03	$0.00 – 2.4e^{4}$	0.606	$1.0e^{12}$	$1.29 – 8.7e^{22}$	0.048
Date [2nd degree]	0.00	0.00 – 0.05	0.009	0.00	0.00 – 0.00	<0.001	3.31	$0.00 – 4.1e^{9}$	0.911
Random Effects									
σ^2	0.00			0.00			0.00		
τ_{00}	$0.00_{Turbine}$			$0.08_{Turbine}$			$0.00_{Turbine}$		
ICC				1.00					
N	$12_{Turbine}$			$12_{Turbine}$			$12_{Turbine}$		
Observations	935			935			935		
Marginal R^2 / Conditional R^2	1.000 / NA			0.930 / 1.000			1.000 / NA		

Table A8: Model prediction for Control and 5.0 m/s operational minimization at Pinnacle wind facility in 2012. These fatality rates and CI were used in the meta-analysis

Treatment	Species	Est Fatalities	LCI	UCI
Control	LABO	0.12	0.07	0.18
5	LABO	0.05	0.03	0.10
Control	LACI	0.13	0.08	0.22
5	LACI	0.05	0.02	0.11
Control	LANO	0.01	0.00	0.02
5	LANO	0.01	0.00	0.04