REWI Renewable Energy Wildlife Institute

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Contact Name	Renewable Energy Wildlife Institute (REWI): Isabel Gottlieb
Contact Title	Senior Research Manager/Scientist
Recipient Email	igottlieb@rewi.org
Recipient Phone Number	(603) 496-4062
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Principal Investigator	Isabel Gottlieb, M.S., Taber D. Allison, Ph.D.; REWI
Research Partners	Carl Donovan, Ph.D.; DMP Stats Michael Whitby; Bat Conservation International Leslie New, Ph.D.; Ursinus College
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Attachments	Attachment 1: Year 1 Report – Curtailment Models for the VBPS Project (June 2022) Attachment 2: Year 2 Report - Experimental Evaluation of the Vestas Bat Protection System (May 2024) Attachment 3: VBPS Curtailment Guidelines (July 2022) Attachment 4: Annual Energy Production Methodology (July 2020) Attachment 5: AEP Analysis Details (February 2024)
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I. Executive Summary

The Renewable Energy Wildlife Institute (REWI; formerly AWWI, the American Wind Wildlife Institute) was appointed prime awardee of DOE award number DE-EE0008729 to lead a team of scientists, wind developers, and turbine manufacturers in a study to develop and test a "smart curtailment" system intended to help reduce bat collisions with wind turbines. The Vestas Bat Protection System (VBPS) is a newly developed software module within the Supervisory Control and Data Acquisition (SCADA) system of Vestas turbines. The VBPS combines data from commercially available environmental sensors and the turbine's built-in sensors with the Vestas SCADA system. VBPS is designed to receive environmental data from sensors on the turbine such as temperature, wind speed, wind direction, time of day, and time of year, relays that information to the SCADA system, and uses that data to determine whether to execute turbine curtailments at any given time.

The goals of this study were to 1) develop a bat fatality risk model based on bat activity data and environmental data collected in year 1, and to 2) evaluate the VBPS, using the bat fatality risk model to implement curtailment, in comparison to "blanket curtailment" (turbines curtailed when wind speed is below 5.0 meters per second (m/s)) and "control" (normally operating, feathered below cut-in speed at 3.0 m/s) turbines in year 2. The field study took place at a wind energy facility in Iowa during the fall bat migration seasons (July – October) in 2021 and 2022.

For VBPS to succeed as a viable strategy for the minimization of bat fatalities, it should meet or exceed the performance of the current standard practice of blanket curtailment. Specifically, the VBPS should meet the following performance targets to demonstrate whether it an effective, practical risk reduction measure:

- Turbines operating VBPS should have equal or fewer bat fatalities compared to turbines operating with blanket curtailment, and significantly fewer bat fatalities compared to control turbines

- Turbines operating VBPS should have greater power production compared to turbines operating with blanket curtailment

The study was completed in accordance with the Statement of Project Objectives and within the terms of the Budget Justification. This Final Report describes the progress, challenges, and outcomes of the study, which are summarized below.

Year 1: The objective of the first year of the study was to collect data on bat activity (thermal camera imagery and acoustics) and environmental conditions, and to use those data to develop a bat activity risk model to be implemented by the VBPS. The project was delayed by a year due to the Covid-19 pandemic. Supply chain issues prevented the project team from acquiring and installing precipitation sensors; precipitation may have been a useful variable to include in the model. Field data were collected from July 1 to October 30, 2021. Throughout the season, the field team collected bat activity and environmental data, and conducted daily post-construction fatality monitoring using human searchers at wind turbines that were operating normally (i.e., no blanket or smart curtailment). The best bat fatality risk model included the variables wind speed, wind direction, time of day, and time of year. Based on this model, the team developed a curtailment prescription for each month from July through October that described the conditions under which turbines operating VBPS would generate power or be curtailed based on the environmental conditions that correlated with bat activity and bat fatalities.

Year 2: The objective of the second year of the study was to conduct a full-scale evaluation of the VBPS's performance in comparison with blanket curtailment and control turbines. Turbines were randomly assigned a treatment each night, and post-construction fatality monitoring using dog teams was conducted daily from June 20 through October 6, 2022. There was a major challenge in implementing the VBPS due to a miscommunication about whether the current version of the VBPS software was capable of issuing curtailment orders based on real-time wind direction data. Wind direction was an important variable in the bat fatality risk model, but that capability was still in development for the VBPS software. To implement VBPS "surrogate rules", Vestas' on-site staff checked the weather forecast each afternoon, and selected an operating procedure for the upcoming night based on the forecasted prevailing wind direction.

Due to the challenges of implementing VBPS at the beginning of the Phase 3 fieldwork, the Project Team conducted two separate analyses; one using data covering the full field season, and a second using only a subset of the data (from August and September) when the surrogate VBPS surrogate rules were correctly applied. Both analyses provided similar conclusions; results using the subset (August/September) data are summarized here:

- Turbines operating VBPS surrogate rules and blanket curtailment both had significantly lower (32%; 31%) bat fatality rates compared to control turbines.
- There was no significant difference between fatality rates at turbines operating VBPS surrogate rules compared to blanket curtailment.

- Turbines operating VBPS surrogate rules and blanket curtailment both produced significantly less (7%; 6.2%) power compared to control turbines.
- There was no evidence of significant differences in power production between turbines operating VBPS-surrogate rules and blanket curtailment.

This report provides details on the tasks, milestones, results, and challenges related to the evaluation of the VBPS.

II. Acknowledgements

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III. Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

IV. Technical Objectives

Introduction

The Renewable Energy Wildlife Institute (REWI; formerly AWWI, the American Wind Wildlife Institute) – was the prime awardee of DOE award number DE-EE0008729 and lead a team of scientists (Bat Conservation International, Ursinus College, DMP Stats), wind developers (MidAmerican Energy Company; MEC), and turbine manufacturers (Vestas Americas; Vestas) in a study to develop and test a “smart curtailment” system intended to help reduce bat collisions with wind turbines. The Vestas Bat Protection System (VBPS) is a newly developed software module within the Supervisory Control and Data Acquisition (SCADA) system of Vestas turbines. The VBPS combines data from commercially available environmental sensors and the turbine’s built-in sensors with the Vestas SCADA system. VBPS receives environmental data from sensors on the turbine such as temperature, wind speed, wind direction, time of day, and time of year, relays that information to the SCADA system, and uses those data to determine whether to execute turbine curtailments at any given time.

The goal of the VBPS is to reduce both bat collision risk from turbine strikes and power loss from curtailment when bats are at a lower risk of collision. REWI partnered with Bat Conservation International (BCI), Ursinus College (Ursinus) and DMP Stats (DMP), to independently evaluate the ability of VBPS to achieve this goal.

The project took place in Adair County at the Orient Wind Farm (Orient), which is operated by MidAmerican Energy Company (MEC). The field study took place during the fall bat migration season (July – October) in 2021 and 2022. The study occurred concurrently with another DOE-supported study to evaluate Turbine Integrated Mortality Reduction (TIMR) a different smart curtailment strategy (Award Number DE-EE0008727). The VBPS and TIMR studies shared control and blanket curtailment turbines during the second field season in 2022.

Project Objectives

The goals of this study were to 1. develop a bat fatality risk model based on bat activity data and environmental variables in year 1 (Attachment 1), and then to 2. evaluate the VBPS, using the bat fatality risk model to implement curtailment, in comparison to “blanket curtailment” (turbines curtailed when wind speed is below 5.0 m/s) and “control” (normally operating) turbines in year 2 (Attachment 2).

Budget Period 1

Objective: Develop detailed study design for Budgets Period 1 and 2

Objective: Collect weather, bat acoustic activity, thermal imaging, and fatality data at the operational wind energy facility

Objective: Use collected data to develop a bat fatality risk model to predict bat fatalities based on weather data. This model will be used as an input for the VBPS curtailment algorithm, which will monitor real-time weather conditions, calculate bat fatality risk, and issue curtailment orders according to the algorithm's risk assessment.

Outcome: Bat fatality risk model incorporated into VBPS curtailment algorithm

Budget Period 2

Objective: Conduct an experimental study at an operating wind energy facility to evaluate the effectiveness of the VBPS curtailment algorithm's ability to reduce bat fatalities relative to blanket curtailment and control treatments.

Outcome: Quantified risk reduction to bats and relative loss in Annual Energy Production from VBPS compared to blanket curtailment and control treatments

Performance Targets for VBPS

For a smart curtailment strategy to succeed as a viable alternative for the minimization of bat fatalities, it should meet or exceed the performance of the current standard practice of blanket curtailment. Specifically, the VBPS should meet the following performance targets to demonstrate whether it an effective, practical risk reduction measure:

- Turbines operating VBPS should have equal or fewer bat fatalities compared to turbines operating with blanket curtailment, and significantly fewer bat fatalities compared to control turbines
- Turbines operating VBPS should have greater power production compared to turbines operating with blanket curtailment

Summary of Work Completed Under Budget Period 1 Objectives

OBJECTIVE: Develop detailed Study Plan for Budgets Period 1 and 2

Outcome: Peer-reviewed Study Plan ready for implementation

Status: Completed

Summary Details: REWI, BCI, and Ursinus collaborated to create a Study Plan to develop a bat fatality risk model and evaluate the VBPS. The Study Plan detailed the project team's methodology to meet all Project Objectives through a 2-year field study to first develop a bat fatality risk model based on bat activity, bat fatality, and environmental data; and then to evaluate the performance of the VBPS, using the bat fatality risk model, in comparison to blanket curtailment at 5.0 m/s and control turbines. The draft Study Plan was submitted to the DOE on December 20, 2019. After three rounds of peer review, REWI submitted the final draft of the Study Plan and reviewer comment matrix on April 22, 2020. The first field season (2021) was conducted in accordance with this study design. Prior to the 2022 field season, The VBPS and TIMR Project Teams (TIMR DE-EE0008787; and VBPS DE-EE0008729) jointly proposed changes to the study designs of their concurrent projects (See Milestone 1.3 for details). The final Study Plan reflecting these updates was submitted to the DOE on April 5, 2022, and was approved by the DOE.

Concurrent with the review process, REWI coordinated with DOE, NREL, Stantec, EPRI, and MidAmerican Energy Company (MEC; the Projects' host) to create a mutually agreeable methodology for estimating the economic comparison of blanket curtailment and the three smart curtailment strategies hosted at the Orient Wind Energy Project (Orient).

OBJECTIVE: Collect weather, bat acoustic activity, thermal imaging, and fatality data at the operational wind energy facility.

Outcome: A robust dataset of weather, bat activity, and fatalities that can be used to develop a bat fatality risk model.

Status: Completed

Summary Details: The purpose of the first field season was to collect bat fatality, bat activity, and environmental data to use in the development of the bat fatality risk model. The first field season was originally scheduled to take place in 2020 but was delayed by one year due to the Covid-19 pandemic. Fieldwork began at the Orient Wind Farm in Adair County, Iowa, on July 1, 2021 and continued through October 30, 2021.

Personnel trained by BCI in established search techniques conducted daily fatality searches within 140m x 140m square search plots beneath ten study turbines. Estimates of fatality rates were adjusted using field bias trials, which consisted of both searcher efficiency and carcass persistence trials. Ultrasonic acoustic detectors were installed at the nacelle of five study turbines to record bat acoustic activity. Two thermal cameras were placed beneath each of two of the study turbines which were also outfitted with ultrasonic acoustic recorders, to record bat flight paths in 3D space. Environmental and operational data was collected from the turbines' built-in sensors and operation logs, including temperature, wind speed, wind direction, time, and turbine status.

Upon the completion of the field season, Bat Conservation International (BCI) processed the bat activity and fatality data and transferred the data to the project statisticians at Ursinus and DMP in January 2022. Acoustic data was quantified using the total number of bat sequences recording in designated intervals (e.g., night, 1 hour, 10 minute). Acoustic data were ultimately excluded from the model due to a lack of sufficient bat calls in the dataset. Thermal video data was quantified using the following metrics summed during the designated intervals (1) flight paths that crossed the rotor swept zone while the turbine was spinning, (2) number of flight paths observed in the field of view while the turbine was spinning, and (3) number of flight paths that occurred at blade height while the turbine was spinning. MEC provided weather (temperature, wind) and turbine operational (RPM, status, energy production) data in 10-minute intervals for all turbines sampled in 2021 to Ursinus in early January 2021. While the study initially planned to use precipitation sensors, covid-related supply chain issues prevented the Project Team from acquiring the equipment and precipitation was therefore excluded from the study.

OBJECTIVE: Use collected data to develop a bat fatality risk model to predict bat fatalities based on weather data.

Outcome: Bat fatality risk model incorporated into VBPS curtailment algorithm

Status: Completed

Summary Details: The Project Team developed a bat fatality risk model by correlating weather data with measures of risk (bat fatality rate and thermal video/acoustic activity rates). Weather data were used as explanatory variables, and the Project Team determined the correct spatial and temporal scale (e.g., 10-minute and 1-hour increments) at which they are most highly correlated with bat fatality risk. The Project team evaluated multiple bat fatality models to find the one that best explains nightly bat fatalities. The models were fitted using a generalized additive mixed model (GAMM) framework, given the likely non-linear relationships between bat fatalities, their behavior, and environmental variables. The Project Team chose a risk tolerance based on fatality rates to reduce fatalities with equal or greater efficacy compared to blanket curtailment at 5.0 m/s. The resulting curtailment schedule used the risk model to set thresholds and the output of the VBPS will be a binary determination of whether to curtail turbines due to bat risk within certain parameters (e.g., time of day, wind speed, wind direction). The Project Team submitted documentation of the bat fatality risk model to the DOE for review on May 12, 2022. The Project Team, DOE, and peer reviewers held two calls on May 22 and June 3 to discuss reviewer comments and subsequent updates to improve the model. Final documentation of the bat fatality risk model was submitted to the DOE on June 14, 2022.

Summary of Work Completed Under Budget Period 2 Objectives

OBJECTIVE: Conduct an experimental study at an operating wind energy facility to evaluate the effectiveness of the VBPS curtailment algorithm's ability to reduce bat fatalities relative to blanket curtailment and control treatments

Outcome: Quantified risk reduction to bats and relative loss in Annual Energy Production from VBPS compared to blanket curtailment and control treatments

Status: Completed

Summary Details: The Project Team conducted the Phase 3 field study to assess the effectiveness of the VBPS to reduce bat fatalities and power loss in comparison to turbines operating blanket curtailment at 5.0 m/s and control turbines. Fieldwork began on June 20, 2022 and concluded on October 6, 2022. Each night, there were nine turbines operating each of the study's three treatments including VBPS, blanket curtailment at 5.0 m/s, and control turbines. Turbines rotated treatments each night using a randomized block design. BCI personnel and Rogues Dogs teams conducted post-construction fatality monitoring daily beneath each study turbine on 140 m x 140 m square plots. There were two significant challenges faced by the Project Team during the Phase 3 study. The first was that the field team was sprayed with agricultural chemicals by a tractor applying the chemicals to an adjacent crop field. There was one major incident in June 2022, followed by several minor incidents or close calls. MEC installed "No Spray" signs at each plot and increased communication with landowners and the spraying cooperative to reduce the risk of exposure to agricultural chemicals, and the field team developed a health and safety protocol to manage risks posed by sprayers. The second challenge was that while the bat fatality risk model included wind direction as an important variable to determine curtailment orders, the VBPS software had not yet finalized that capability. The Project Team worked with Vestas staff to develop and implement a set of surrogate rules to implement the bat fatality risk model. This resulted in a revision to the VBPS Curtailment Guidelines (Attachment 3), which prescribed a curtailment plan based on the forecast for the prevailing wind direction each evening. Please see Section VI., Challenges, Risks, and Mitigation for further details.

BCI cleaned up the datasets for the Phase 3 study and provided them to REWI, Ursinus, and DMP by January 3, 2023. Datasets included the search schedule, treatment schedule, bat carcasses observed, carcass persistence, searcher efficiency, density-weighted proportions, and operations data. Due to the challenges of implementing VBPS at the beginning of the Phase 3 fieldwork, the Project Team conducted two separate analyses; one using data covering the full field season, and a second using only a subset of the data (from August and September) when the surrogate VBPS surrogate rules were correctly applied. Both analyses provided similar conclusions; results using the subset (August/September) data are summarized here:

- Turbines operating VBPS surrogate rules and blanket curtailment both had significantly lower (means: 32% and31%, respectively) bat fatality rates compared to control turbines.
- There was no significant difference between fatality rates at turbines operating VBPS surrogate rules compared to blanket curtailment.
- Turbines operating VBPS surrogate rules and blanket curtailment both produced significantly less (7%; 6.2%) power compared to control turbines.
- There was no evidence of significant differences in power production between turbines operating VBPS-surrogate rules and blanket curtailment.

The draft report detailing the findings of the study was submitted to the DOE on July 7, 2023. The Project Team used written and verbal feedback from the DOE and peer review panel to revise the report, which was resubmitted to the DOE on August 23, 2023.

V. Comprehensive Summary of Work Performed in Budget Period 1: Tasks, Subtasks, Milestones, and Deliverables

The Statement of Project Objectives (SOPO), as modified in August 2022, included the following result by the conclusion of Budget Period 1:

Expected End Result: A bat fatality risk model (to be incorporated into the VBPS curtailment algorithm) and a detailed study design for Budget Periods 1 & 2 (including the experimental study design for the evaluation of the VBPS curtailment algorithm in Budget Period 2). The study design and the bat fatality risk model will be submitted to the U.S. Department of Energy/Energy Efficiency and Renewable Energy (DOE/EERE) for review.

The Go/No-Go decision to proceed with Budget Period 2 activities was based on the following criteria from the Statement of Project Objectives:

1. Successful development of a study plan for Budget Period 1 and Budget Period 2 activities.
2. Successful submission and approval of AEP Methodology.
3. Successful development of bat fatality risk model for the VBPS.

Success of the bat fatality risk model development will be determined through one or more of the approaches outlined below, though additional methods of model evaluation may be employed as appropriate. The most appropriate approach(es) for this evaluation will be determined during the model development phase. The most likely approaches to evaluate model development include:

a. Checking goodness of fit, to assess whether the values estimated are consistent with the values observed in the data.
b. Cross-validation, using separate subsets of the data for model training and testing, to test the predictive power of the model and assess consistency of the results
c. In the unlikely event that there are not enough fatality events in the data to conduct cross-validation, we will apply data augmentation to the training dataset to reduce overfitting and ensure that the training data set is structurally similar to the original dataset.

4. Adherence to schedule, budget, and submission of deliverables in Budget Period 1. As a result of a Go/No Go review, in its discretion, EERE may take one of the following actions:
   - Authorize Federal funding for the next budget period for the Project;
   - Recommend redirection of work under the Project;
   - Place a hold on the Federal funding for the Project, pending further supporting data; or
   - Discontinue providing Federal funding for the Project beyond the current budget period as the result of insufficient progress, change in strategic direction, or lack of available funding.

The Project Team met the Expected End result, achieved the Milestones associated with Budget Period 1 Tasks and Subtasks, and met the criteria for the “Go/No-Go” decision point, as defined in the Statement of Project Objectives. Subsequently, the Project Team was granted a “Go” decision from the DOE to proceed with Budget Period 2 activities.

A summary of the Budget Period 1 Milestones is found in Table 1. Details of Budget Period 1 tasks, subtasks, milestones, and deliverables are described afterward.

Table 1. Budget Period 1 Milestones at a Glance

#	Description	Status	Planned[1] Completion Date	Actual or *Estimated* Completion Date	Attachments or Notes
1.1	**Intellectual Property Management Plan complete**	Complete	Q1: M3	December 17, 2021	
1.2	Draft Study Design complete	Complete	Q1: M3	December 20, 2019	
1.3	Final peer-reviewed Study Design complete	Complete	Q2: M6	March 25, 2020	
2.1	Project permitting complete	Complete	Q3: M9	July 1, 2020	
3.1	Selection of array of sensors to use for the VBPS complete	Complete	Q2: M5	March 18, 2020	
3.2	Installation/testing of the VBPS, environmental sensors, bat acoustic monitors and thermal imaging cameras complete	Complete	Q6: M18	July 15, 2021	
4.1	Approval of a methodology for estimating AEP differences	Complete	Q4: M10	December 17, 2020	Attachment 4
4.2	Agreement from MEC to provide necessary data	Complete	Q6: M18	March 17, 2021	
4.3	DOE's decision regarding NREL's third-party review	Complete	Q7: M20	June 2022	
5.1	Site preparations/field team prep complete	Complete	Q7: M21	June 2021	
6.1	Complete analysis of field data from bat fatality risk model study	Complete	Q10: M28	April 2022	Attachment 1
6.2	Complete development of bat fatality risk model for use in the VBPS	Complete	Q10: M30	June 2022	Attachment 1
6.3	Updated performance targets for VBPS based on data and insight	Complete	Q10: M30	June 2022	

#	Description	Status	Planned[1] Completion Date	Actual or *Estimated* Completion Date	Attachments or Notes
	gathered during Tasks 4 and 5				
7.1	Bat fatality risk model incorporated into VBPS	Complete	Q11: M32	June 2022	
7.2	Field study preparations for host site, field logistics, and personnel complete	Complete	Q11: M33	June 2022	
Go/ No-Go 1	Submit Award Continuation Application	Complete	Q11: M33	February 28, 2022	

[1] Planned completion date based on current SOPO from Modification 3, approved by DOE on September 15, 2020.F

Task 1.0: Development of Intellectual Property Management Plan (IPMP) and Peer-Reviewed Study Design

Task Summary: *The Project Team developed an Intellectual Property Management Plan and a detailed study design based on the tasks outlined in the SOPO for Budget Periods 1 & 2.*

REWI, with support from the Project Team, achieved Milestones 1.1, 1.2, and 1.3 in a timely manner and to the satisfaction of the DOE Contracting Team. Below, we summarize and provide details on the activities and accomplishments for each of these Milestones:

Milestone 1.1: Intellectual Property Management Plan Completed

Summary: The purpose of the IPMP is to address the protection and disposition of intellectual property developed during the study. The objectives include promoting rapid dissemination of breakthrough scientific studies and technological innovations for the public good, and to set practices and expectations that govern the transfer, handling, and dissemination of background intellectual property used, and foreground intellectual property created during the project. A preliminary version of the IPMP was submitted to DOE on December 18, 2019. The IPMP was revised to include feedback from the DOE and other project team members and the fully executed IPMP was submitted to the DOE on December 17, 2021.

Milestone 1.2: Draft Study Plan Completed

Summary: REWI successfully collaborated with the Project Team, DOE, and peer reviewers to produce a scientifically rigorous Study Plan to develop and independently evaluate a model-based smart curtailment strategy based on bat activity and behavior (i.e., acoustics and thermal video), bat fatalities, and environmental variables using the Vestas Bat Protection System (VBPS); and evaluate the economic and production implications of this risk reduction strategy, relative to blanket curtailment.

The Study Plan was reviewed by external reviewers led by the DOE/EERE. The Study Plan was revised by the Project Team to address three rounds of comments from the external reviewers. Revised drafts of the Study Plan and corresponding responses to the comment matrix were submitted to the DOE on February 14, 2020, March 25, 2020, and April 22, 2020.

During the review process, the Project Team, along with the two other Project Teams conducting concurrent smart curtailment studies at the Orient Wind Energy Project were asked to develop a methodology to evaluate the impact of the smart curtailment strategies on Annual Energy Production (AEP). The biological aspects of the Study Plan would be completed under Task 1, but a new Task 4: Annual Energy Production (AEP) Impact Methodology was added to the SOPO in the 3rd modification (approved September 15, 2020).

Milestone 1.3: Final Study Plan Completed, Incorporating Comments from DOE/EERE

Summary: The third revision to the study plan was submitted to the DOE on April 22, 2020, REWI received notification from DOE on May 7, 2020 that this version was approved by the DOE and became the Final Study Plan for all biological aspects of the Project. Please see Milestones under Task 4 for more details about the development of the AEP impact methodology.

In the spring of 2022, the Project Team proposed a revision to the study design for Budget Period 2 (Task 8: Experimental Study Comparing the Smart Curtailment Algorithm to Blanket Curtailment and Control Treatments). The VBPS Project Team and the TIMR Project Team (Award Number DE-EE0008727) proposed to share turbines between studies. Previously, each study planned to use 18 turbines unique to each study, split between 3 treatments of 6 turbines each: control, blanket curtailment at 5.0 m/s, and smart curtailment (VBPS, TIMR respectively). Under the new arrangement, the 36 turbines were shared between the projects and split into four treatments of nine turbines each: control, blanket curtailment at 5.0 m/s, smart curtailment using VBPS, and smart curtailment using TIMR. The VBPS study did not use data from turbines on nights when they operated TIMR, and vice versa, so each study had data from 27 turbines on any given night. This change effectively increased the sample size of each treatment for both studies by 50%, without increasing the cost of either project. The revised study design also replaced human searchers for post-construction fatality monitoring with dog search teams, because dog teams have a higher searcher efficiency compared to human searchers, leading to an increased number of carcasses in the dataset and statistical power. A revised study design was submitted to the DOE on April 5, 2022, and was approved.

The final Study Plan included three phases:

Phase 1: Data collection: The purpose of the Phase 1 field study was to collect data on bat activity and fatalities at normally operating turbines, as well as environmental and turbine operation data, to be used as the basis to develop the bat fatality risk model. This field study was originally scheduled for July – October of 2020, but was delayed to 2021 due to the Covid-19 pandemic. Bat fatality risk was quantified using daily post-construction fatality monitoring using human searchers, and bat activity data using acoustic detectors and 3-D thermal videography collected at the wind energy facility. Weather data was collected from the turbines' built-in sensors. Turbine operation data was collected and used to estimate the VBPS's impact on power production.

Phase 2: Bat Fatality Risk Model Development: The Project Team used the data collected in Phase 1 to develop a model to predict the risk of bat fatalities; the selected model defined the curtailment parameters for the VBPS. The available explanatory variables for the fatality risk model included bat activity via acoustic and thermal video recordings, as well as weather data (e.g., temperature, wind speed, wind direction). The best performing model was used to define curtailment parameters to be integrated into the VBPS. Possible curtailment parameters were evaluated based on estimated power loss and expected fatality reduction. Selection of the final curtailment parameters targeted a balance between reducing bat fatalities and power production loss, with the goal of reducing power production no more than blanket curtailment at 5.0 m/s.

Phase 3: Test of VBPS Efficacy: The study culminated in a study to evaluate the effectiveness of the VBPS at reducing bat fatalities and preserving power generation in comparison to turbines operating under blanket curtailment at 5.0 m/s and control treatments. Every night, nine turbines operated each of the treatments (VBPS, blanket curtailment, control), which rotated each night using a randomized block design. Post-construction fatality searches were conducted by dog teams during Phase 3 to increase searcher efficiency, and therefore increase the number of bat carcasses in the dataset, and statistical power. The resulting analysis included a comparison of costs and power production loss between smart curtailment, blanket curtailment, and control turbines.

Task 2.0: Project Permitting and NEPA Review

Task Summary: *The Project Team coordinated with DOE-EERE, USFWS and other relevant regulatory bodies to ensure that all federal and local regulatory requirements are met to allow for all activities associated with the Budget Period 2 operational changes to turbine operations for the project to proceed with a concluded NEPA review.*

Milestone 2.1: All project permitting completed to allow field work to proceed. REWI submits necessary NEPA information to DOE.

Summary: DOE-NEPA and REWI collaborated on the approach for reviewing the environmental impacts of the project, per National Environmental Policy Act (NEPA) guidelines and requirements. DOE, as a funder of the project, conducted informal consultation with the local U.S. Fish and Wildlife Service (USFWS) office with jurisdictional responsibilities for the Project host site. On October 25, 2019, DOE-NEPA instructed the Project Team to assemble and submit a Biological Evaluation, with input from the Project Team, that DOE-NEPA and USFWS would rely on for Section 7 agency-to-agency consultation. The Project Team requested from the USFWS and the host site a Biological Opinion from an unrelated permitting action with relevant technical information. REWI notified DOE-EERE that preparation of a Biological Evaluation was not contemplated in the approved SOPO or budget. REWI coordinated with the host site, other Orient-based studies, and USFWS to complete the Biological Evaluation. REWI submitted a draft Biological Evaluation to the DOE-NEPA contact on March 30, 2020.

The Iowa Department of Natural Resources issued the recovery permit necessary to collect bats to BCI on March 26, 2020.

On April 08, 2020, REWI received a draft Biological Opinion from DOE in response to the Biological Evaluation. This draft was near-final but required some clarification from the Project Team regarding take estimates (this issue was shared with EPRI-TIMR project, too). On May 07, 2020, REWI received from DOE-EERE on behalf of USFWS the final Biological Opinion and NEPA determination. The DOE contracting team incorporated the Biological Opinion and recommendation from the NEPA determination into the VBPS prime award.

All necessary permits were in place prior to initiating the bat fatality risk model study (Task 5) in June 2021. The tailored, special conditions of the Biological Opinion were incorporated into the Project's governing documents and the NEPA hold was lifted for all SOPO tasks and included in the second modification to the prime award, dated July 1, 2020.

Task 3.0: Installation and testing of environmental sensors complete

***Task Summary**: The Project Team reviewed available environmental sensors and made selections that could be 1) safely installed on the nacelles of wind turbines and 2) could easily transfer data to the VBPS. The Project Team installed the selected environmental sensors on a test set of wind turbines to integrate the VBPS with the SCADA system at the host site. Environmental sensors collected weather data to supplement wind and temperature data measured at the turbine to be used as potential covariates for the bat fatality risk model development in Tasks 4 and 5. The Project Team also installed acoustic bat detectors and thermal imaging cameras at a subset of the wind turbines involved in the study.*

Milestone 3.1: Selection of sensors to use for the VBPS.

Summary: REWI authorized BCI in January 2020 to procure certain field supplies, including environmental sensors to accommodate the lead-time required to receive and calibrate those supplies in advance of field study preparations. BCI purchased, received, built, and calibrated the necessary equipment including directional microphones, cables, a computer, acoustic data storage units, and thermal cameras. The Project Team initially intended to include precipitation sensors in the study. However, pandemic-related supply chain issues prevented the team from acquiring the precipitation sensors for use in the study.

Milestone 3.2: Installation of the VBPS, acoustic and thermal cameras, and environmental sensors complete.

Summary: The uncertainty introduced by COVID-19 in early 2020 caused the Project Team to actively monitor possible impacts to the field study, including the installation of field equipment. The Project Team deliberated between two possible scenarios: 1) a delayed 2020 start of "Phase

1” fieldwork, or 2) a June 2021 start of “Phase 1” fieldwork. It was determined in mid-May 2020 that the first scenario was not feasible, and the Project Team and DOE agreed to postpone Phase 1 fieldwork until June 2021. All equipment installation was postponed until Spring 2021. In CY20-Q4, BCI field tested an acoustic deployment strategy off-site, prepared proposals for equipment mounting strategies, and prepared a work plan for MEC to review and ensure it was in line with on-site policies. In CY21-Q1/2, REWI, MEC, and Vestas finalized the arrangements and obligations for the installation of equipment. On June 8, 2021, Vestas shared with the Project Team the various, engineering-approved SOW/instructions for installing the acoustic sensors, data loggers, and associated infrastructure. By June 28, 2021, MEC’s installation subcontractors completed all installations of the acoustic sensors, data loggers, and associated infrastructure. In July 2021, University of Iowa delivered thermal video cameras to Orient. BCI and University of Iowa cooperated to achieve full installation of thermal video cameras by July 15, 2021.

Task 4.0: Annual Energy Production (AEP) Impact Methodology

***Task Summary**: A methodology was developed to determine the differences in power production between treatments that is consistent with the guidance provided by DOE in August 2019 for how projects should assess AEP differences between treatments. The methodology was submitted to DOE for review on December 14, 2020.*

Milestone 4.1: Approval of a methodology for estimating AEP differences between treatments based on a plan submitted by EPRI.

Summary: From CY20-Q2 to CY20-Q4, REWI coordinated with DOE, NREL, Stantec, EPRI, and MEC to establish a mutually agreeable methodology for estimating the economic comparison of blanket curtailment and the three smart curtailment studies hosted at the Orient Wind Energy Project. DOE announced formal approval of the proposed AEP Impacts methodology, whose development was led by EPRI (TIMR Study, DE-EE0008787), on December 14, 2020 (Attachment 4). These methods were formally incorporated into the VBPS study design on December 17, 2020.

Milestone 4.2: Agreement from MEC to provide data necessary to conduct the approved AEP analysis methodology.

Summary: Upon DOE approval of the AEP methodology, an AEP data-sharing agreement was drafted by EPRI in January 2021 for review by MEC, Stantec, and REWI (the host site and all three DOE-supported smart curtailment projects at Orient 1). In this agreement, MEC agreed to provide any and all data necessary to conduct the AEP analysis as per the peer-reviewed and DOE-approved methodology. The agreement was fully executed on March 17, 2021.

Milestone 4.3: DOE decision whether NREL will conduct a third-party review of analysis and establishment of an NDA with NREL if the decision is affirmative.

Summary: DOE determined whether the National Renewables Energy Laboratory (NREL) will conduct a third-party review of the analysis, once completed. If DOE does appoint NREL to conduct such a review, a Non-disclosure Agreement (NDA) will be established with NREL. EPRI has offered to support the out-of-scope AEP effort for this project. Peer review by NREL of the methodology was conducted in the fall of 2023. EPRI and NREL were the primary participants of the peer review, but REWI staff attended meetings and provided comments on the draft protocol throughout the process. The peer review was complete and protocols finalized on November 17, 2023.

Task 5.0: Bat Fatality Risk Model Study

***Task Summary**: The Project Team prepared for and conducted a bat fatality risk model study at a sample set of fully operational wind turbines to collect data related to weather variables (e.g., wind speed, temperature, precipitation, etc.), bat activity and bat fatalities.*

Milestone 5.1: Field Study Preparations Completed

Summary: The Project Schedule was delayed by 12-months to accommodate postponing the Phase 1 fieldwork from Summer/Fall 2020 until 2021 due to COVID-19. On June 22, 2020, REWI submitted a revised SOPO to DOE reflecting schedule changes given this postponement. This change was approved on September 15, 2020, in the third modification to the Prime Award. In December 2020, BCI updated their budget for the Phase 1 field season due to the continuing impact of COVID-19 and prepared a draft workplan for the anticipated 2021 field season. In early 2021, the Project Team completed all site preparations including plot clearing, planning for field logistics and data management, and both the hiring and training of field personnel. As per guidance from DOE (4/01/21), REWI submitted on April 09, 2021, a formal memo to DOE detailing the request to transfer ~$69K from BCI's BP2 into its BP1 funding pools. BCI and MEC continued collaborating on further refinement of BCI's draft COVID mitigation workplan to ensure compatibility with on-site (MEC-Orient) policies. All requisite supplies were procured, field crew members hired, and housing/travel logistics coordinated. The Project Team met weekly beginning mid-May 2021 to focus on field study and installation preparations. Preparations for fieldwork were completed in late June 2021.

Milestone 5.2: Fieldwork for bat fatality risk model study: Completed

Summary: Fieldwork began at the Orient Wind Farm in Adair County, Iowa, on July 1, 2021 and continued through October 30, 2021. Personnel trained by BCI in established search techniques conducted daily fatality searches within 140m x 140m square search plots beneath ten study turbines, which operated normally throughout the field season (i.e., no curtailment and feathered below the cut-in speed of 3.0 m/s). Estimates of fatality rates were adjusted using field bias trials, which consisted of both searcher efficiency and carcass persistence trials. Ultrasonic acoustic detectors were installed at the nacelle of five study turbines to record bat acoustic activity. Two thermal cameras were placed beneath each of two of the study turbines that were also outfitted with ultrasonic acoustic recorders, to record bat flight paths in 3D space. Thermal camera data collection began on July 15th, 2021. Environmental and operational data were collected from the turbines' built-in sensors and operation logs, including temperature, wind speed, wind direction, time, and turbine status.

The field crew experienced challenges with landowner cooperation which adversely affected plot accessibility and therefore data collection. For these reasons, one sampling plot was dropped from the study in late August 2021.

Task 6.0: Development of the Bat Fatality Risk Model

***Task Summary**: The Project Team correlated bat activity data with simultaneous weather variables and related these data to bat collision fatalities. The Project Team used the identified environmental correlates to develop a bat fatality risk model to be used as an input to the VBPS and executed by the SCADA system. The Project Team chose not to make further updates to the performance targets based on data collected during Phase 1 fieldwork because the performance targets already in place remained relevant and appropriate.*

Milestone 6.1: The Project Team completed the analysis of data collected during Phase 1 fieldwork to determine useful environmental correlates to use in the bat fatality risk model.

Summary: BCI formatted and conducted QA/QC on the data collected during Phase 1 field work. The finalized datasets were provided to Ursinus in early January 2022. These data include acoustic data, thermal camera data, weather data, and turbine operational data. Data analysis and modeling took place in Q1 and Q2 of 2022. Due to a lengthy data processing time and limitations on Ursinus's bandwidth in the Spring 2022 semester, the Project Team added DMP to the Project Team to support the data analysis and development of the bat fatality risk model. The environmental covariates selected to be included in the bat fatality risk model were date, time of day (relative to sunset and sunrise), wind speed, and wind direction. Temperature was also considered but was not included in the final model.

Milestone 6.2: Development of Bat Fatality Risk Model Complete

Summary: DMP Stats and Ursinus collaborated to develop and evaluate a bat fatality risk model using data collected during Phase 1 fieldwork (Attachment 1). The final model estimated bat fatality risk based on date, time of day, wind speed, and wind direction. The Project Team submitted documentation of the bat fatality risk model to the DOE for review on May 12, 2022. The Project Team, DOE, and peer reviewers held two calls on May 22 and June 3 to discuss reviewer comments and subsequent updates to improve the model. The Project Team finalized the documentation of the model in response to comments provided by the DOE on June 6, 2022. The final documentation was submitted on June 14, 2022. The model was then used to develop VBPS Curtailment Guidelines, which defined, for each month from July through October, the conditions under which turbines operating VBPS would curtail vs generate power, based on time, wind speed, and wind direction (Attachment 3).

Milestone 6.3: Updated Performance Targets for VBPS Complete

Summary: After the development of the bat fatality risk model was complete, the Project Team determined that the Performance Targets proposed in the Project's Statement of Project Objectives remain relevant, straightforward, and meaningful. The Project Team did not recommend any further changes to the performance targets.

Task 7.0 (Bridge Task): Preparation for Experimental Study Comparing the Smart Curtailment Algorithm to Blanket Curtailment and Control Treatments

***Task Summary**: Based on the approved study design developed in Budget Period 1, the Project Team prepared for an experimental study to assess the effectiveness of the VBPS to reduce bat fatalities.*

Milestone 7.1: Full Integration of Bat Fatality Risk Model into VBPS Complete

Summary: The Project Team held weekly meetings in May and June to ensure that the bat fatality risk model was integrated into the study turbines prior to the field season. Final updates to the software were made at the facility, after which the model's curtailment schedule was configured in the SCADA system.

As the Phase 3 study began, it became apparent that there had been a miscommunication about whether the VBPS software was already capable of issuing curtailment orders based on real-time wind direction data, which caused a major challenge in implementing the VBPS curtailment guidelines. Wind direction was an important variable in the bat fatality risk model but recording wind direction was still in development for the VBPS software. To implement a "surrogate" VBPS model, Vestas' on-site staff checked the weather forecast each afternoon around 4:00 PM Central Time and selected an operating procedure for the upcoming night based on the forecasted prevailing wind direction. The VBPS Curtailment Guidelines were updated to account for this revised implementation procedure (Attachment 3).

Milestone 7.2: Second Year's Field Study Preparations Complete

Summary: REWI and BCI conducted an analysis to confirm that 140 x 140 m plots would provide sufficient power for the planned statistical analyses. The VBPS and TIMR project teams coordinated with each other and the DOE to share turbines between the two studies to increase the sample size of turbines operating each treatment, and to use dog teams to conduct post-construction fatality monitoring to increase searcher efficiency, number of carcasses in the dataset, and statistical power. The Study Plan was updated to reflect those changes and was submitted to the DOE in April 2022.

The Project Team contracted with Rogue's Dogs to conduct post-construction fatality monitoring for the study, and BCI hired crew leaders and secured housing for staff to oversee the field study. Turbine selection and treatment schedules were finalized. BCI staff traveled to the study site and ensured that the plots and field logistics were prepared. Field preparations were completed by June 20, 2022.

VI. Comprehensive Summary of Work Performed in Budget Period 2: Tasks, Subtasks, Milestones, and Deliverables

The Statement of Project Objectives (SOPO), as modified in August 2022, included the following result by the conclusion of Budget Period 2:

Expected End Result: The final product will be one or more manuscripts to be submitted to a peer-refereed journal in addition to the peer-reviewed final report submitted to the DOE/EERE.

The Project Team has achieved the Milestones associated with Budget Period 2 Tasks and Subtasks. Upon acceptance of the report by the DOE, the manuscript will be formatted for a scientific journal and submitted for review and publication.

A summary of the Budget Period 2 Milestones is found in Table 2. Details of Budget Period 2 tasks, subtasks, milestones, and deliverables are described afterward.

Table 2. Budget Period 2 Milestones at a Glance

#	Description	Status	Planned Completion Date	Actual Completion Date	Attachments/ Notes
8.1	Field work for experimental study complete	Complete	Q13: M38	October 6, 2022	
9.1	Data analysis for the year 2 study completed	Complete	Q12: M44	May 2023	
9.2	Draft year 2 report completed.	Complete	Q12: M45	July 7, 2023	
10.1	Peer-reviewed, final year 2 report completed	Complete	Q16: M48	July 23, 2023	Attachment 2
10.2	Manuscript submitted to a peer-reviewed journal for publication	In Progress	Q16: M48	To be submitted after project close out	

Task 8.0: Experimental Study Comparing the Smart Curtailment Algorithm to Blanket Curtailment and Control Treatments

***Task Summary**: Based on the approved study design developed in Budget Period 1, the Project Team conducted an experimental study to assess the effectiveness of the VBPS curtailment algorithm to reduce bat fatalities. The VBPS smart curtailment system was compared to blanket* *curtailment and control turbines. The Project Team evaluated the performance of the algorithm using fatality data collected during daily searches of each treatment turbine across the study period.*

Milestone 8.1: Field work for experimental study complete.

Summary: The Project Team conducted the Phase 3 field study to assess the effectiveness of the VBPS to reduce bat fatalities and power loss in comparison to turbines operating blanket curtailment at 5.0 m/s and control turbines. Fieldwork began on June 20, 2022, and concluded on October 6, 2022. Each night, there were nine turbines operating each of the study's three treatments including VBPS, blanket curtailment at 5.0 m/s, and control turbines. Turbines rotated treatments each night using a randomized block design. BCI personnel and Rogues Dogs teams conducted post-construction fatality monitoring daily beneath each study turbine on 140 m x 140 m square plots.

There were two significant challenges faced by the Project Team during the Phase 3 study. The first was that the field team was sprayed with agricultural chemicals by a tractor applying the chemicals to an adjacent crop field. There was one major incident in June 2022, followed by several minor incidents or close calls. BCI, REWI, and MEC coordinated closely to mitigate the risks to the field crew and dog teams. MEC installed "No Spray" signs at each plot and contacted each landowner whose land contained study turbines and the spraying cooperative to increase coordination and communication regarding spraying schedules and to reduce the risk of exposure to agricultural chemicals. The field team developed a health and safety protocol to manage risks posed by sprayers. Upon the initial incident, fieldwork halted, and was resumed on a turbine-by-turbine basis as landowners were contacted.

The second challenge was that while the bat fatality risk model included wind direction as an important variable to determine curtailment orders, the VBPS software had not yet finalized that capability. The Project Team worked with Vestas staff to develop and implement a set of surrogate rules to implement the bat fatality risk model. This resulted in a revision to the VBPS Curtailment Guidelines (Attachment 3), which prescribed a curtailment plan based on the forecast for the prevailing wind direction each evening.

Please see Section VI., Challenges, Risks, and Mitigation for further details.

Task 9.0: Analysis of the Experimental Study Data and Draft Report

***Task Summary**: The Project Team conducted a statistical analysis of the data to determine the effectiveness of the bat fatality risk model and the VBPS smart curtailment system to reduce bat fatalities relative to blanket curtailment and control treatments. Simultaneously, the Project Team compared the relative Annual Energy Production (AEP) among the treatment groups of turbines. The Project Team prepared a draft report and submitted it to the DOE/EERE for review.*

Milestone 9.1: Data analysis for the study completed.

Summary: BCI cleaned up the datasets for the Phase 3 study. Datasets included the search schedule, treatment schedule, bat carcasses observed, carcass persistence, searcher efficiency, density-weighted proportions, and operations data. The Project Team met several times in late 2022 and early 2023 to prepare for and coordinate the analysis and reporting of the study. BCI provided the data to REWI, Ursinus, and DMP in two batches in late 2022 and early 2023. The final datasets were delivered on January 3, 2023, at which time data analysis began in earnest.

Data analysis was initially scheduled to be completed by March 31, 2023, but was delayed until early May due to challenging nuances in the data. Due to the challenges of implementing VBPS at the beginning of the Phase 3 fieldwork, the Project Team conducted two separate analyses; one using data covering the full field season, and a second using only a subset of the data (from August and September) when the surrogate VBPS surrogate rules were correctly applied. Data analysis was completed in May 2023.

Milestone 9.2: Draft report completed. Results from the study, in the form of text, tables, and figures will be included in the draft final report.

Summary: Data analysis and the initial draft report were circulated amongst the Project Team in May 2023 for review and comment. The draft report was revised based on the feedback from the Project Team. The draft report detailing the findings of the study was submitted to the DOE on July 7, 2023.

Deliverable 9.2: Draft report submitted to DOE/EERE for review.

Summary: The draft report detailing the findings of the study was submitted to the DOE on July 7, 2023.

Task 10.0: Final Report, Manuscript, and Dissemination

***Task Summary**: DOE coordinated a peer review of a draft report. The Project Team considered and incorporated peer review comments and submit a final project report to the DOE/EERE. The final report includes a summary of the tasks completed, results of the study, a thorough cost analysis of implementing blanket and smart curtailment, and an estimate of the cost of adopting the smart curtailment system. The results of the study will be made public and disseminated on relevant websites (e.g., BWEC, REWI). The manuscript will also be submitted to a peer-reviewed journal for publication in the scientific literature. Results also will be presented at one or more professional meetings.*

Milestone 10.1: Peer-reviewed, final report completed.

Summary: The DOE-appointed peer review team provided feedback to the Project Team on July 27, 2023, in the form of comments within the report document, and a comment matrix. The Project Team met with the DOE and peer reviewers to discuss their feedback on August 9, 2023. The Project Team then coordinated to address reviewer comments through revision of the report and responding to each comment in the comment matrix. The revised report was submitted to the DOE on August 23, 2023.

Due to the challenges of implementing VBPS at the beginning of the Phase 3 fieldwork, the Project Team conducted two separate analyses; one using data covering the full field season, and a second using only a subset of the data (from August and September) when the surrogate VBPS surrogate rules were correctly applied. Both analyses provided similar conclusions; results using the subset (August/September) data are summarized here:

- Turbines operating VBPS surrogate rules and blanket curtailment both had significantly lower (32% and31%, respectively) bat fatality rates compared to control turbines.
- There was no significant difference between fatality rates at turbines operating VBPS surrogate rules compared to blanket curtailment.
- Turbines operating VBPS surrogate rules and blanket curtailment both produced significantly less (7% and 6.2%, respectively) power compared to control turbines.
- There was no evidence of significant differences in power production between turbines operating VBPS-surrogate rules and blanket curtailment.

Deliverable 10.1: Final report submitted to DOE/EERE and released to the public.

Summary: The Final Technical Report was submitted to the DOE on August 31, 2023.

Milestone 10.2: Manuscript submitted to a peer-reviewed journal for publication.

Summary: The Project Team will reformat and submit the manuscript to a peer-reviewed journal upon completion of the peer-review process with the DOE.

VII. Challenges, Mitigation, Changes in Approach, Lessons Learned

The Project Team encountered a variety of challenges, both technical and logistical/administrative, which resulted in various delays and changes in approach during the Project. Each of the significant challenges encountered during the study is described below, along with the actions the Project Team took to address and resolve them.

Covid-19 Pandemic; Impact on Schedule, Budget, and Equipment: When the Covid-19 pandemic hit in March of 2020, the Project Team was actively preparing for the Phase 1 fieldwork, which was scheduled to begin in June 2020. As the pandemic progressed, the Project Team actively monitored the situation and determined, in coordination with the DOE that the Phase 1 of the Study Plan would be postponed. Due to the seasonal nature of the research, which needs to be conducted during the summer/fall bat migration season, the study could not begin any sooner than Summer 2021. The Project Team and DOE collaborated to assess the impact of the pandemic and the associated delays on the schedule and budget of the study. REWI requested a 12-month extension and cost increase to the study totaling $182,402 (of which, $132,670 was additional cost share provided by MEC, and $49,732 was additional funding requested from the DOE) to compensate for the impact of Covid-19 on the project's schedule and budget. This request was approved by the DOE in Q3 of 2020. REWI coordinated with MEC and Vestas to ensure that arrangements were made (e.g., contractual items, coordination with landowners) to accommodate the delay in the schedule.

In the Spring of 2021, the Project Team and DOE determined that Phase 1 fieldwork would commence as planned in June 2021. The Project Team further analyzed the budget needs for the upcoming field season and submitted a request to transfer $69,000 from BCI's Budget Period 2 funds into Budget Period 1. This transfer mitigated all known issues identified by the Project Team to proceed with Phase 1 and would allow additional time to identify any further needs. Close coordination between Project Team members and the DOE allowed the project to accommodate the delay in Phase 1 fieldwork and to implement necessary adjustments to the budget.

In addition to delays in the project schedule, the Covid-19 pandemic also affected the availability of equipment and subsequent data that the Project Team could use to develop the bat fatality risk model. The Project Team originally intended to install precipitation sensors at the study site, and to use precipitation as a potential covariate in the bat fatality risk model that would determine curtailment decisions by the VBPS. Unfortunately, Covid-19-related supply chain issues prevented the Project Team from obtaining and installing precipitation sensors for the study. The project proceeded without the use of precipitation sensors, though precipitation could be a valuable environmental component to inform smart curtailment systems in the future.

Lengthy Negotiation for Project Team Agreements: Some of the key documents that govern the study including the Terms of Agreement and the Intellectual Property Management Plan, took much longer to negotiate between the Project Team members than originally anticipated. Originally, these documents were scheduled to be completed in the first quarter of the study (i.e., by December 2019), but review and revisions moved slowly. The Terms of Agreement was fully executed on September 30, and the Intellectual Property Management Plan was fully executed on October 8, 2021.The delay in executing these agreements did not interfere with the progress of the Phase 1 fieldwork. For future projects collaborating with large companies in the renewable energy sector, the Project Team recommends building ample time into the schedule for review of any legal documents, because there can be significant wait times before personnel from the legal team is able to review project-related documents.

Challenges with Landowner Cooperation: The field studies relied on cooperation from private landowners upon whose land MEC's Orient Wind Farm turbines were sited. Despite the considerable time and effort that MEC put into coordinating with landowners in advance of the study and developing agreements with them regarding the use of their property and maintenance of search plots on their land, the Project Team removed one plot from the sampling pool in August 2021 due to a lack of cooperation from the landowner.

Delays in Thermal Camera Installation, Field Season Completion, and Bat Fatality Risk Model Development: There were delays in the delivery of the thermal cameras needed for the study. Instead of being installed in late June 2021, the thermal cameras were not deployed until July 15, 2021. This delay caused a ripple effect that delayed the timing of the remaining tasks in Budget Period 1, causing concern that the bat fatality risk model may not be developed and implemented in time for the Phase 3 field season in July 2022.

The Project Team extended the field season to the end of October 2021 to fulfill the Project Team's commitment to conducting a 120-day study, and to ensure the robustness of the dataset. This led to a subsequent delay in the data cleaning, QA/QC/ data transfer, and development of the bat fatality risk model. Data transfer was initially planned for October 2021, but did not occur until January 2022.

Originally, the Project Team's lead statistician, Dr. Leslie New, who is a faculty member at Ursinus College, planned to develop the bat fatality risk model during the fall semester of 2021. Dr. New's teaching schedule had been arranged accordingly to give her ample availability during Q4, 2021 for data analysis and model development. Dr. New was unable to arrange a light teaching load in Spring 2022, so when the data management and transfer was delayed until January 2022 and it was clear that the model development could not begin until then, the Project Team determined that it needed additional statistical support. Dr. New recruited Dr. Carl Donovan, of DMP Stats, to support the development of the bat fatality risk model as a subrecipient of the study.

The Project Team worked closely with DOE to adjust the timelines of deliverables, to ensure that the bat fatality risk model would be integrated into the VBPS, and to ensure that the Project Team could complete the Continuation Application and navigate the Go/No-Go decision process in time for the Phase 3 fieldwork. The due date for the bat fatality risk model was shifted from February 28, 2022, to April 29, 2022. The DOE was able to conduct the peer review of the bat fatality risk model and the Go/No-Go decision point in a timely manner. Thanks to the cooperation and coordination between the Project Team and the DOE, the model review and Go/No-Go Decision was concluded in time for the 2022 Phase 3 fieldwork.

Implementation of the VBPS Curtailment Rules: During the final preparations for the field season in June 2022, as the Vestas operations staff were programming the bat fatality risk model and associated curtailment schedule into the VBPS system, it became apparent that the VBPS was unable to implement that bat fatality risk model as intended. There had been a miscommunication between Project Team members regarding what capabilities the VBPS module already had completed and available for use, versus what capabilities were still in development. As of June 2022, the VBPS did not yet have the ability to issue curtailment orders based on real-time wind direction. This was a major concern because wind direction was an essential component of the bat fatality risk model developed by the Project Team, as well as the component that differentiated it from a blanket curtailment-like strategy.

REWI, Vestas, and DMP Stats worked together to revise the approach and devise a surrogate strategy for the model's implementation for the Phase 3 fieldwork. The revised approach entailed the following: each afternoon, Vestas operations staff checked the weather forecast for around 4:00 PM Central Time to determine the predicted prevailing wind direction over the course of the upcoming night. The weather forecast data used was NOAA's forecast for the township of Orient, Iowa, which is approximately 1 mile from the nearest Orient Wind Farm turbine. Each month (July through October) had different curtailment criteria based on the risk model for how the wind direction forecast was applied. These "curtailment guidelines" were provided to Vestas staff to inform daily curtailment implementation decisions (Attachment 3). Based on the predominant wind directions for the upcoming night, Vestas staff determined whether the VBPS turbines would 1) be curtailed during the curtailment time window regardless of wind speed; 2) run curtailment based on time and windspeed criteria (changes monthly); or 3) generate power all night regardless of wind speed. REWI met with the DOE to discuss this issue on July 15, 2022, and then proceeded to implement the surrogate rules for the remainder of the season.

Vestas has since finalized and introduced the capability to issue curtailment orders based on real-time wind direction. This is an important feature for VBPS, though the direct applicability of the results of this study using VBPS surrogate rules to the implementation of this feature of VBPS is imperfect. For future applications of the VBPS, operators will be able to program curtailment instructions based on real-time wind direction. The addition of the capability to curtail based on real-time wind direction has the potential to improve the performance of VBPS.

There was also an issue with the implementation of the VBPS programming due to the nightly rotation of treatments and randomized block design. This was a challenge due to the nature of the study and rotating treatments, but not a shortcoming of the VBPS system itself. Each night, the study turbines were assigned a treatment; control, blanket curtailment, or smart curtailment via VBPS or TIMR (Award Number DE-EE0008727; the wo concurrent DOE-supported smart curtailment studies were conducted at the Orient Wind Farm, and they shared study turbines to increase the sample size for both studies). The VBPS program is designed to be programmed according to calendar dates, but since the study treatments spanned two calendar dates over the course of one night, it came to our attention in early August that the VBPS would start each night running as planned, but at midnight, the VBPS program would stop. Vestas staff helped to address this issue by putting in place two separate programs for each night; one which covered sunset through midnight, and another for midnight through sunrise. The new program was in place and running on August 10, 2022. This challenge is specific to operating a study using treatments that rotate on a nightly basis and is not a problem that will impact VBPS during normal operations.

Agricultural Spraying Issues: On July 3, 2022, there was an incident on one of the study plots in which a dog fatality search team was sprayed with agricultural chemicals by a tractor. The sprayer did not directly spray the dog team; however, the adjacent field was being sprayed, and the wind carried the chemicals into the plot, causing headache and nausea to the field technician. The dog was also exposed, but any symptoms the dog may have experienced are unknown. This was an urgent safety issue, and REWI, BCI, EPRI, and MEC coordinated closely to address this issue and minimize risks to field staff and working animals. The field team developed conservative protocols to halt work and leave the premises if there was a tractor in the area spraying or about to spray a field. MEC provided NO SPRAY signs to be posted at every survey plot. MEC and BCI staff had multiple conversations with the local spraying coop and landowners in the area, though the spraying coop was less cooperative and less receptive than anticipated regarding implementing safety protocols for project team field staff. Despite ongoing conversations with the spraying coop, there were multiple “close call” situations after the initial incident. The Project Team actively coordinated to implement solutions to keep field staff safe while collecting field data. MEC contacted every landowner involved in the project and requested information about spraying plans and schedules for the remainder of the season so the field team could avoid plots during and immediately after spraying. By the middle of August, all spraying activities for the season were complete and there were no further disruptions for the field team.

This health and safety hazard was extremely frustrating, and the Project Team has reservations about the possibility of conducting any further studies in an agricultural landscape, particularly if they require daily fieldwork on each plot, which makes it difficult to accommodate agricultural spraying activities without compromising data collection. While there were agreements in place in advance with the landowners, future studies should consider organizing short meetings between field crews, land owners, and any other agricultural groups (i.e. spraying coops) conducting work that may be hazardous to field teams, so that there is a better understanding in the community about the research being done and the risks posed to field staff, and to encourage a more open line of communication enabling health and safety hazards to be avoided.

Changes in Key Personnel: Over the course of the Project, there were several instances of changes in key personnel on the Project Team, including turnover of staff from REWI, BCI, and Vestas; the addition of DMP stats to support the statistical modeling of the study; and the transition of the project's lead statistician, Dr. Leslie New, from Washington State University to Ursinus College. While the Project Team was proactive about orienting new Project Team members to the study and to their roles and responsibilities, it is possible that turnover in staff contributed to misunderstandings during the study, such as the status of VBPS's ability to use real-time wind direction data to implement curtailment decisions. For future studies, the Project Team recommends clear communication about the development state and precise capabilities of any technology that is in development prior to its evaluation.

Application of the Results to Broad Commercial Use of VBPS: This study provides a valuable step in the development of bat fatality risk models for application in smart curtailment using VBPS or other systems. However, there were two environmental variables (precipitation, wind direction) that the Project Team anticipated would be important factors informing the smart curtailment implementation, which could not be incorporated into the Phase 3 evaluation of VBPS as intended. Precipitation was excluded from the model altogether because pandemic-related supply chain issues prevented the Project Team from acquiring the precipitation sensors. The bat fatality risk model included wind direction as a key variable, but at the time of the Phase 3 evaluation, the VBPS was not yet capable of implementing curtailment decisions based on real-time wind direction, so the Project Team had to implement "surrogate rules" (see Implementation of Curtailment Rules, above, for details), to operate the VBPS. The prevailing wind direction was usually fairly consistent over the course of a night, so the implementation of the surrogate rules was a useful proxy for how the VBPS will operate in practice, as the capability to curtail based on real-time wind direction is now integrated into the VBPS software module. The Project Team recommends that all future studies related to VBPS should include precipitation and real-time wind direction.

This study provides evidence that the use of smart curtailment is a useful strategy for minimizing bat fatalities at wind energy facilities, but the VBPS will not be implemented as tested (i.e., manually with surrogate rules) in a commercial setting, limiting the direct applicability of this study's results.

It is unclear to what extent the bat fatality risk model developed based on data collected at the Orient Wind Facility will be applicable to bat activity and collision risk in other locations. Full-scale field studies such as this one are extremely expensive, so it is unlikely that every wind facility considering the use of VBPS would be able to conduct a comparable study to develop a site-specific bat fatality risk model. One viable alternative could be to develop regional bat fatality risk models that use only bat activity data (thermal imaging and/or acoustics), and not data from post-construction bat fatality monitoring, as that data is exorbitantly expensive to obtain unless it is already being collected by the facility operator for other purposes.

VIII. Results Summarized

Below we summarize the results of the study including the development of the bat fatality risk model (Attachment 1) and the evaluation of VBPS surrogate rules in comparison to control turbines and blanket curtailment at 5 m/s (Attachment 2).

Year 1 Results: Development of the Bat Fatality Risk Model

The objective of the first year of the study was to collect data on bat activity (thermal camera imagery and acoustics) and environmental conditions, and to use the data to develop a bat activity risk model to be implemented by the VBPS. Throughout the season, the field team collected bat activity and environmental data, and conducted daily post-construction fatality monitoring using human searchers at wind turbines that were operating normally (i.e., no blanket or smart curtailment). The resulting bat fatality risk model was based on wind speed, wind direction, time of day, and time of year.

Time of day was found to be the most influential predictor of bat activity. However, this was largely due to the transition from day to night - given the surveying period starts during daylight hours, when there was no bat activity. There was a clear fluctuation of bat activity over the field season, with peak bat activity from mid-August to early October, supporting a strategy of curtailment being applied variably over time to balance power production and fatalities. Wind speed was an influential predictor of bat activity, with greater activity at lower wind speeds, with the peak of bat activity occurring below a wind speed of 5.0 m/s, though there was still significant bat activity up to 8.0 m/s.

Wind direction was an influential predictor of bat activity, with higher activity when winds were from a northerly direction. This could be related to the migratory nature of several bat species during this time of year.

The team developed a curtailment prescription based on the bat fatality risk model and operational constraints for each month from July through October that described the conditions under which turbines operating VBPS would generate power or be curtailed based on the environmental conditions that correlated with bat activity and bat fatalities, shown below.

Table 3: distilled VBPS-surrogate rules for manual implementation. The rules are derived from the bat fatality risk model developed in VBPS phase 1. Time to sunset/sunrise values are in minutes, where negative values indicate minutes after sunset or sunrise.

	Time curtailment window		Windspeed curtailment	Wind direction curtailment "wedge" (assume 3-letter precision e.g. NNE)		
Month	**Time to sunset (mins)**	**Time to sunrise (mins)**	**Windspeed upper bound (m/s)**	**Wind Direction Lower bound (degrees)**	**Wind Direction Upper bound (degrees)**	**Implementation - note OR (blue) and AND conditions (green)**
Jul	11	73	5.3	10 (N)	320 (NW)	Within time window, curtail if wind speed below bound **OR** wind direction forecast >50% within curtailment wedge
Aug	-20	58	6.1	120 (ESE)	275 (W)	Within time window, curtail if wind speed below bound **AND when** wind direction forecast >50% within curtailment wedge
Sept	-21	120	6.1	135 (SE)	230 (SW)	Within time window, curtail if wind speed below bound **AND when** wind direction forecast >50% within curtailment wedge
Oct	-23	160	5.4	30 (NE)	350 (N)	Within time window, curtail if wind speed below bound **OR** wind direction forecast >50% within curtailment wedge

Details of the Bat Fatality Risk Model are presented in Attachment 1.

Year 2 Results: Evaluation of the VBPS

The objective of the second year of the study was to conduct a full-scale evaluation of the VBPS's performance in comparison with blanket curtailment and control turbines. Turbines were randomly assigned a treatment each night, and post-construction fatality monitoring using dogs was conducted daily from June 20 through October 6, 2022. There was a major challenge in implementing the VBPS due to a miscommunication about the capabilities of the VBPS software. Wind direction was an important variable in the bat fatality risk model, but the capability to issue curtailment orders based on real-time wind direction was still in development for the VBPS software at the beginning of the field season. To implement VBPS “surrogate rules”, Vestas’ on-site staff checked the weather forecast each afternoon, and selected an operating procedure for the upcoming night based on the forecasted prevailing wind direction. Details on the curtailment implementation guidelines are in Attachment 3.

Due to the challenges of implementing VBPS at the beginning of the Phase 3 fieldwork, the Project Team conducted two separate analyses; one using data covering the full field season, and a second using only a subset of the data (from August and September) when the surrogate VBPS surrogate rules were correctly applied. Both analyses provided similar conclusions; results using the subset (August/September) data are summarized here:

- Turbines operating VBPS surrogate rules and blanket curtailment both had significantly lower bat fatality rates compared to control turbines (32% and 31%, respectively).
- There was no significant difference between fatality rates at turbines operating VBPS surrogate rules compared to blanket curtailment.
- Turbines operating VBPS surrogate rules and blanket curtailment both produced significantly less power compared to control turbines (7% and 6.2%, respectively).
- There was no evidence of significant differences in power production between turbines operating VBPS-surrogate rules and blanket curtailment.

The AEP analysis estimated that implementation of the VBPS during the fall bat migration season may result in an average annual power loss of 0.75% in comparison to control turbines. Blanket curtailment at 5.0 m/s and at 6.9 mps were estimated to result in an average annual power loss of 0.49% and 2.25%, respectively.

Details of the results from the evaluation of VBPS are presented in Attachment 2. Further details related to the AEP Analysis are presented in Attachment 5.

IX. Award and Modifications to Prime Award and the Statement of Project Objectives (SOPO)

The project underwent six award modifications to its prime award over the course of the study. The major developments to the project that were included in those modifications are described below. Note that the attachments referenced in this section are part of the Prime Award and are not attached here.

Original Award (September 19, 2019): Established and launched the study via the Assistance Agreement and Special Terms and Conditions. The Project Period for this award is 09/01/2019 through 08/31/2022 consisting of the following: Budget Period 1: 09/01/2019 to 04/30/2021; Budget Period 2: 05/01/2021 to 08/31/2022

Modification 1 (March 1, 2020): 1) Delete and replace Attachment 1, Statement of Project Objectives; and 2) Delete and replace the Special Terms and Conditions, to incorporate the following changes: a. Add Term 41, Foreign National Access Under DOE Order 142.3A, “Unclassified Foreign Visits and Assignments Program”; and b. Delete and replace Term 8, NEPA Requirements

Modification 2 (July 1, 2020): 1) Delete and replace Attachment 1, Statement of Project Objectives; and Add Attachment 8, Biological Opinion; and 2) Delete and replace the Special Terms and Conditions, to incorporate the following changes: a. Delete and replace Term 8, NEPA.

Modification 3 (September 15, 2020): 1) Extend the Period of Performance end date through April 30, 2022; 2) Increase the Government Share, Cost Share, and Total, as shown: Govt. Share: $1,109,818.00; Cost Share : $1,008,225.00; Total : $2,118,043.00; 3) Provide $49,732 in additional funding; 4) Delete and replace Attachment 1, Statement of Project Objectives and Attachment 2, Budget Information; and 5) Delete and replace the Special Terms and Conditions, to incorporate the following changes: a. Delete and replace Term 26 Cost Sharing; and b. Delete and replace Term 31, Payment Procedures.

Modification 4 (November 16, 2020): 1) Update the DOE Project Officer, now Michael Carella.

Modification 5 (June 17, 2021): 1) Delete and replace Attachment 2, SF424A Budget Information; and 2) Delete and replace the Special Terms and Conditions, to incorporate the following change: a. Delete and replace Term 26, "Cost Sharing".

Modification 6 (August 30, 2022): 1) Approve the continuation application, allowing the Recipient to move from Budget Period 1 to Budget Period 2; 2) Delete and replace Attachment 1, Statement of Project Objectives; 3) Delete and replace Reporting Checklist; 4) Delete and replace Attachment 2, Budget Information; and 5) Delete and replace the Special Terms and Conditions, to incorporate the following changes: a. Add Term 42, Export Control; and b. Add Term 43, Prohibition on Certain Telecommunications and Video Surveillance Services or Equipment (TVSS)

Modification 7 (July 7, 2023): 1) Update the DOE Award Administrator, now Tameka Colden.

Modification 8 (July 26, 2023): 1) Delete and replace Attachment 2, FARC: and 2) Update Cost Share amount of the Assistance Agreement to match approved budget: Govt. Share: $1,109,818.00; Cost Share : $1,008,225.00; Total : $2,118,043.00

Attachment 1: Year 1 Report – Curtailment Models for the VBPS Project

Curtailment models for the VPBS project

Project Title: Developing and Evaluating a Smart Curtailment Strategy Integrated with a Wind Turbine Manufacturer Platform

Award Number: DE-EE0008729.0000

June 13, 2022

Renewable Energy Wildlife Institute 1990 K Street NW, Suite 620

Washington, DC 20006 www.rewi.org

Prepared By

Renewable Energy Wildlife Institute (REWI)

Principal Investigator(s): T. Allison, PhD, Project Management: I. Gottlieb

DMP Stats (DMP)

Statisticians: C. Donovan, PhD, R. Wiff, PhD

1 Contents

2 Overview

Detailed here are fatality models to underpin turbine curtailment decisions for the Vestas Bat Protection System (VBPS). Broadly two statistical models that have been fitted to field retrievals of bat carcasses and turbine sensor and activity data. Curtailment rules arising from these will be subject to further experimental evaluation.

2.1 Project description

The goal of the study was to develop and independently evaluate a smart curtailment strategy based on bat activity (i.e., acoustics and thermal video), bat fatalities, and environmental variables using the Vestas Bat Protection System (VBPS). The VBPS is a newly developed software module within the Supervisory Control and Data Acquisition (SCADA) system of Vestas wind turbines. The VBPS combines data from commercially available environmental sensors and the turbine's built-in sensors with the Vestas SCADA system. Sensors will collect data such as temperature, wind speed, time of day, and time of year, relay that information to the SCADA system, and determine whether to execute turbine curtailments at any given time based on risk level for bat fatalities. The VBPS platform was developed by Vestas engineers and is able to receive data from third party environmental sensors and fully integrate with the Vestas SCADA system to issue curtailment orders based on model parameters. In this study, the Project Team used data on environmental conditions, bat activity, and bat fatalities to develop the bat fatality risk model that will be used as the input for the VBPS smart curtailment system, and then evaluate the risk model and the VBPS smart curtailment system in comparison to blanket curtailment and control turbines. The objective is a smart curtailment strategy that provides lower bat fatalities than blanket curtailment but maintains equivalent power production levels.

Objective relevant to this report (paraphrased from the Statement of Project Objectives): Use collected data to develop a bat fatality risk model which will allow prediction of bat fatalities based on weather and temporal data. This model will be used as an input for the VBPS curtailment algorithm, which will monitor real-time weather conditions, calculate bat fatality risk, and issue curtailment orders according to the algorithm's risk assessment.

The Project Team collected weather, bat acoustic activity[1], thermal imaging, and fatality data at the study site in 2021. These data were used in the development and fitting of the models presented here.

[1] NB Sensor issues rendered most acoustic data unusable.

2.2 Modelling approach

The Project Team sought to model bat fatalities as a function of several variables including weather conditions and temporal components (seasons, time of day, etc.). A two-stage process was adopted:

a) modelling of bat activity as a function of time (e.g., time to/from dawn and dusk) and weather conditions, and

b) modelling of bat fatalities as a function of activity.

Combined, these models could provide predictions of fatalities as a function of weather and time components.

The initial model fitted for activity was a Generalized Additive Mixed Model (GAMM - Hastie & Tibshirani, 1990; Wood 2017) with Poisson errors and log-link. The covariates considered were an index for stage of night, wind-speed, wind-direction, temperature, and date-related terms which were entered as non-linear smooths. The study design included precipitation, but this was not obtained due to sensor supply-chain issues.

Other models were considered, such as machine-learning methods (e.g., gradient boosting machines), but practical constraints on how model outputs are integrated into the VBPS favors simple functional relationships, rather than black-box methods. This is described in detail in section 4.1.

The fatality model fitted carcass recovery data to the observed bat activity and was based on a negative binomial Generalized Linear Model (GLM). Carcass recoveries were conducted on approximate daily scale, so the activity covariate is necessarily aggregated to the same resolution. Various aggregated activity measures were considered, with a measure of maximum daily activity found to be the best predictor (described in appendix 7). Despite substantial modeling efforts, no compelling model could be fitted to this data, for a range of reasons outlined in sections 4.2 and 7. A simple proportional model was adopted instead, whereby fatalities are assumed to increase in line with activity, which is sufficient to estimate the relative effects of different curtailment options.

The overarching modelled relationships between covariates and fatalities provided the basis for curtailment rules. The conditions of turbine operation were objectively measured against implied fatality rates and power outputs to find the best balance – such as reduced fatalities for the same expected power output, or relatively small power reductions for proportionately large reductions in fatality. This optimization is described in section 5.2.

Note, the fatalities and activity data used here are indices, as the data were not sufficient to permit adjustment of these to absolute measures. In particular, potential double-counting for bat observations within the thermal video data is irresolvable with the current data. Relatedly, species-level modelling is largely impossible, as these are not classified within the video data.

All data preparation and model fitting were done in the R statistical programming environment version 4+ (R Core Team, 2021), using the R-Studio IDE version 2022.02.0+443.

3 Data

Data for these analyses were provided by Bat Conservation International (M. Whitby, *pers. comm.* Feb 2022). These are briefly described here, along with their main treatments and notable issues.

3.1 General description

- **Activity data - turbine activity sensors:** Activity data were collected via passive acoustics[2] and thermal imaging. The acoustic data was unusable due to the recording of very few bat calls, attributable to background turbine noise levels and technical difficulties in the field (*pers. comm.* M. Whitby). Video activity data[3] was collected at two turbines T038 and T150 for the VBPS project. These data consisted of 33,287 individual bat tracks recorded from July to October 2021. This included information for date and time (at the minute resolution), track length, number of points, altitude, and sinuosity.

- **Carcass recovery data:** Data for bat fatalities on each night (from sunset to sunrise the following day) were collected between July and October 2021 at nine study turbines. These data consisted of 85 bat carcasses grouped across all species[4]. Each carcass was assigned to a specific turbine with the estimated night of fatality.

- **Sensor data:** Environmental data regarding temperature, wind speed and wind direction were available for each turbine considered in the VBPS project. This information is available at 10-minute resolution and spanned 15th June 2021 to 30th October 2021.

- **Derived temporal data**: all sensor data was time-stamped. This was further decomposed into light/night indices fundamentally from the sun's angle to the horizon for the time and turbine location (Thieurmel & Elmarhraoui, 2019).

3.2 Data treatment and issues

- **Limited turbines, aggregating.** Information regarding bat activity (thermal video data) was collected at two turbines, T038 and T150. These turbines were treated separately in terms of their activity and environmental data. Bat carcasses at these turbines however were infrequent - 5 and 7 respectively. Of these, 4 and 5 were estimated as being within 24 hours of death. Such low numbers necessitated the aggregation of carcasses over the entire facility to attempt modelling of a relationship between activity and fatalities. This aggregation implicitly assumes activity and environmental covariates for T038 and T150 were representative of all turbines across the wind facility at any point in time. The weather conditions across turbines can

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[2] Binary Acoustics (Phoenix AZ, USA) FR123-EXT with an ar125 equivalent Microphone. Mounted on nacelle above the radiator pointed to the leeward side from the anemometer pole.

[3] two flir A65 cameras at each turbine

[4] *Eptesicus fuscus* Big brown bat; *Lasiurus borealis* eastern red bat; *Lasiurus cinereus* hoary bat; *Lasionycterus noctivagans* silver-haired bat; *Nycticeius humeralis* evening bat; *Perimyotis subflavus* tri-colored bat

verified as similar, but activity cannot, as only two turbines have this recorded. As detailed in section 4.2 & 7, even with aggregated carcasses, this model was not sufficiently precise for determining the curtailment rules, making the assumption moot.

- **Acoustic data:** VBPS acoustic data consisted of 341,704 records collected at five turbines[5] from June to October 2021. However, only 226 bat detections were recorded in total, with the majority of bat calls (146 records) recorded at T038 during August 2021. Given the sparse and fragmented acoustic data, these were not used further for model development.

- **Thermal video data.** Individual bat tracks (an individual seen continuously over several frames) were recorded in 20-minute blocks with coverage of 85 nights. When the video sensors were marked as operating, any 20-minute block without activity was treated as zero and informative (absence of bat activity). Data for days when sensors were not operating were discarded – leaving 48 operational days out of 97 for turbine T150 and 55 operational days out of 95 for turbine T038, giving a total of 85 days where at least one activity sensor was collecting data.

- **Fatality data, aggregating**. Fatality data was aggregated across turbines and species. The counts of dead bats (including days with zero fatalities) were assigned to survey nights using the estimated date of fatality. Carcasses were estimated to be 0, 2 or 4 days old (65%/20%/15% respectively). The accuracy of these times of death is unclear and may be a contributory factor to the poor fatality model fit outlined in section 7. This model was not progressed to determining curtailments in favor of a proportional approach (section 4.2).

[5] mounted on nacelle above, the radiator pointed to the leeward side from the anemometer pole

4 Fitted models

Two models were developed for the study – one, relating temporal and sensor data from the turbines to bat activity (from thermal video), the other relating this bat activity to a fatality index. Collectively these allowed the estimation of effects of various mitigations based on bat activity.

4.1 Bat activity – thermal video

A model was fitted to predict levels of bat activity as a function of real-time environmental sensor data. This informs curtailment rules, where conditions of high bat activity are avoided, balanced against power output.

4.1.1 Data

The activity models used thermal video activity data and sensor-derived temporal & weather data, as described in section 2. The number of distinct bat-tracks within 20-minute blocks is used as the “bat activity index”, which was the response variable for the model. Covariates were necessarily restricted to those collected/known at the turbines (wind-direction, wind-speed, temperature, and time), as curtailment rules can only be defined at the turbine from these.

Bat activity data (thermal video) was limited to two turbines T038 and T150, collected during July – October, 2021. Time was re-expressed to reflect the stage of evening, and thereby account for the variation in night-length over seasons. This was done by deriving a “proportion of night” variable, with 0 being sunset and 1 being sunrise. Values outside [0,1] reflecting daylight. For example, 0.1 means 10% of the night has elapsed, 1.1 means 10% of the night length after sunrise.

4.1.2 Modelling approach and fitting

Curtailment rules need to be defined in a binary fashion (if condition A is true, do action X) based on information available at the turbine. Models cannot be integrated directly into the turbine software, but turbines can have pre-defined schedules of rules created from models. For this reason, explicitly functional models were favored, as opposed to “black-box” methods, as the relationships can be easily extracted and examined. The relationships between covariates and the response variable were *a priori* likely to be complex and the response activity is a count variable that is frequently zero. Further, the repeated measures close in time implies correlated errors for a fitted regression model.

Generalized Additive Mixed Models (GAMMs) were fitted, modelling the activity counts as a function of wind-speed, week of the year, stage of night, temperature, and wind direction. The model assumed a log-link, Poisson-errors, with a further autoregressive error (AR1) within nights to account for the lack of independence of repeated 20-minute blocks. These were fitted with the mcgv package (Wood, 2017), which estimates the covariate relationships by way of penalized regression splines. Smooth terms were specified for all covariates, with wind-direction specified as a cyclic spline to reflect its circular nature. Model selection was performed as part of the fitting process, using shrinkage (Wood, 2017). Distributional diagnostics are given in section 8.

Initial marginal models (Figure 1) indicate clear patterns in bat activity with regards to covariates. This figure gives the estimated smooth relationships between each covariate and activity, indicated by "s(x)" on the y-axes, showing activity as an estimated smoothed function of each covariate "x". As a log-link GAMM, these are on the log-scale, where they are additive, but can be interpreted simply as showing activity with respect to the indicated covariate. The higher the value, the higher the predicted activity. The mgcv package used to fit the models estimates the level of complexity for each of the smooth terms, as measured by the effective degrees of freedom (EDF), indicated in brackets on the y-axes (Figure 1). Uncertainty about the estimated activity is indicated by the gray envelopes about the curves – which is typically larger near the boundaries of the data, where there is less data to support the estimation of the relationship.

Broadly, activity began before sunset (values below 0), peaking soon after and decreasing over the evening towards sunrise – with little activity beyond this. There was a marked "seasonal" component, reflected in the week of the year – with weeks 32 to 37 being notably more active. Activity was highest with low windspeeds (approximately below the 5 m/s curtailment boundary, with marked decreases in activity above approximately 8 m/s) and for low temperatures, noting some confounding between night and temperature. There was a clear increase in activity when wind-direction was from Northerly directions. Distributional assumptions of the model were satisfied, with Poisson errors a very good approximation to those observed. The sample variance was well explained by the covariates, with an Adjusted R^2 of approximately 54%.

Further modelling with explicit interactions between the week of year and stage of night (Figure 2) showed the seasonal nature of activity – a nightly window capturing a certain level of bat activity would vary in length over the weeks. In this figure, the predicted intensity of activity is color-coded as a function of both week (x-axis) and stage of night (y-axis).

The nightly window of peak activity contracts and expanded as weeks progressed. This is particularly pertinent, as it suggests a dynamic window of curtailment over time will offer different properties in terms of power production and bat fatalities. This also suggested the nightly curtailment window could be narrower earlier in the year (before week 34) but required to be broader in the remaining weeks.

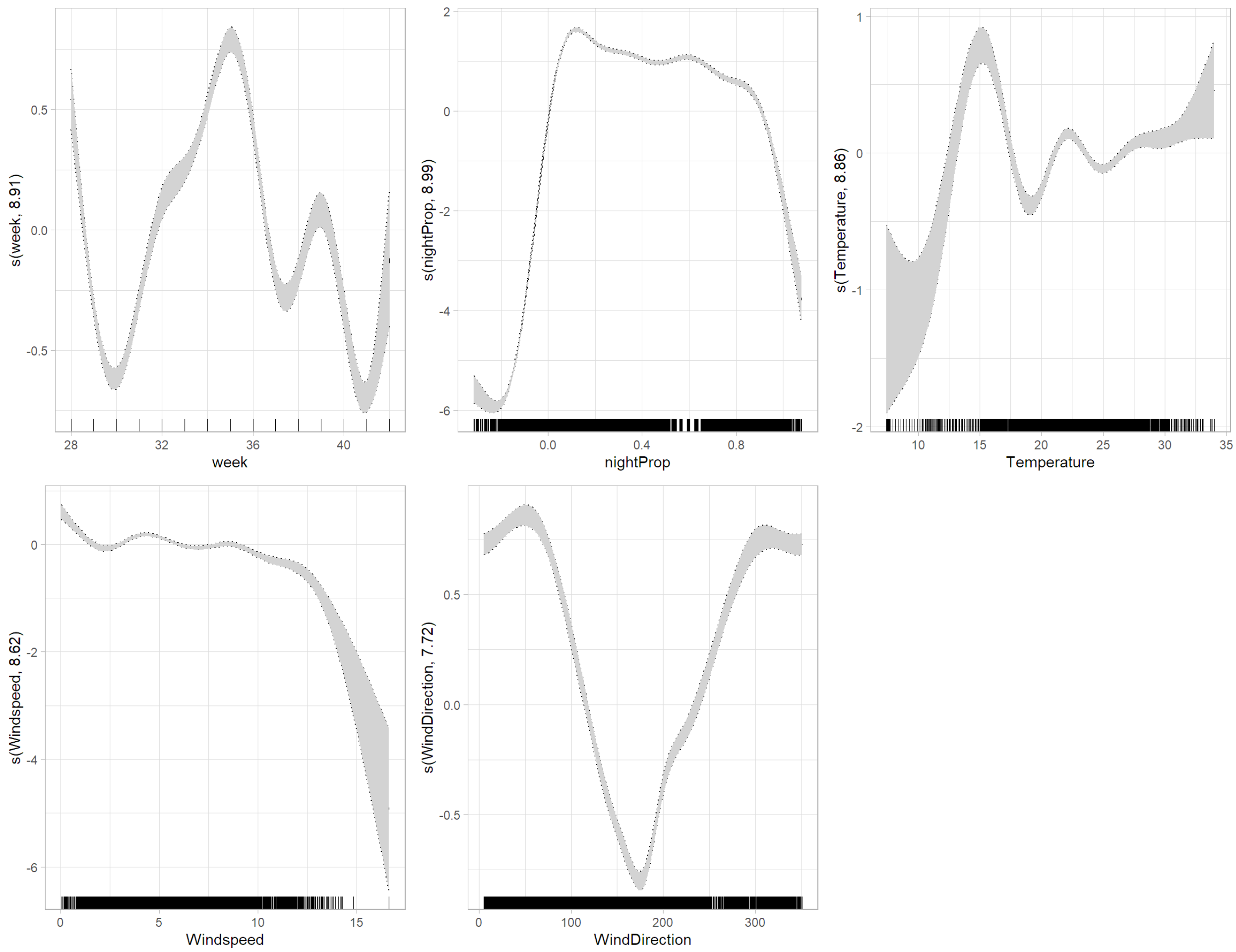


Figure 1: Link/log-scale estimated smooth terms for the GAMM predicting bat activity. Envelopes are +/-1 standard error for the mean. nightProp is a standardized index of night – sunset and sunrise being 0/1 respectively, Week is week of year (1-52), windspeed is in m/s, temperature in °C, wind-direction in degrees (0 to 360). Numbers on the y-axis labels are the effective degrees of freedom for the smooth term – refer to the body of the text for more detailed description.

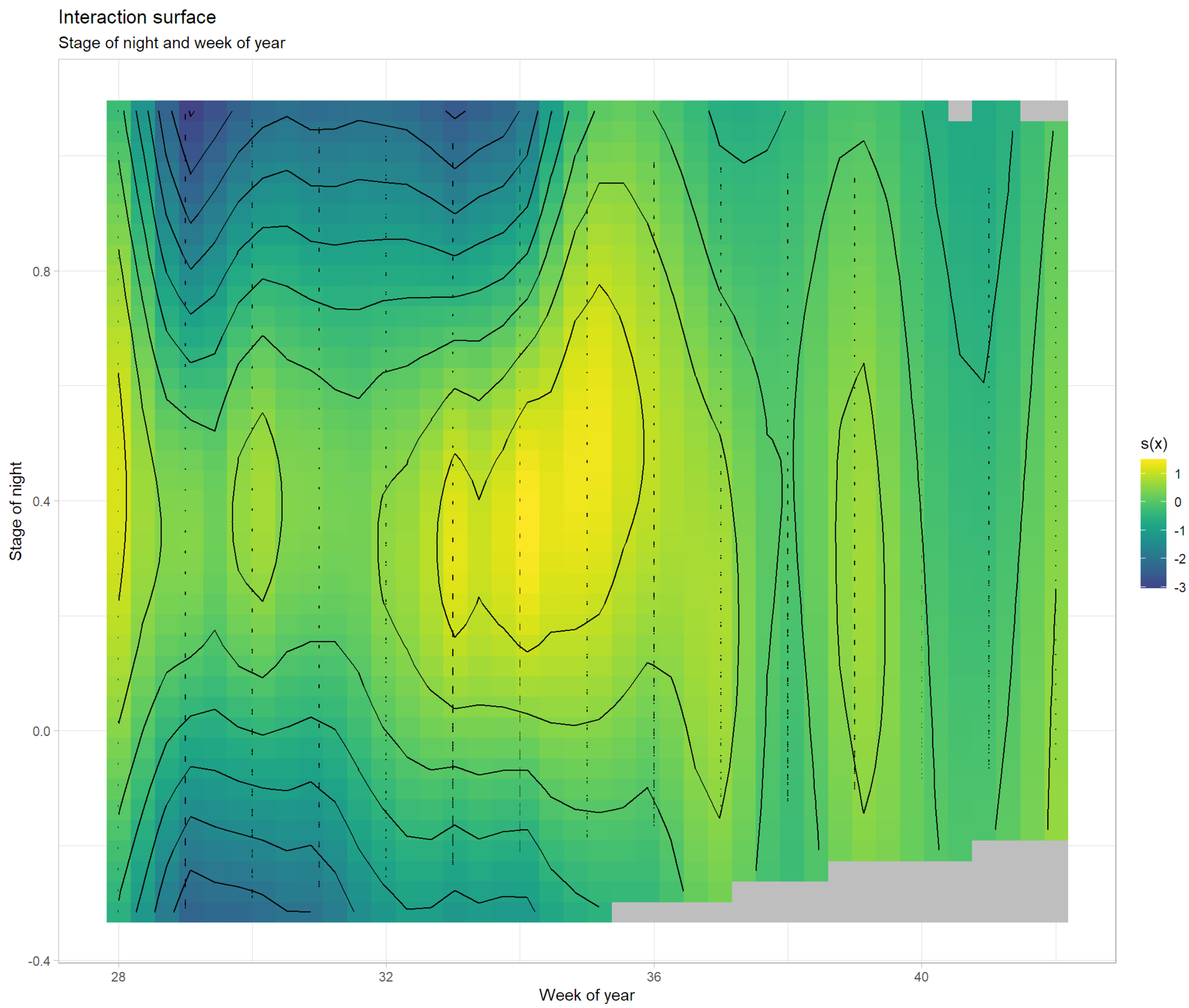


Figure 2: Link/log-scale estimated interaction surface for the GAMM predicting bat activity. Here the interaction is between week of the year and stage of night (sunset and sunrise being 0/1 respectively). The predicted level of (log-scale) activity is given by the color-scale, yellow indicating high levels, blue, low levels.

4.1.3 Summary and notes

1. The stage of night was found to be the most influential predictor of bat activity. However, a large component of this was due to the transition from day to night - given the surveying period starts during day-light hours, where there was no bat-activity. Changes in activity over the course of the evening were much less pronounced. It did however indicate that curtailment with regards light-levels needs to be treated carefully i.e., should be estimated/defined as precisely as possible, as activity increases/decreases markedly over approximately hourly timescales (Figure 1).

2. There were clear indications of fluctuating bat activity over the course of the study, reflected here at a weekly level (week of the year). Approximately weeks 32 to 40 were the peak periods for bat activity, suggesting curtailment windows could be applied variably over time to balance power production and fatalities. For example, curtailment may be applied over a relatively narrow period of night before week 32, but broader thereafter. In those cases, approximately similar levels of bat activity were predicted to be within 0%-70% of the night before week 32, as those predicted pre-sunset to 100% of the night after week 32. However, given annual variability is unknown with a single year's data, weekly-level estimates are unlikely to be robust.

3. Windspeed is an influential predictor, with greater activity at lower speeds. Blanket curtailment at 5 m/s did capture the peak activity region, but activity levels did not decrease markedly until 8 m/s. There were varying estimated levels of bat activity for speeds below 4m/s but would be best interpreted tentatively given the amount of data and proximity to the data boundary.

4. Wind-direction was clearly influential on activity over the study period, with higher activity for winds from a generally northerly direction. Given the migratory nature of the bats over this season, this was likely related to this, and valid for general prediction for turbines over the facility, not just the two for which data was collected.

5. Temperature was the least influential variable but indicated peak bat activity to be approximately <18C. This however is somewhat correlated with the stage of night and time of year, so ought to be viewed tentatively.

6. The model allowed back-calculation of curtailment rules based on thresholds of activity and, by extension from the adopted activity-fatality relationship, rules to achieve relative fatality targets. Further, these estimated relationships indicated what curtailment strategies ought to be searched over, to provide simple rules that offer the best fatality reductions for a given loss of power production. These are explored in section 5.

4.2 Collision Fatalities

Data on fatalities was collected on a day-scale and to species-level, and further assigned to the turbine responsible. Combined with turbine sensor data, these could in principle form the basis of a day-level model relating fatalities to environmental covariates. However, the real-time smart curtailments sought are on much finer time-scales and must necessarily be based on activity data which has the requisite temporal scale and is relatable to the available covariates.

In this context the fatality data had utility in translating activity into expected turbine fatalities. Usable activity data (thermal video) was collected at two turbines, and few carcasses were collected at these sites (13 in total). Aggregating carcasses over the entire study site increased sample sizes to 85, subject to strong assumptions about the representativeness of the two turbines with activity data to the whole site. The issues and assumptions surrounding time scales (day-level to sub-hour level), accuracy of carcass aging, aggregation of turbine carcasses and their general paucity, collectively made the modelling challenging.

Substantial modelling was conducted, with the best model being a negative binomial GLM, relating the maximum activity levels (from thermal video bat-tracks) to carcass recoveries. The deviance explained was negligible, uncertainty around estimates was very large and no compelling relationship could be established. The details of the modelling are given in the appendix 7.

A simple proportional model is therefore assumed between bat activity and consequent fatalities. This does not allow estimation of an expected number of fatalities for a given activity level but does allow estimation of the relative effects of curtailment options. Specifically, we calculate percentage changes in this fatality index for varying curtailment options, despite the absolute numbers of fatalities being some unknown function of this. This is not uncommon – avian collision-risk models for wind-farms adopt a similar approach, all other variables equal (species, avoidance rates, turbine properties) the mean fatality estimates frequently scale directly with the expected number of birds (refer Masden and Cook, 2016 for a review of avian collision risk models). The principal short-comings of this approach are a lack of estimates of absolute fatalities and the possibility of different curtailment decisions if the relationship activity-fatality relationship is non-linear, rather than proportional. While there was insufficient data to verify this, the underlying assumption that the probability that a bat collides with a turbine is independent of other bat's activity, is a reasonable position.

5 Derivation of curtailment rules

Integration of the model outputs into the VBPS is only via a set of scheduling (turbine on/off) rules, which can be linked to the turbine sensor data and temporal information. The sensor data is collected/recorded continuously at a 10-minute resolution and the model can be used to define a series of binary rules based on the temporal/sensor inputs. Turbines operating VBPS should have equal or fewer bat fatalities compared to turbines operating with blanket curtailment, and significantly fewer bat fatalities compared to control turbines. For this study, the goal is to understand whether the VBPS can be used instead of blanket curtailment without loss of conservation value. However, if adopted more broadly as a strategy, the thresholds chosen are management decisions, balancing turbine operation against fatality numbers, and cannot be objectively determined from the models alone.

The process is first illustrated here comparing blanket curtailment and a set of rules including wind-direction (section 5.1). A brute-force search of curtailment rules, informed by the activity model, is presented in section 5.2, from which the curtailment scheduling for the turbines is calculated.

5.1 Example curtailment comparison

As an example, three specific scenarios are compared:

1. Control/no curtailment action – turbines have operated without constraint, as dictated by the empirical wind-speed-power curve i.e. the total potential power from the two turbines without downtime.
2. A "blanket curtailment" – turbines do not operate at wind-speeds below 5 m/s, between sunset and sunrise.
3. A model-derived curtailment – turbines do not operate when the following conditions are met: wind-speeds below 4.95 m/s applied between 3% and 90% of the night cycle, and no operation between 350 and 70 degrees (broadly North-North East). In practice this means a nightly curtailment window that over time varies in length, i.e., being a variable number of minutes before/after sunset and after sunrise.

The example curtailment was chosen from the search described in 5.2, as it gives greatest reduction in fatality for a small reduction in power (within a band of 2-3% power loss relative to blanket curtailment).

The amount of potential power production (in KWh) is presented for each scenario, based on an empirical relationship with wind-speed (*pers. comm.* M. Whitby). Note, this is not the entire power output over this period, as windspeed data only covers the nightly data-collection periods. A 20-minute resolution is used in calculations, in keeping with the resolution of the activity data used in modelling.

Figure 3 and Figure 4 give a comparison of these in both power production and bat fatalities. Considering the endpoints of the three scenarios:

- The reduction of power across the two turbines is 5.6% comparing blanket curtailment to control, for an estimated reduction in fatality of 42% from control.

- The reduction of power across the two turbines is 8.5% comparing the model curtailment to control, for an estimated reduction in fatality of 53% from control.

- The model curtailment reduces joint turbine power output by 3% compared to the blanket curtailment for an estimated reduction in fatality of 17% compared blanket curtailment.

While there is a general tradeoff between turbine operation and fatalities, it is not always directly proportional and is non-linear given the range of possible curtailment options. A brute-force search over potential curtailment rules is given in section 5.2.

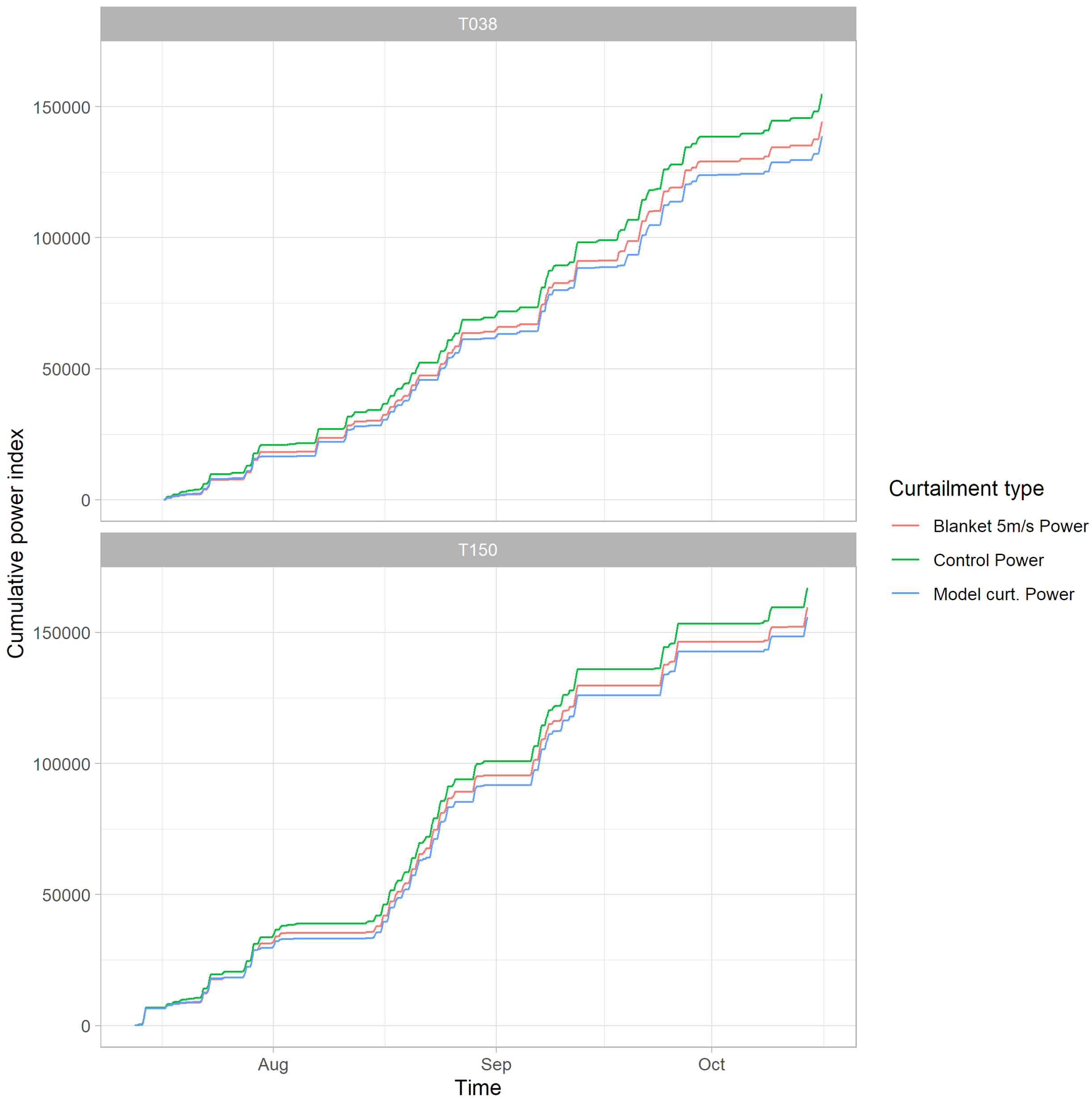


Figure 3: cumulative potential power over the study period. Three scenarios: control, blanket curtailment based on windspeed and sunrise/sunset and, a more complex set of conditions from the activity model.

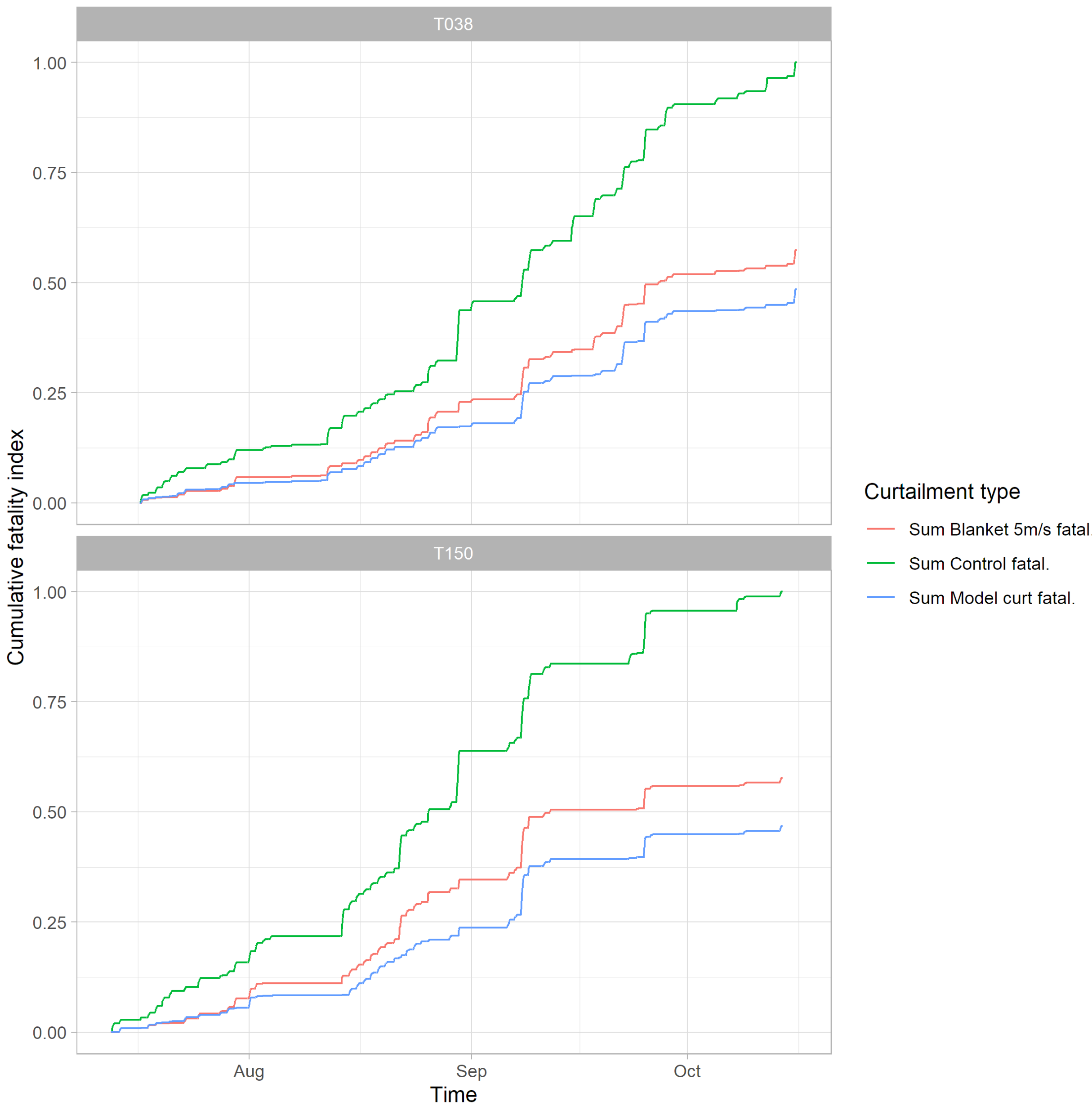


Figure 4: cumulative fatality index over the study period. Three scenarios: control, blanket curtailment based on windspeed between sunrise and sunset and, a more complex set of conditions from the activity model.

5.2 Optimization of curtailment rules

Due to the control software for the turbines, the models fitted here cannot control turbines in real-time i.e., decisions can be made in near-continuous time, but against a pre-defined set of rules/thresholds which can instruct the facility to curtail or operate the turbines at 10-minute intervals. For this reason, the GAMM of 4.1 was used to inform a brute-force search over covariates, to find simple decision rules that balance power production and fatalities. In short, the estimated functional relationships indicate general ranges where bat activity is low, and turbines might be profitably curtailed.

Here the search has been conducted over 220,000 sets of curtailment rules, each based around: the stage of night (a variable window where curtailments might be needed), wind-speed, wind-direction and temperature. These are further permitted to vary on a monthly and weekly basis, leading to approximately 900 thousand and 3.3 million potential rules respectively.

The results are posed as changes d assumed fatalities for the proposed curtailment, relative to the blanket curtailment for wind-speeds of <5 m/s between sunset and sunrise. These are based on data from the two turbines T038 and T150 but pooled in terms of both fatalities and power production.

Similar power outputs are achieved through various curtailment rules, but these can have markedly different effects on rates of fatality. For this reason, the results have been binned by approximately equivalent power outputs. An optimal curtailment is defined as a rule that produces the lowest relative fatalities, for an equivalent amount of turbine operation (defined as the total revolutions achieved). Figure 5 provides estimates for all explored curtailment rules, whereas Figure 6 bins these results by their similarity of power production. In any event, curtailment rules at the lower boundary are considered optimal.

The practical output from this brute-force search, is a series of curtailment rules (monthly or over the year) based on stage of night, wind-speed, and wind-direction.

As an example (Table 1 – line marked with †) , using a curtailment window starting at 3% of the night, and finishing at 91% of the night, within which turbines do not operate below 5.3 m/s windspeed, or when wind is between 350 and 80 degrees (i.e., broadly North), then there is an estimated reduction of 5% power, for a further 27% reduction in fatalities over blanket curtailment. Similar rules would achieve approximately no power loss compared to blanket curtailment, for an 8.5% reduction in fatalities compared to blanket curtailment (grey shaded line, Table 1).

Curtailment rules are presented for the monthly-varying search (Table 2), and non-time-varying search (Table 1). The weekly-varying schedule is likely to be too sensitive to annual variations to be employed, so not presented. Data over additional years would allow some quantification of annual variability.

Five-fold cross-validation was conducted (section 8) to assess the generalization error and potential overfitting from the large-scale search over curtailment rules. Performance on validation datasets was consistent with that found on training data, and the results presented here for the full dataset.

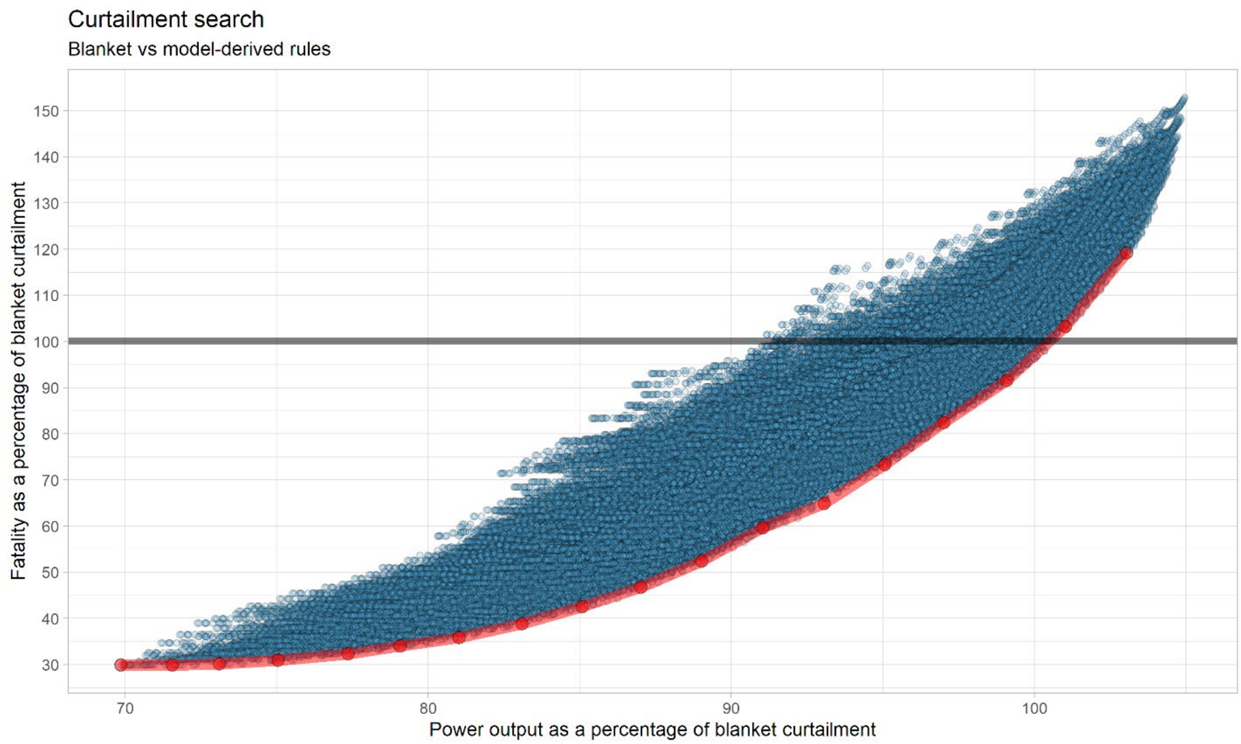


Figure 5: power versus fatality reductions for a brute force search of 220000 curtailment rules, informed by the model in section 4.1. The lower boundary of points gives curtailments that best balance reductions in fatalities versus power production. Red points give a selection of best curtailments for a given power reduction. These are also presented in Table 1.

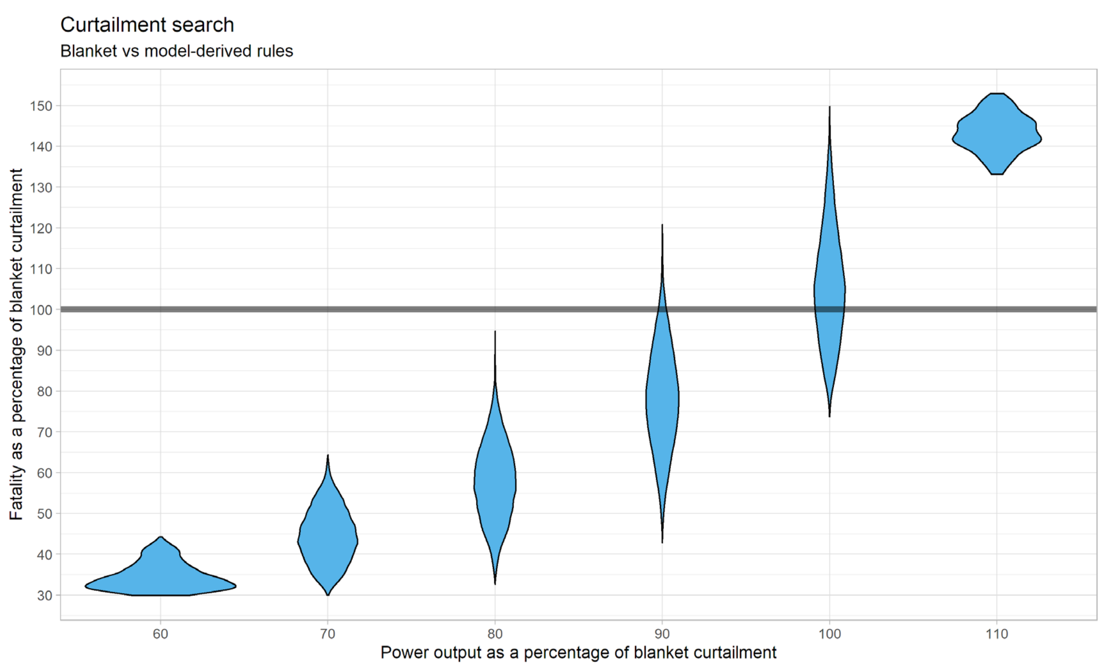


Figure 6: power versus fatality reductions for a brute force search of curtailment rules – power binned to the nearest 10. Points below the horizontal line indicate lower fatality than blanket curtailment.

Table 1: greatest reductions in fatality for a range of power reductions, all relative to blanket curtailment. Gray shading indicates approximately no difference in power production relative to blanket curtailment. Night start/finish are relative to the night cycle (sunset being 0, sunrise being 1), windspeed (m/s) is an upper bound and conditional on the nightly window, wind-direction upper/lower define a window outside which curtailment occurs regardless of other parameters. † is referred to as an example in the preceding text.

Curtailment parameters					Relative to blanket curt.	
Night start	**Night finish**	**Windspeed**	**Wind-dir. Lower**	**Wind-dir. upper**	**Power %**	**Fatality %**
-0.30	1.10	6.0	100	270	70	29.9
-0.13	1.10	6.0	100	270	72	29.9
-0.08	1.10	6.0	100	270	73	30.1
-0.02	1.02	6.0	100	270	75	30.9
-0.02	0.98	6.0	100	280	77	32.3
-0.02	0.98	5.8	90	280	79	34.0
-0.02	0.91	5.8	90	280	81	35.8
0.03	0.91	5.8	80	280	83	38.8
0.03	0.91	5.3	100	280	85	42.5
0.03	0.91	4.9	80	280	87	46.7
0.03	0.91	4.7	80	290	89	52.4
0.03	0.91	4.6	80	300	91	59.6
0.03	0.91	4.9	80	320	93	64.8
0.03	0.91	5.3	80	350	95	73.3†
0.03	0.91	4.9	70	350	97	82.4
0.03	0.83	5.2	20	350	99	91.5
0.03	0.87	4.9	10	350	101	103.2
0.03	0.83	4.6	0	350	103	119.2

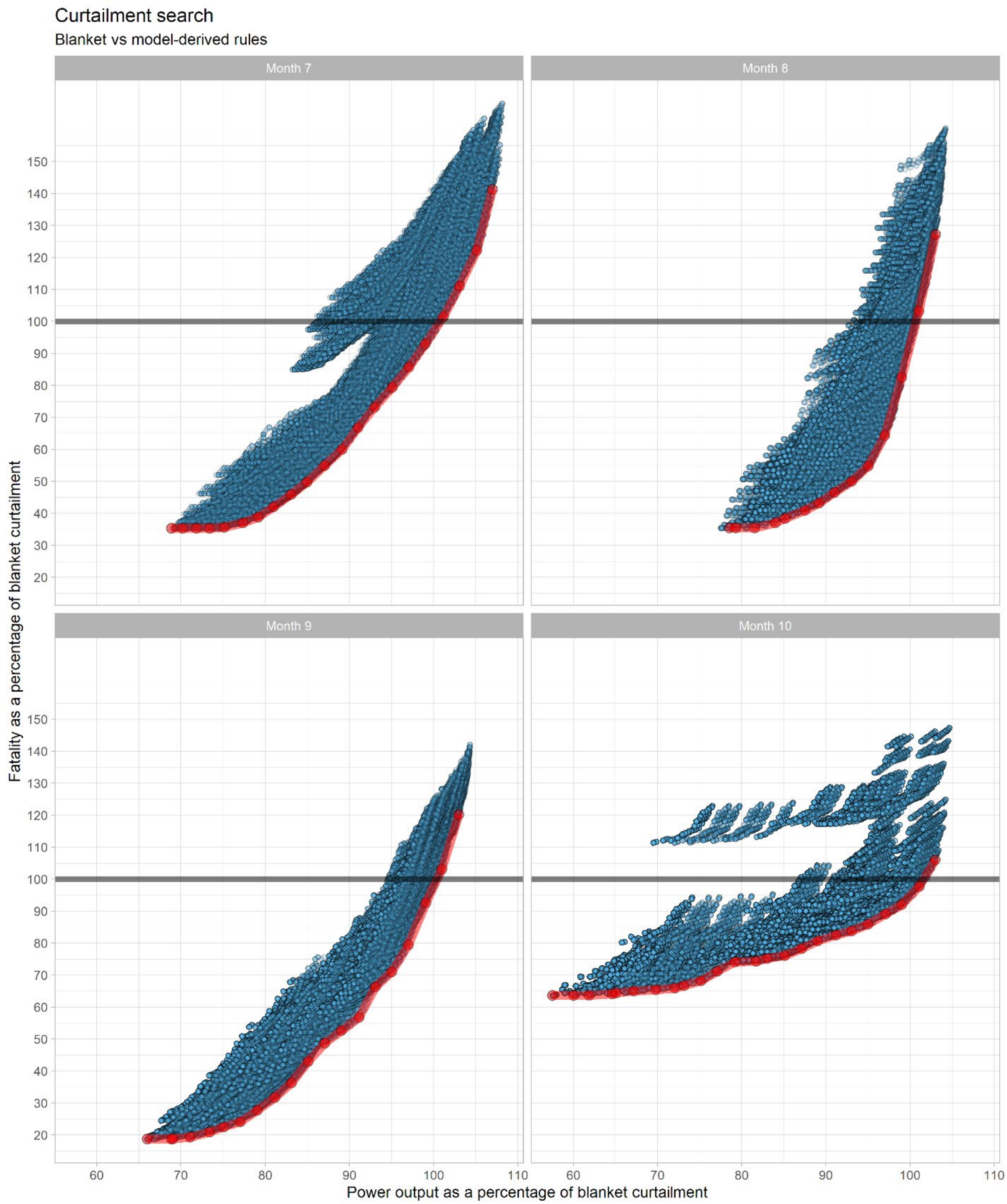


Figure 7: power versus fatality reductions for a brute force search of 880k curtailment rules allowed to vary by month, informed by the fatality model. The lower boundary of points gives curtailments that best balance reductions in fatalities versus power production. Red points give a selection of best curtailments for a given power reduction. A selection of these are given in Table 2. Some parameter combinations were markedly poorer for October, as evidenced by the upper cluster of points.

Table 2: selection of reductions in fatality for a range of small power reductions by month, all relative to blanket curtailment. Gray shading indicates approximately no difference in power production relative to blanket curtailment. Night start/finish are relative to the night cycle (sunset being 0, sunrise being 1), windspeed (m/s) is an upper bound and conditional on the nightly window, wind-direction upper/lower define a window outside which curtailment occurs regardless of other parameters.

	Curtailment parameters					Relative to blanket curt.	
	Night start	Night finish	Windspeed	Wind-dir. Lower	Wind-dir. upper	Power %	Fatality %
Month 7	-0.02	0.91	5.4	10	340	95	79.4
	-0.02	0.87	5.3	10	320	97	85.7
	-0.02	0.87	5.2	0	340	99	92.9
Month 8	0.03	0.91	4.8	100	290	95	54.8
	0.03	0.94	4.8	80	350	97	64.2
	0.09	0.87	4.3	80	350	99	82.5
Month 9	0.03	0.87	6.0	10	340	95	71.0
	0.03	0.83	5.9	0	350	97	79.4
	0.03	0.83	5.5	0	350	99	92.6
Month 10	0.03	0.75	5.8	80	350	95	85.9
	0.03	0.87	5.5	60	350	97	89.1
	0.03	0.79	5.4	30	350	99	92.0

6 Discussion

We have developed models on the basis of the project data, that relates bat activity to temporal and environmental covariates. By extension we can derive estimates of bat fatalities as a proportional function of these same inputs. This allows development of potentially complex curtailment rules, which can balance power production against reductions in bat fatalities.

6.1 Model curtailments vs blanket curtailment

The "blanket curtailment" of turbines for windspeeds <5 m/s between sunset and sunrise is estimated to produce large reductions in bat fatalities for relatively small losses of power production. Mildly more complex curtailment rules are estimated to reduce fatalities by a further 8.5% compared to blanket curtailment for no further loss of power production, principally on the basis of shortening the nightly curtailment window and avoiding northerly winds (shaded portion of Table 1).

A larger average reduction in fatalities is estimated, also for no further loss of power, compared to blanket curtailment if monthly-varying curtailment rules are employed. Fatalities are estimated to be reduced by approximately 10% compared to blanket curtailment (shaded portions of Table 2).

There are indications of strong variations in bat activity at a weekly level, and curtailments are calculable to this level. However, the lack of repeated year's data means annual variability is unknown. For this reason curtailments based on fine-scale time components are unlikely to be robust and inadvisable.

6.2 Selecting curtailment rules

Defining the best curtailment rules requires a subjective balance of fatalities to power production. Given an objective of not reducing the power output appreciably compared to blanket curtailment, the shaded regions of Table 1 & Table 2 give the best curtailment estimates. The single refined curtailment rule of Table 1 is likely the most robust to currently unknown annual variability. Monthly curtailments offer a modest improvement in performance, but with the concomitant uncertainty of annual fluctuations with regards monthly effects.

Notably the reduction in fatalities is non-linear with regards power production – some small reduction in power relative to the blanket curtailment is estimated to produce proportionally larger reductions in fatalities. For example, an estimated 3% reduction in power from blanket curtailment is estimated to provide an additional 9% reduction in fatalities, relative to blanket curtailment (Table 1).

6.3 Further scope for improved curtailment

Notably the curtailment levers available from the study data are not particularly different to those within the blanket curtailment, which uses time of night and wind-speed. The models here do allow the use of temperature, but this is relatively unimportant. The addition of wind-direction and seasonal components, along with objective refinement of nightly curtailment windows provided avenues for improvement.

The project was intended to collect precipitation data but was unable to do so due to pandemic-related supply chain issues. This would have offered a wholly different curtailment lever, compared to blanket curtailment. Were this to be collected going forwards, with barometric pressure[6], further improvements would be expected.

[6] Fields in the turbine data suggest this can be collected at turbines but were not populated in this study.

7 Appendix – fatality modelling

This section outlines the modelling applied to carcass recovery data, which attempted to relate observed deaths to real-time turbine conditions. As discussed in section 4.2, data limitations were such that a simple proportional model was adopted for developing curtailment rules, rather than the models described here.

7.1 Data exploration

Activity data is limited to thermal video tracking of bats at two turbines (T038 and T150), with individual bat track information (an individual seen continuously over several frames) summarized at 20-minute resolution. All turbine data for days when video sensors were not operating were discarded, providing 54 and 47 days of data (a total of 14,286 and 19,001 bat-tracks) for T038 and T150 respectively.

Bat fatalities were assigned to turbines and nights based on their location and estimated carcass age. Where a bat carcass was assigned to an evening without operational video coverage, their data were discarded. Over the entire study site, 85 fatalities were coincident with video activity data.

Activity data were collected at approximately 20-minute intervals, whereas bat fatalities were known at a day/night resolution. Modelling fatalities as a function of activity requires the data be on the same resolution – necessarily dictated by the coarser fatality data. Aggregation of the activity data to day scale required summarization, and as it was not clear which would be the best characterization three variants were considered:

- Average activity: the average number of individual bat-tracks per 20 min block per night.
- Maximum activity: the largest number of accumulated bat-tracks per 20 min block in a night.
- Summed activity: the sum of all tracks in a night.

Exploratory analyses (plotting and GLMs - not presented) indicated no relationship between the average nightly activity and carcass counts, so was not considered further. The maximum and summed activity measures were highly correlated, indicating only one warranted formal modelling (Figure 8, Figure 9 & Figure 10) - a log-log transformation chosen as it dampens the mean-variance relationships typical of count data. It further mirrors the response implied in common modelling for count data, log-link GLMs.

Further exploratory analysis (plotting and simple GLMs – not presented) suggested maximum activity to the stronger predictor of bat fatalities over both turbines – hence this response variable was carried forwards to formal modelling (7.2).

Given the need to aggregate carcass counts over the entire study site, the operational status of turbines other than the two focal turbines needed consideration. There are similarly weak and imprecise relationships between nightly carcasses and the number of operational turbines (Figure 11), nonetheless this is a fundamental input along with activity, and was also considered in the formal modelling of section 7.2.

Collectively, explorations do not indicate clear relationships between potential predictors and the observed fatalities and suggest any estimates will be imprecise.

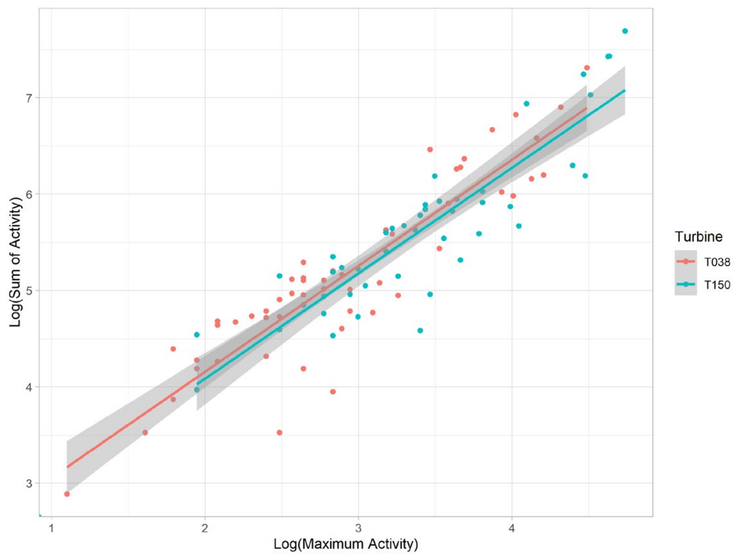


Figure 8: Log-log relationship between sum of activity and maximum activity

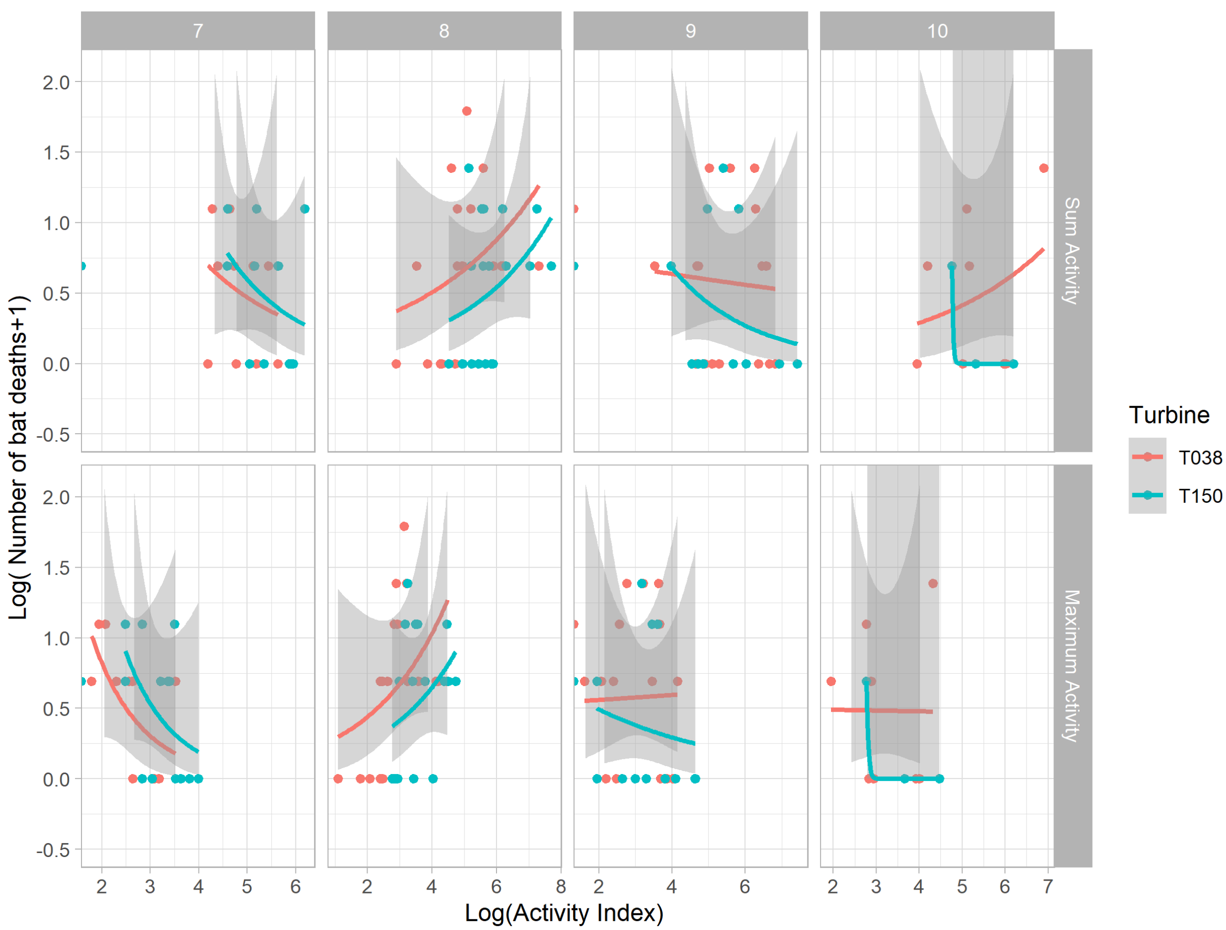


Figure 9: log-log relationships between number of bat deaths and activity indices by turbine and month. Solid lines and shaded area represent a linear model for counts and 95% confidence intervals, respectively.

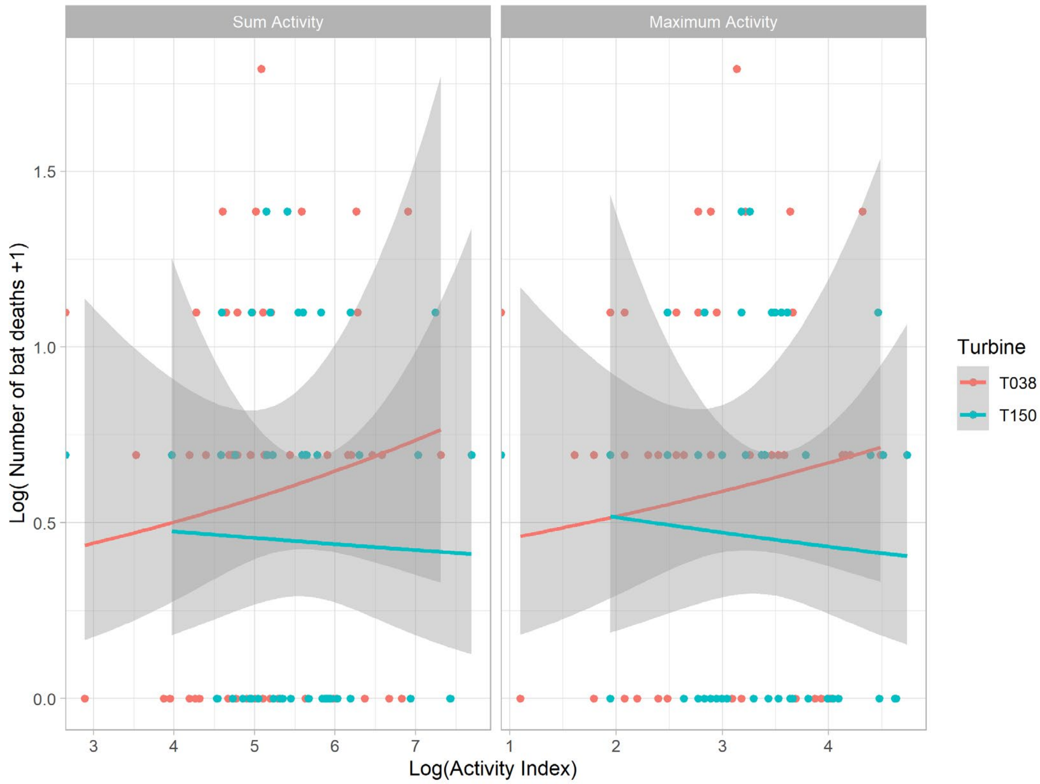


Figure 10: Exploratory plots for log-log relationship between number of dead bats and the activity index by turbines for all months combined. Solid lines and shaded area represent the linear model for counts data and 95% confidence interval, respectively.

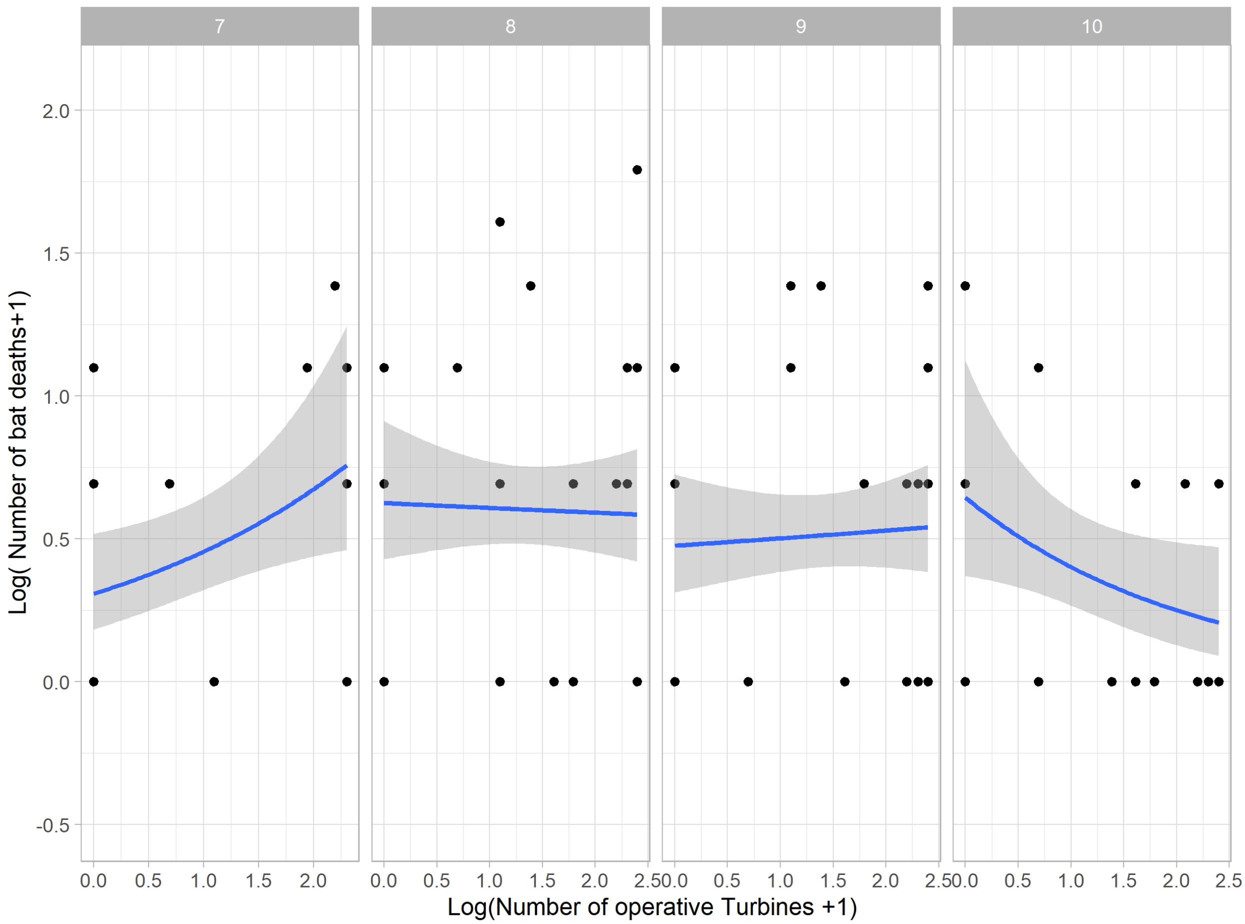


Figure 11: Exploratory plots for log-log relationship between number of dead bats and the number of operating turbines by month. Solid lines and shaded area represent the linear model for counts data and 95% confidence interval, respectively.

7.2 Summary and notes

1. Several models for the relationship between bat fatality and activity were considered but discarded in favor of the simple model presented. For example, a Generalized Additive Model (GAM) produces models that predicts zero deaths at high activity and is difficult to interpret – although this is likely due to data sparsity and influential data.

2. A very weak positive relationship was estimated between bat collision fatalities and activity in T038. The best bat activity index for this purpose was based on maximum activity observed in a night.

3. The T038 model provides more marginally precise estimates for fatality from activity in comparison to T150. Coupled with the positive slope estimate, the T038 model is best amongst the candidates as a predictor of fatalities but is objectively still a poor model and not a compelling basis for curtailment calculations.

4. Combining turbines did not provide for a more compelling model. This is the coarsest scale possible, using all site-level carcasses and recorded bat activity.

5. Overall, the carcass data is very sparse for the purpose of relating fatalities to turbine and/or bat activity. Coupled with differing temporal data scales, uncertainties in turbine operation, small coverage of activity sensors and probable uncertainties in carcass aging, no model of good utility is currently possible.

6. Given the findings here, a simple model of proportional fatality was adopted as per section 4.2.

7.3 Model approach and fitting

For modelling count data (fatalities per night) there are several standard error distributions, most popular being Poisson (and Quasi-Poisson), negative binomial or zero inflated models. Presented are estimates for Poisson and negative binomial distributions, as days with zero deaths were not so dominant as to require zero-inflated models.

The candidate models are compared using Akaike's Information Criterion (AIC) covering predictor, error distribution and turbine (Table 3). The negative binomial distribution was marginally favored over the Poisson distribution, noting that an AIC difference of less than 2 units does not indicate substantive superiority. Additional exploration of error distributions (not presented) indicated evidence of overdispersion relative to the Poisson, further favoring the negative binomial error distribution.

The negative binomial model without offset was carried forwards as preferred and model diagnostics indicated no notable distributional violations. Two further treatments were considered:

- Separate turbine models (Table 4).
- An aggregate model that combines estimates from the individual turbine models (weighted by Mean Squared Error – MSE, Figure 12). Parameters are aggregated by resampling from turbine's bivariate Normal distributions, with inverse-weighting by the MSE (bespoke coding in R).

The estimated Intercept and distributions are very similar between turbines – however, slopes are positive in T038 and negative in T150. The combined turbine distributions also provides slope estimates very near zero, offering little utility. Practically, only estimates from T038 offer any plausible link between activity and the observed fatalities, but this is both weak and very imprecise. Overall no compelling modeling was possible for these data, requiring a simple proportional model for curtailment calculations, as detailed in section 4.2.

Table 3: AIC values for the GLMS considering different activity indices as predictors and by turbines. Grey shading indicates the best model by AIC – although differences less than 2 units are not considered substantive.

T038		
	Poisson	Neg. Binomial
Max Activity	156	155
Max Activity + Offset	175	197

T150		
	Poisson	Neg. Binomial
Max Activity	117	116
Max Activity+ Offset	142	142

Table 4: Summary of estimates from the negative binomial GLMs for fatality and maximum activity by turbine.

T038		**Estimate**	**Std. Error**	**z value**	**p-value**
	Intercept	-0.021364	0.228114	-0.094	> 0.05
	Max. Activity	0.002342	0.007033	0.333	> 0.05
	Adjusted R-sq	-0.0171			
	Dev Explained	0.20%			
	N	54			
T150		**Estimate**	**Std. Error**	**z value**	**p-value**
	Intercept	-0.1025	0.28142	-0.36	> 0.05
	Max. Activity	-0.004681	0.006647	-0.704	> 0.05
	Adjusted R-sq	-0.0109			
	Dev Explained	1.01%			
	N	47			

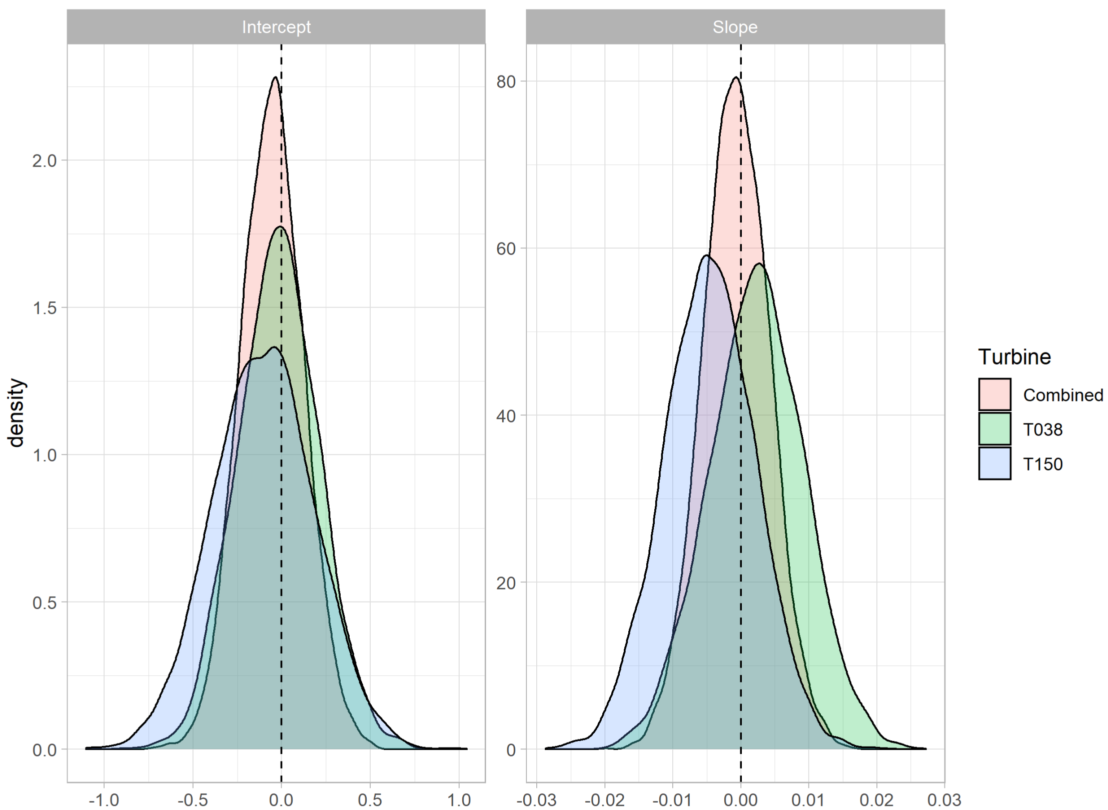


Figure 12: Distributions (probability density functions - PDFs) for the log-scale intercept and slope parameter values (x-axis) from the fitted models. PDFs are given for individual turbines and combined with inverse-MSE weighting.

8 Appendix - activity model diagnostics and validation

Two types of model validation were conducted and presented here:

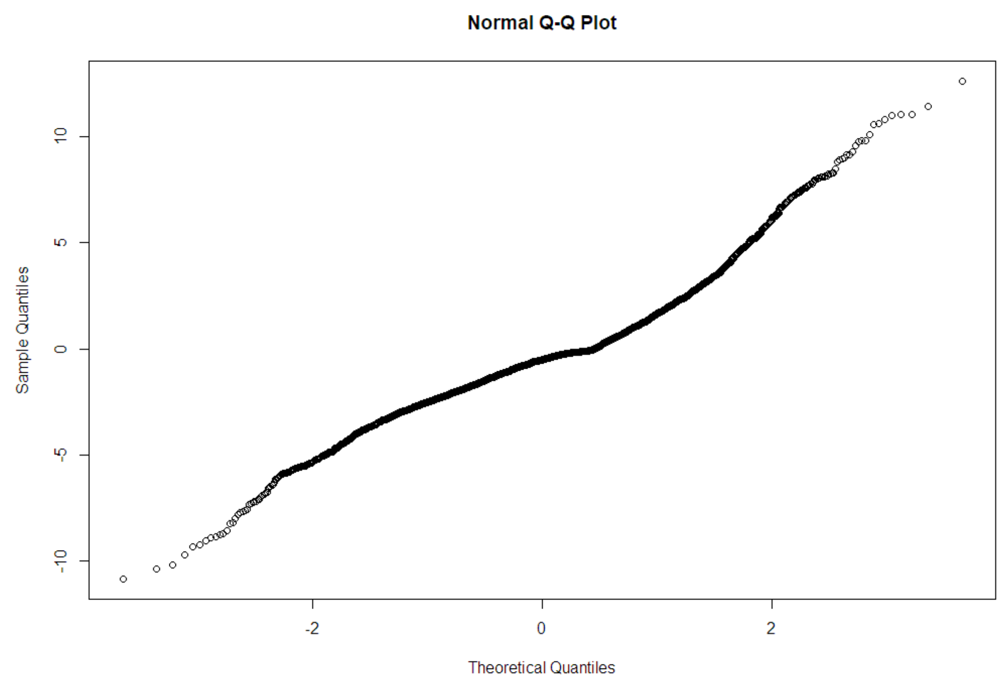
1. General goodness of model fit, in terms of predictive power to the sample data and distributional assumptions.

2. 5-fold cross-validation, using 20% blocks of the data iteratively, to test performance on data not used in the construction of the curtailment rules.

8.1 Model fit

The GAMM model fitted within section 4.1 specified a log-link and Poisson error structure, with smooth relationships estimated between several covariates and the count response. Diagnostics on the model residuals showed the distributional assumptions to be acceptable, with approximate Normality of the Pearson residuals (QQ-Norm plot below).

An approximate adjusted R^2 of 54% indicated a substantial proportion of the data variance is captured by the fitted model. The approximate deviance explained was >61%, similarly indicating a model that extracts substantive signal from the response data.



8.2 Validation

The curtailment search was subjected to 5-fold cross-validation to provide estimates of generalization error. The data was split into training (80%) and validation (20%) sets. Given the time-series nature of the data, this was done by systematic sampling based on days i.e., every fifth day was excluded to create five sets of training/validation dataset pairs.

A curtailment search was conducted on each of the training datasets, with the best rules chosen (minimizing fatalities) for differing levels of power production. Estimated fatalities were calculated for each validation dataset using these curtailments, meaning data used in the determination of curtailment rules was not used in the calculation of presented fatalities. These are presented in Figure 13. There is some variability in both the power production and fatalities across the validation datasets, indicating estimates to be roughly +/- 2.5% in terms of generalization error.

In the context of the results in section 5, this indicates the boundary for optimal curtailment rules (e.g., Figure 5) has some uncertainty/fuzziness. This has been accounted for in the determination of the curtailment rules put forwards for implementation.

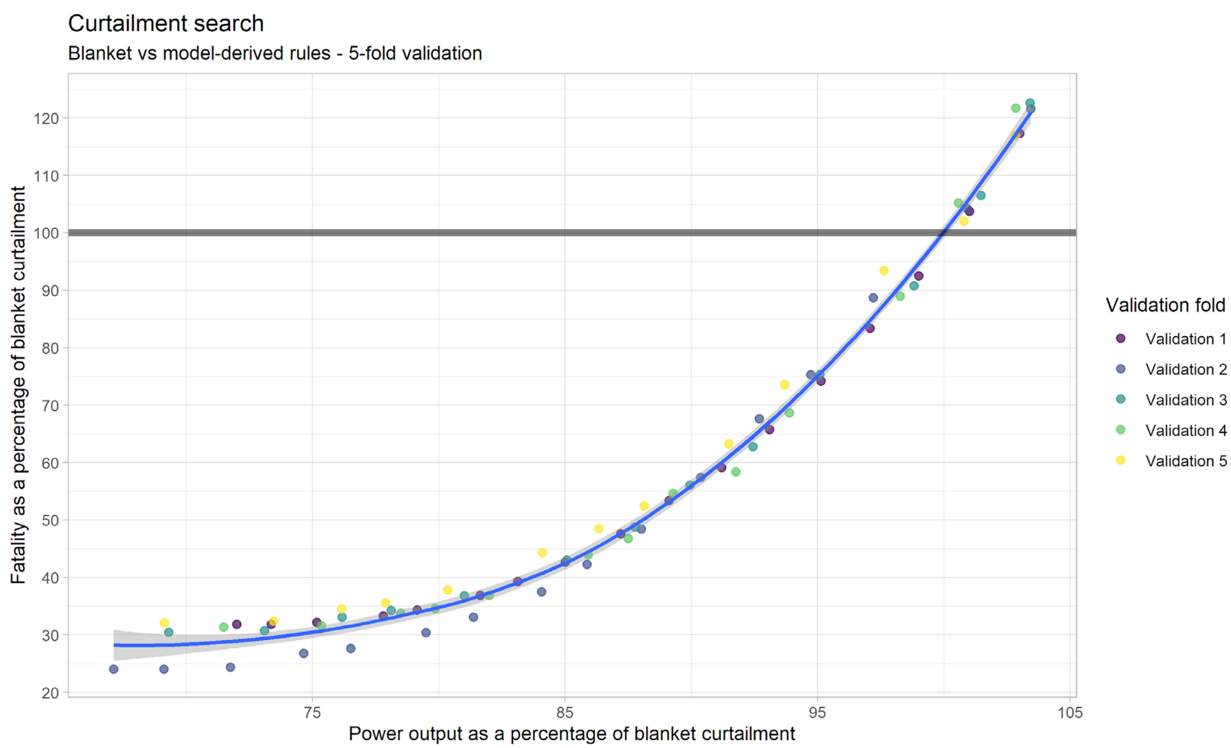


Figure 13: 5-fold cross-validation for the curtailment search given in section 5.2. The blue line is a fitted smooth line, with 95% confidence envelope (gray shading).

9 References

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Attachment 2: Year 2 Report - Experimental Evaluation of the Vestas Bat Protection System

Experimental Evaluation of the Vestas Bat Protection System (VBPS)

Project Title: Developing and Evaluating a Smart Curtailment Strategy Integrated with a Wind Turbine Manufacturer Platform

Award Number: DE-EE0008729.0000

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Renewable Energy Wildlife Institute 700 12th Street, NW, Suite 700

Washington, DC 20005 www.rewi.org

Prepared By

Renewable Energy Wildlife Institute (REWI)

Principal Investigators: T. Allison, PhD, I. Gottlieb

Ursinus College

Statistician: L. New, PhD.

DMP Statistical Solutions UK Ltd (DMP)

Statisticians: C. Donovan, PhD; R. Wiff, PhD

Bat Conservation International

Field Lead/Statistician: M. Whitby

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2 Overview

In this report we have described the analysis of the data collected during the second experimental phase of the Vestas Bat Protection System (VBPS) project, where different curtailment treatments and a control were applied to turbines within the hosting windfarm. The focal treatment was the manual implementation of the smart curtailment strategy “Vestas Bat Protection System” (VBPS) via surrogate rules, which was compared to a simple “blanket” curtailment scheme and no curtailment (the control). The blanket curtailment treatment restricted turbine operation to windspeeds of >5 m/s during night-time hours. The control treatment operated without night-time constraint. For the all treatments, operation ceased below wind-speeds of 3 m/s, i.e., blades were feathered below cut-in speed to reduce bat fatalities, as below this cut-in speed the turbines are not able to generate any appreciable power; blanket curtailment had a cut-in speed of 5 m/s. The operation of turbines under the VBPS treatment was determined by time of day, wind-speed, and wind direction. These variables were selected based on the results of phase 1 of the project (REWI 2022) and was dynamic, changing over time to reflect variation in modeled collision risk to bats in response to the selected variables.

2.1 Project description

The goal of the study is to develop and independently evaluate a smart curtailment strategy based on bat activity (measured by acoustic recorders and thermal video), bat fatalities, and environmental variables that could be integrated into the Vestas Bat Protection System (VBPS). The VBPS platform is a newly developed software module developed by Vesta engineers that would be fully integrated within the Supervisory Control and Data Acquisition (SCADA) system of Vestas wind turbines to issue curtailment orders based on modeled parameters collected at environmental sensors. Sensors would collect data such as temperature, wind speed, time of day, and time of year, relay that information to the SCADA system, and determine whether to execute turbine curtailments in real-time based on an estimate of collision risk level for bats.

In this study, the Project Team used data on environmental conditions, bat activity, and bat fatalities to develop the bat fatality risk model to be used as the input for the VBPS smart curtailment system. We then evaluated the risk model in comparison to blanket curtailment and control turbines. A goal of VBPS was to have a smart curtailment strategy that reduced bat fatalities comparable to blanket curtailment but at lower power production loss relative to blanket curtailment.

In 2021 during phase 1 of the project, the Project Team collected weather data, bat activity[1] data estimated from acoustics and thermal imaging, and fatality data at the study site (REWI 2022). These data were used to develop a bat fatality risk model which predicted bat fatalities based on weather and time of day. The effectiveness of the bat fatality risk model was evaluated in phase 2 where the model was used as input for the VBPS curtailment algorithm; real-time weather conditions were monitored and curtailment orders were issued according to the algorithm's prediction of bat fatality risk.

The analysis of the data collected in phase 1 resulted in a bat fatality risk model with windspeed, wind-direction and time of day relative to sunrise and sunset as influential predictors. Higher bat activity was identified at lower wind speeds and when the winds were from a generally northerly direction, likely related to the migratory nature of bats over the season in which the data were collected. While the bat fatality risk model was initially developed for real-time curtailment, at the time phase 2 began the software/hardware automated turbine curtailment based on wind direction had not yet been implemented at the study site. As a result, a set of VBPS-surrogate rules was applied manually each night during phase 2 of the project. The details of these rules are provided in Section 2.2.2 of this report.

Objective relevant to this report (paraphrased from the Statement of Project Objectives): Analyze the data collected from a randomized block-design experiment intended to compare daily bat fatalities, as determined from post-construction monitoring, between turbines implementing smart curtailment (i. e., the VBPS-surrogate rules), blanket curtailment, and no curtailment (control).

The Project Team collected turbine-level operation data at 1-minute intervals and bat fatality data from daily turbine searches at the study site in 2021. These data were used in the application and evaluation of the models described in this report.

2.2 Study Methodology

2.2.1 Study design

The study site consisted of 244 Vestas turbines -180 were model V110 turbines configured in 2.0-2.20 MW capacities and 64 were model V120 2.2 MW turbines. Only Vestas V110 turbines (95 m towers, 110

[1] NB Sensor issues rendered most acoustic data unusable.

m rotor diameter) were used in the study and Generalized Random Tessellated Sampling was used to randomly select 36 turbines that were spatially balanced. Of these 36 turbines 14 were 2.0 MW, one was 2.15 MW and 21 were 2.2 MW, noting there is no difference in the physical attributes (i.e., hub height and rotor diameter) of these turbines, only software differences. Variation in MW capacity in the sample is desirable for representativeness, as well as providing the primary needs of an adequate sample size and good spatial coverage.

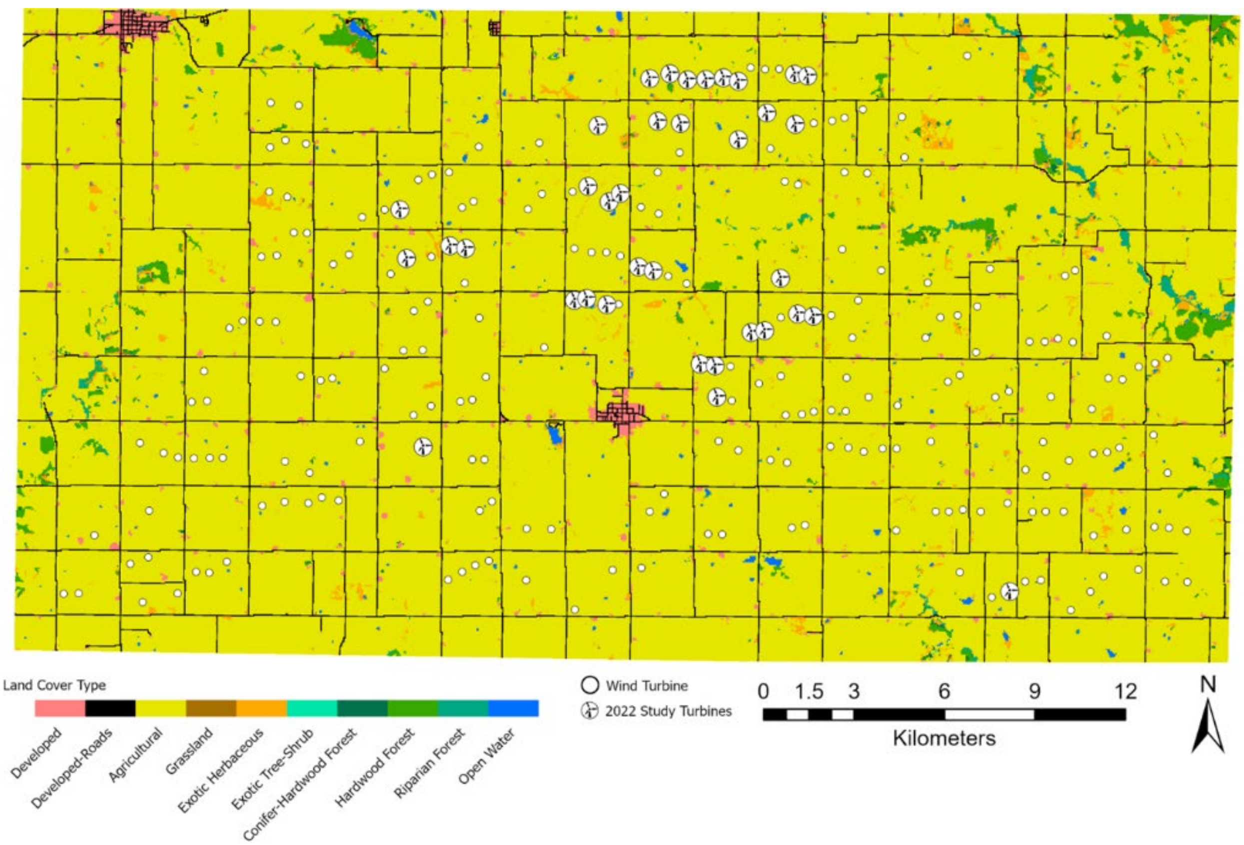

Figure 1. Map of study turbine locations and land uses

The project shared study turbines with a concurrent study to evaluate another smart curtailment strategy called Turbine Integrated Mortality Reduction (TIMR), which was also supported by the Department of Energy (award number DE-EE0008727). The VBPS and TIMR projects used two identical treatments, and shared study turbines to increase the sample size and statistical power of both studies. A Randomized Block Design (RBD) with turbine as the blocking factor was used, with four treatments (section 2.2.2) assigned over 36 turbines, with 9 turbines per treatment each night. Each treatment was assigned randomly and balanced across nights and within an 8-day period. Each night nine turbines were operating under each treatment, and each turbine was assigned each treatment twice in an 8-day period. The study was conducted for 108 nights (June 20th - October 5th 2022), thus each treatment was assigned to each turbine 27 times, for a total of 972 turbine-nights per treatment type.

2.2.2 Treatments

Control: defined as normal operating procedures, with a cut-in speed of 3 m/s, with feathering the blades (rotating the angle of the blades so that the wind does not cause the turbine to spin)) below the cut-in windspeed to minimize spinning and bat fatalities when energy is not being produced.

Blanket curtailment: Considered the benchmark for fatality reduction, with the cut-in speed increased from 3.0 m/s to 5.0 m/s between sunset and sunrise, and feathering below the cut-in windspeed to minimize spinning and bat fatalities when energy is not being produced.

TIMR: Turbines operating a smart curtailment run by the TIMR system, for the study sharing turbines with this project. This analysis does not include data from the TIMR treatment.

VBPS-surrogate rules: The VBPS-surrogate rules define the curtailment parameters on a monthly basis. Each month's rules consist of a nightly curtailment window (start and stop time relative to sunset and sunrise), a wind speed for use as a cut-in speed for curtailment, and a subset of wind directions that trigger an increased level of curtailment (see Table 1 and Figure 2 for details). Ideally the system would have operated in real-time, with sensors providing all inputs, but automation of curtailment based on real-time wind direction was not possible under the constraints of the software and hardware available at the time of the experiment. Consequently, the bat fatality risk model developed in phase 1 was distilled to a set of monthly rules that were implemented daily and manually by a human operator. As applied, a human operator assessed the forthcoming weather conditions using the NOAA forecast for Orient, IA between 4:00-5:00 PM Central Time, to determine which operational rule would apply each night. As a result, any wind direction data collected by the turbines was not utilized in making curtailment decisions. With regards to wind direction, if the forecast direction was found to be within the boundaries of the curtailment *wedge*[2] for >50% of the evening, the associated decision rule would be applied. These rules are summarized in Table 1, and the explanatory material presented to turbine

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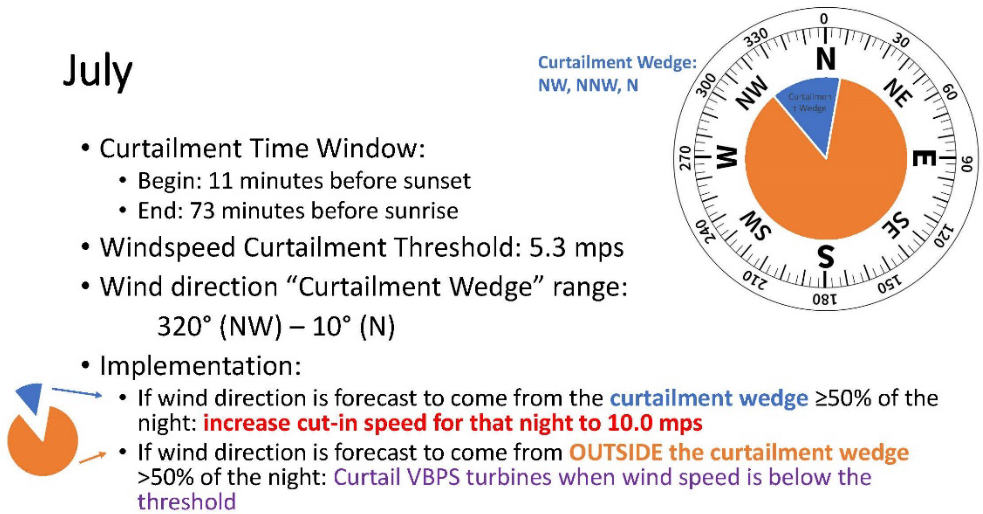
[2] The term "wedge" was adopted to make ranges of wind-direction clearer for the operators of the surrogate-VBPS.

operators explaining how to implement the VBPS-surrogate rules is presented in Figure 2[3], which provides a visual representation of the "curtailment wedge" and instructions on how to implement curtailment for the coming evening based on the forecasted wind direction. Since the completion of the experiment, the VBPS software module has introduced the ability to issue curtailment decisions based on real-time wind direction data. VBPS surrogate turbines implemented feathering below the cut-in windspeed to minimize spinning and bat fatalities when energy is not being produced.

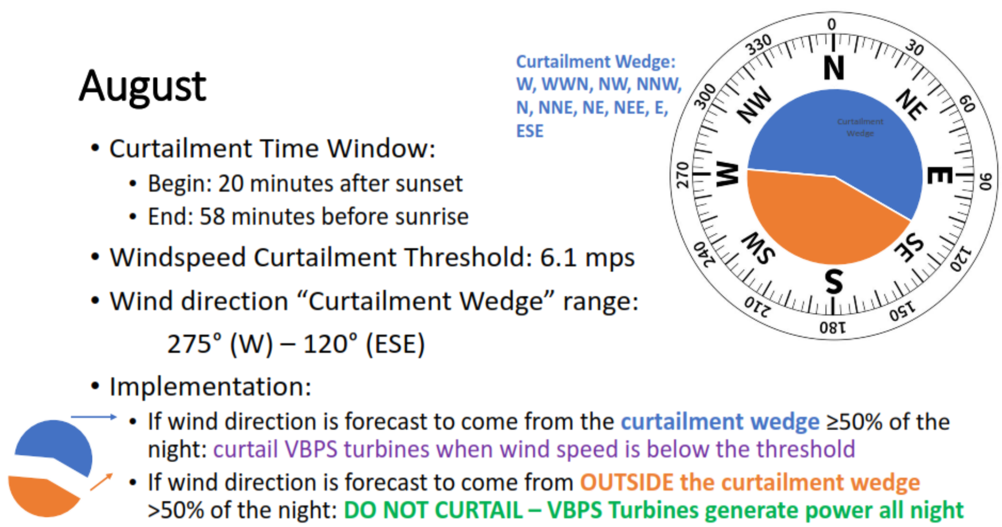
Table 1: distilled VBPS-surrogate rules for manual implementation. The rules are derived from the bat fatality risk model developed in VBPS phase 1. Time to sunset/sunrise values are in minutes, where negative values indicate minutes after sunset or sunrise.

	Time curtailment window		Windspeed curtailment	Wind direction curtailment "wedge" (assume 3-letter precision e.g. NNE) - clockwise lower to upper		
Month	**Time to sunset (mins)**	**Time to sunrise (mins)**	**Windspeed upper bound (m/s)**	**Wind Direction Lower (degrees)**	**Wind Direction Upper (degrees)**	**Implementation - note OR (blue) and AND conditions (green)**
July	11	73	5.3	320 (NW)	10 (N)	Within time window, curtail if wind speed below bound **OR** wind direction forecast >50% within curtailment wedge
August	-20	58	6.1	275 (W)	120 (ESE)	Within time window, curtail if wind speed below bound **AND when** wind direction forecast >50% within curtailment wedge
Sept	-21	120	6.1	230 (SW)	135 (SE)	Within time window, curtail if wind speed below bound **AND when** wind direction forecast >50% within curtailment wedge
October	-23	160	5.4	350 (N)	30 (NE)	Within time window, curtail if wind speed below bound **OR** wind direction forecast >50% within curtailment wedge

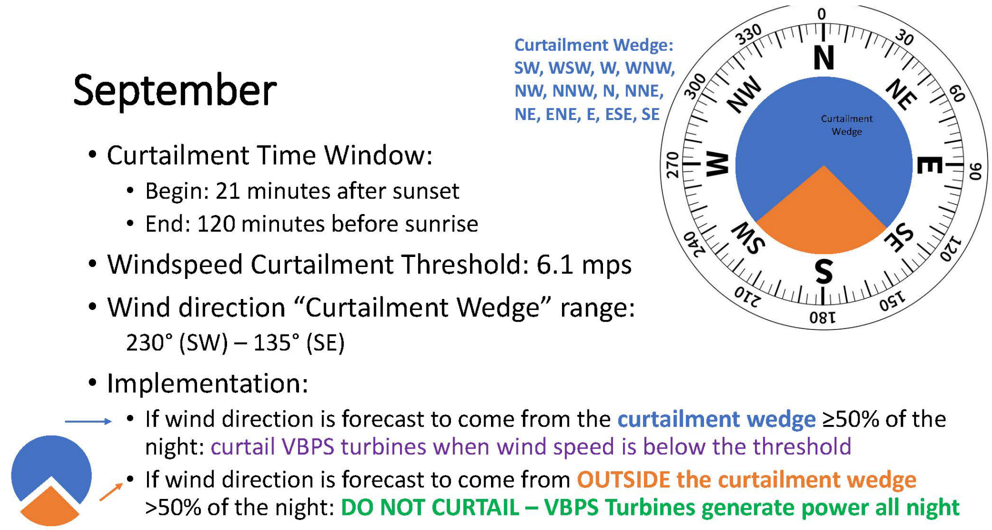
[3] The wind direction descriptors on Table 1 and Figure 2 do not follow standard terminology, but are the exact wording and information provided to the operators implementing the VBPS-surrogate rules. The non-standard terminology is used here so that the report reflects the experiment as it was conducted.



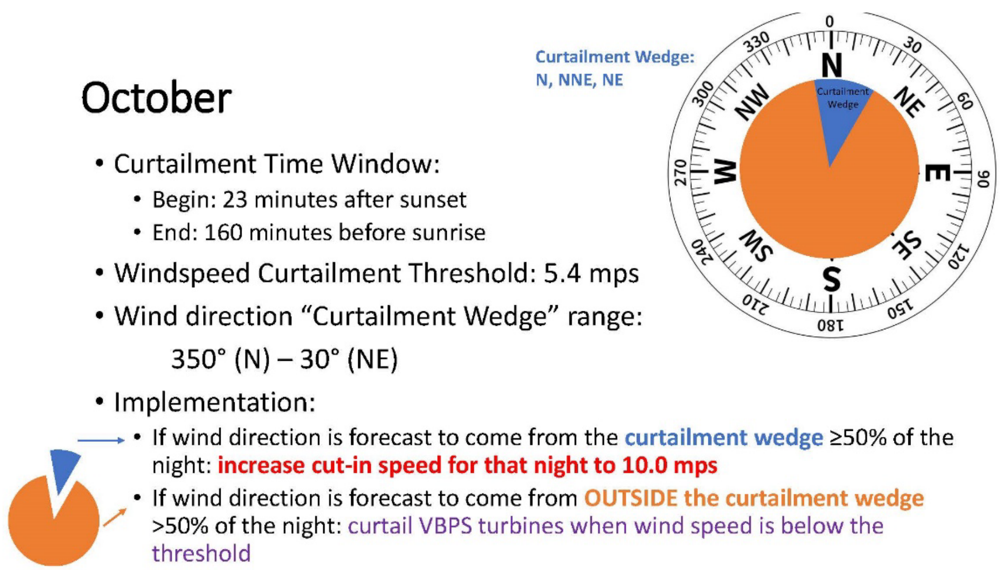
2a. July



2b. August



2c. September



2d. October

Figure 21: Descriptions provided for VBPS operation using the surrogate rules for July [a], August [b], September [c], and October [d].

2.2.3 Fatality Surveys

To facilitate identification of bat carcasses, a square, 140 m x 140 m search plot was established around each turbine and maintained to keep grass height less than 6 inches. Plots were oriented with corners in the cardinal directions, when possible, with some adjustment to limit impact on crops.

Dog and handler teams conducted daily carcass searches of each plot. The teams walked transects perpendicular to the wind at 10 m intervals to increase searcher efficiency of the dog team. While field crews were aware of the nature of the project, they were not informed as to when treatments were active at any given turbine. This "blind assignment" helped ensure unbiased fatality searches. When a team found a carcass, its location, species (when possible), estimated age and decay state were recorded. Carcass aging is difficult and depends on indicators such as eye desiccation and decay, insect infestation level and general wing and body desiccation, all evaluated in the context of recent weather conditions. Field crews were asked to be conservative in estimating fresh carcasses, and based on the carcass age distribution, the Project Team believes the field crew misclassified approximately 50% of fresh carcasses as older.

While searcher efficiency and carcass persistence trials were carried out at the study site, they are not needed for the analysis presented in this report. We assumed that searcher efficiency and carcass persistence would affect all searches equally, so any percent reduction in bat fatalities due to treatment effects would be the same for both observed and estimated total carcasses. Furthermore, while it is possible to fit the models to the estimated total carcasses per turbine night, this would introduce additional sources of uncertainty, lowering the statistical power to detect a treatment effect.

We estimated that searcher efficiency was 54.4% (38–70%) for fresh bats in 2022. This value is low compared to other reported searcher efficiencies for dog and handler teams (e.g., 77.8% in Domínguez de Valle et al. (2020)), in part because the search teams were asked to be conservative in estimating fresh carcasses, and possibly because of the difference in scent between freshly killed carcasses and those carcasses that are older.

Based on data exploration and the proportion of bats in each age class, from another study in 2021, we believe that searcher efficiency of fresh carcasses is approximately 25%-50% in 2021. We worked to improve this percentage in 2022. In the week prior to the study, dog teams were trained on live big brown bats (*Eptesicus fuscus*) from a local rehabilitation organization. Additionally, search teams were all trained on fresh or live bats encountered during the first two weeks of the study. In 2022, we designed searcher efficiency trials to distinguish searcher efficiency between bats killed the night before and older carcasses.

2.3 Modeling approach

The analysis consists broadly of two sets of models, directed towards the two focal points of a curtailment system: bat fatalities and electrical power production.

2.3.1 Bat fatality modeling

Bat fatality information is necessarily on a day/night-level resolution, in keeping with carcass searches and the precision with which carcasses can be aged. As treatments are rotated daily, carcasses need to be allocated to turbines with day-level precision to be usable. Given that each turbine is surveyed multiple times throughout the season, mixed models are fitted to these data to account for repeated measures. Within these models, the response variable is counts of carcasses for a given turbine on a given day, leading to a generalized linear mixed model, where turbines and days are treated as random effects with a log-link and Poisson errors. Model diagnostics showed no marked violations of those model assumptions. The estimated treatment contrasts are of primary interest for comparison of VBPS-surrogate rules (i.e., smart curtailment), blanket curtailment, and controls.

2.3.2 Power production modeling

Information on the power produced by each turbine is is available at a 1-minute resolution. Initial modeling is approached as for fatalities, but with the response being average or total daily power production**.** Generalized additive mixed models are used, with turbines and days similarly treated as random effects, but with an identity-link and Tweedie-error structure. Model diagnostics showed no marked violations of model assumptions. The estimated treatment contrasts remain of primary interest, for comparison of VBPS-surrogate rules, blanket curtailment, and controls.

The variability of the turbines' status and power production, information about maintenance interruptions, uncertainties in treatment application, and the ability to model power production as a function of windspeed, offers additional modeling options. Modeling is also provided for theoretical power production at the individual turbine-level over time, based on known wind speeds, for all treatments.

2.3.3 Software

All data preparation and model fitting were done in the R statistical programming environment version 4+ (R Core Team, 2022), using the R-Studio IDE version 2023.03.1 Build 446. Statistical significance is set to the 5% level, and confidence intervals are 95%. Two-tailed inference is used throughout.

Mixed models are fitted using the glmmTMB package (Brooks *et al.,* 2017). Modeling of individual turbine's power curves is done using monotonic Generalized Additive Models (GAMs) using the scam package (Pya, 2022), which is an extension of Wood's implementation of GAMs (Wood, 2011) but permits constrained basis functions for monotonically increasing functions.

3 Data

Data for these analyses were provided by Bat Conservation International (M. Whitby, *pers. comm.* Feb 2023). These are briefly described here, along with their main treatments and notable issues.

3.1 General description

There are four main data sources used for analysis:

- Bat carcass data: the numbers of carcasses recovered from searches around the turbines, including estimated carcass age. These data were provided in pre-processed form and subsequently restricted to fresh carcasses, where the allocation to turbines/treatments has minimal error. The main information used is the number of carcasses per day associated with each turbine.
- Treatment schedule: the *a priori* allocation of treatments to turbines for each evening of the study period. These rotate over turbines daily. There were deviations from the treatment plan in the case of the VBPS-surrogate rules, which were accounted for – for example the VBPS-surrogate treatment was not in effect until the 5th of July, meaning previously designated VBPS turbines act as additional control data.
- Turbine operational data: 1-minute resolution, turbine level data comprising sensor information (e.g., wind-direction), operational status (e.g., online or curtailed) and power production.
- VBPS operator's log: this is a daily record of the operator's view of forecasted wind-direction and the subsequent curtailment rules implemented. This also contains information about when the VBPS-surrogate rules were not applied as intended.

3.2 Data treatment and issues

There were several issues found with the data sources, which required remedial work (e.g., additional modeling with/without data that may be incorrect) when comprehensive correction was not possible. The main issues of significance follow.

3.2.1 Online/offline status

A turbine's operational status was recorded as one of four values: avian curtailment, offline, online and resource unavailable. Note thatthe status "avian curtailment" is recorded within the operational logs, but also covers curtailments for bats at night. Therefore, all bat curtailment was logged as avian curtailment, although no curtailment for avian species occurs at night[4]. While the operational data mainly covers evenings, starting a small period before sunset to slightly beyond sunrise, there is an amount of day-time information contained in the raw data. A small amount of day-time curtailment is observable, where "avian curtailment" exists under the control treatment. Given the balanced nature of the study, this particular ambiguity does not affect the fatality modeling or the turbine-level electrical power generation analysis in Section 4.2.

Discriminating between a turbine being off for curtailment or off for other reasons has relevance to both the fatality modeling and the power modeling. For example, turbines may be offline for prosaic reasons, like maintenance, for significant portions of an evening. In these cases, the turbine's data ought to be excluded from the analyses, as despite having a treatment assigned, that treatment is not active, and because the turbine is offline, we would expect zero fatalities and zero power production. Inclusion of these data would create the false impression that the treatment was extremely effective in reducing fatalities, but at the cost of power production.

Unfortunately, the manual assignment of operational status by a human operator was inconsistently applied across treatments, as no curtailment was recorded for the VBPS (Figure 2a), despite the

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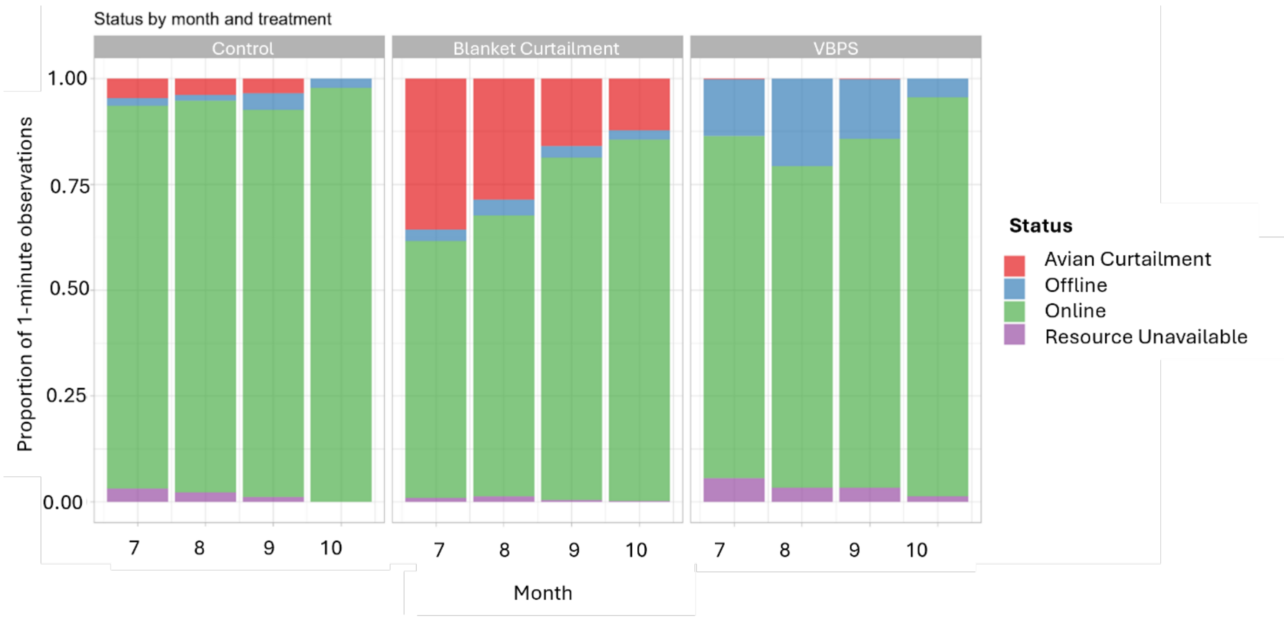
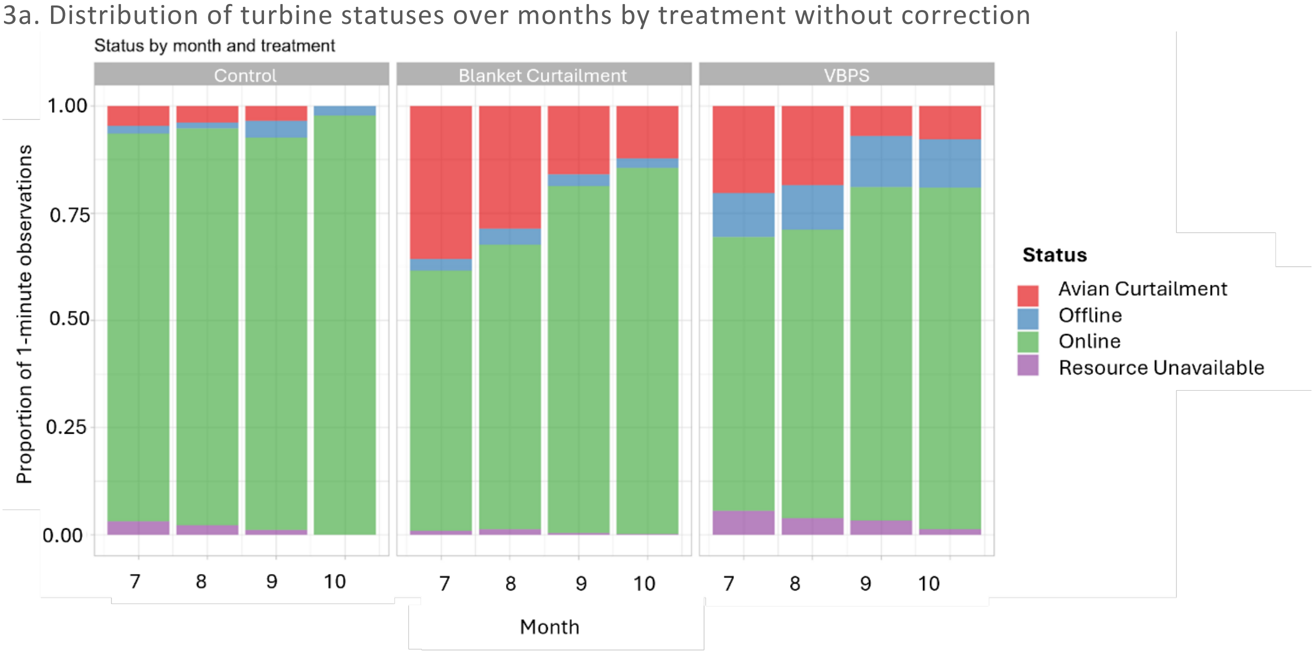
[4] The phrase "avian curtailment" has been retained at this point to accurately reflect what was actually recorded in the data, as no separation was made in the logs between curtailment for the purpose of reducing the fatalities of avian species and curtailment for the purpose of reducing the fatality of bat species. However, avian curtailment in the traditional sense was not active in the nighttime, just as curtailment for bats did not occur during daylight hours. The two curtailment types under "avian curtailment" are separable from time of day.

operator logs indicating that the VBPS-surrogate rules were being applied. This issue was pursued by the project team but could not be retrospectively rectified to the 1-minute data level. Instead, the turbine status was inferred by examination of a turbine's power production when under the VBPS-surrogate rule treatment. Periods of low electrical power production (nominally < 200 kWh), when the VBPS-surrogate rules ought to theoretically allow activity, were back-calculated as "Offline" if the wind-speeds were not so low as to qualify for "Resource Unavailable". This is shown in Figure 3b for the 4 months that the VBPS-surrogate rules were in effect. There is a notably higher incidence of offline instances under the VBPS-surrogate rules, but this may reflect difficulties with the manual implementation of the surrogate rules by human operators.



3a. Distribution of turbine statuses over months by treatment without correction



3b. Distribution of turbine statuses for the VBPS-surrogate rules after corrections

Figure 3: Distributions of the variable status described in 3.2.1, where “avian curtailment” covers bat curtailments applied during night-time. Curtailment under VBPS-surrogate rules erroneously recorded as “offline” - the top and bottom plots show necessary amendments [a] top, distribution of turbine statuses over months by treatment without correction, [b] bottom, distribution of turbine statuses for the VBPS-surrogate rules after corrections. Avian curtailment seen under the control is due to some daytime data in the operational dataset – meaning some curtailment was in effect to avoid avian fatalities. Daytime data play no part in later analyses of the treatment efficacies.

3.2.2 VBPS-surrogate rules treatment interruptions

The VBPS operator's log shows delays in implementing the VBPS-surrogate rules, meaning treatment/experimental period was 2022-07-05 to 2022-10-05 for VBPS, compared to the study period of 2022-06-20 to 2022-10-05. The turbines scheduled to receive the VBPS-surrogate rule treatment prior to 2022-07-05 were reassigned as control sites, to give greater power for certain model contrasts. There were also notes in the log indicating possible problems with the VBPS-surrogate rule implementation on some evenings –these data were excluded from analysis where relevant (August 1^{st} to 4^{th}).

3.2.3 Inconsistencies in VBPS-surrogate rule treatment

Examination of the log files and turbine-level data shows the VBPS-surrogate rules to have been inconsistently applied in July and October. For these two months:

- The curtailment rule was misinterpreted/misapplied given the forecast wind direction in the operator log.
- The wind-direction forecasts logged by the operators and used to implement the VBPS-surrogate rules bore little resemblance to observed weather conditions as recorded on turbines – so the VBPS-surrogate rules were failing to emulate a true VBPS smart curtailment, where wind-direction and speed is known.

In the case of bat fatality data, July and October cannot be used for valid comparisons between treatments as the VBPS-surrogate rule treatment was not applied as intended. As a result, two sets of analyses were done. The first was conducted using the data from the full study period (July-October), regardless of the implementation issues. This was done as an indication of the actual experimentation conducted. The second analysis only uses those data from August and September to obtain estimates of the differences between treatments in their intended forms.

In the case of electrical power generation, back-calculations were possible to account for any incorrect application of VBPS-surrogate rules, i.e., the amount of electrical power that would have been theoretically produced if the rules were correctly applied. When the turbine was intended to be operational, electrical power can be calculated from the observed wind-speeds and an empirical electrical power production curve fitted to each individual turbine. When the turbine was not intended to be operational due to curtailment, electrical power production is treated as negligible. Analysis is presented for the experimental data as collected (observed electrical power production), as well as the theoretical electrical power production where treatments were applied as intended.

3.2.4 Treatment interruptions

For a given turbine and study night/day, a treatment will have been assigned according to the study design, however whether the treatment was practically in effect is unclear in some cases. For example, the wind speed might be below 5 m/s for 10% of the night, but a turbine assigned to blanket curtailment may not be operating for 65% of the night for prosaic reasons, such as being off-line for maintenance reasons for some period of the night. In effect the experiment is not being fully realized for this turbine and night – offering spurious reductions in fatalities and electrical power generation. Here a semi-arbitrary threshold of 50% is adopted. Therefore, if a treatment was recorded as being applied for less than half of a night because the turbine was offline, the data from that turbine was excluded for that treatment night. Results were run with different thresholds and the conclusions were found to be insensitive unless this threshold figure is made extremely small or large.

3.2.5 Carcass aging

Analysis of treatment effects on bat fatalities used only fresh carcasses because of the uncertainty in aging older carcasses, which makes it unclear under which treatment they died (*pers. comm.* M. Whitby). At a study level, this provided 224 carcasses out of a total of 740 found.

4 Results

Results are presented for the two broad model types, the first focusing on the treatment efficacy in terms of minimizing bat fatalities, and the second in terms of comparing electrical power losses due to curtailments. In each case, more than one model is fitted that reflects: the data largely as received, but with some level of errors in the application of the VBPS-surrogate rules (see section 3.2); and additional models with either these data excluded or amended.

4.1 Treatment efficacy - bat fatalities

Models were fitted to the carcass data, combined with turbine operation data to estimate the relative effects of treatments. Here three treatment effects are estimated for comparison: normal operations/control, blanket curtailment below wind-speeds of 5 m/s and VBPS-surrogate rules.

The modeling data consists of turbine level information for each night/day of the study period. The response is the number of fresh carcasses, with turbine status as the basic treatment covariate, along with turbine IDs and temporal components for the remaining predictors.

A generalized linear mixed model with log-link and Poisson error structure was fitted. The covariates were the treatment as a fixed effect, and random effects for the turbine and day/night of the study. This accounts for the inter-turbine variability and the repeated measures taken over time.

More complex spatio-temporal models are not feasible given the data, nor sought given the study objectives. The experiment was designed to establish whether there is a treatment effect, and by design reduces to simple treatment contrasts once the effect of turbines and days are controlled for by their inclusion as random effects. The statistical power of the experimental design was predicated on estimating treatment contrasts, meaning there is little planned fundamental power for estimating more complex effects. As such, estimated turbine level effects would be expected to be imprecise given the design, and in actuality, given the few turbine-level fatalities observed in the study. These sparse fatality data are reduced further if attempting to explore turbine-level temporal effects. Turbine-level effects are also not sought as they are a subset of a larger "population" of turbines, meaning their treatment as random effects is appropriate, and the details of the individual turbine estimates aren't truly relevant, being chance recruitments to the study.

4.1.1 Full study period (July 5 – October 5, 2023)

Treatment contrasts with 95% confidence limits (CL) for the estimates are presented in Figure 4 and Table 2, based on the entire study period. Note VBPS-surrogate rule treatments scheduled for days prior to 2022-07-05 have been assigned as control sites, as the VBPS-surrogate rules were not applied during this period.

There were significant differences between both curtailment systems and the control, although none between the VBPS-surrogate rules and blanket curtailments. Fatalities under the control were estimated as 45% (95% CL: (1.3%, 108%)) and 46% (95% CL: (1.1%, 112%)) higher than for the blanket curtailment and the VBPS-surrogate rules, respectively.

There was not a statistically significant difference between the blanket curtailment and VBPS-surrogate rules (0.6%, 95% CL: (-33%, 50%)).

Table 2: Estimated ratios contrasting bat fatalities under different treatments. A ratio of 1 indicates no difference, while a ratio greater than 1 indicates that the treatment in the

numerator has more fatalities than the treatment in the denominator. Grey shading indicates statistical significance at the 5% level.

Contrast	Ratio estimate	Std. Err.	Lower 95% CL	Upper 95% CL	*p*-value
Control / Blanket curtailment	1.453	0.267	1.013	2.083	0.0421
Control / VBPS	1.461	0.275	1.011	2.112	0.0437
Blanket curtailment / VBPS	1.006	0.207	0.672	1.505	0.9785

Table 3: Reversal of contrasts in Table 2 and expressed as percentage reductions.

Contrast	% reduction	Lower 95% CL	Upper 95% CL
Blanket curtailment /Control	31.2%	1.3%	52.0%
VBPS/Control	31.6%	1.1%	52.7%
VBPS/Blanket curtailment	0.6%	-48.8%	33.6%

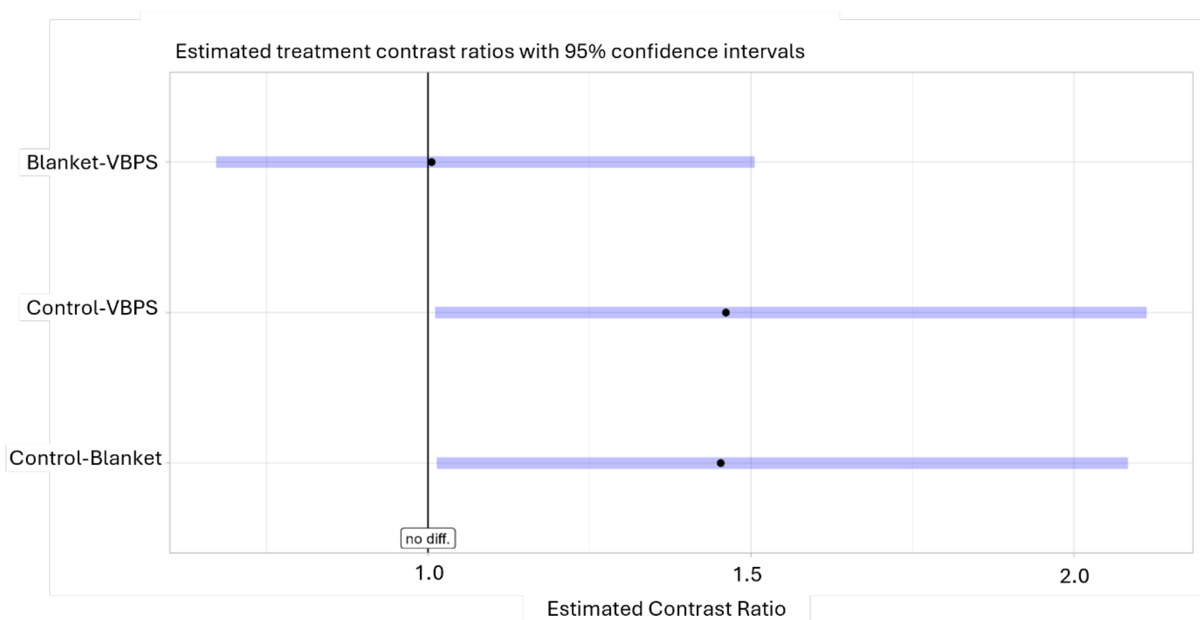


Figure 4: Estimated contrast ratios from Table 2 for fatalities under differing treatments (data from July 5-October 5 2023). Blue bars give 95% confidence intervals for the estimates. The

black dots are the mean estimated differences, and a ratio of 1.0 (solid vertical line) indicates there is no difference between the treatments being contrasted.

4.1.2 August-September alone

Here data from July and October are excluded for VBPS-surrogate rule treatments, as per section 3.2.3. The results in this section reflect treatment contrasts where the VBPS-surrogate rules were unambiguously applied as intended, i.e., excluding suspected and logged errors in the VBPS-surrogate rule implementation (July, October and 4 days in August).Treatment contrasts with 95% confidence limits for the estimates are presented in Figure 5 and Table 4.

There is a statistically significant difference between the VBPS-surrogate rules and the control, although no longer between blanket curtailment and the control. The VBPS-surrogate rules are estimated to have lower fatalities compared to the control sites, with the control fatalities being 57% higher (95% CL: (2.5%, 140%)). Blanket curtailment is not found to be significantly different from the control with this reduced set of data.

There remains no statistically significant difference in bat fatalities between blanket curtailment and the VBPS-surrogate rules (18.6%, 95% CL: (-28.0%, 48.2%)).

Table 4: estimated ratios contrasting bat fatalities under different treatments (excluding July and October data). A ratio of 1 indicates no difference, while a ratio greater than 1 indicates that the treatment in the numerator has more fatalities than the treatment in the denominator. Grey shading indicates statistical significance at the 5% level.

Contrast	Ratio estimate	Std. Err.	Lower 95% CL	Upper 95% CL	*p*-value
Control / Blanket curtailment	1.279	0.254	0.866	1.890	0.2156
Control / VBPS	1.571	0.342	1.025	2.408	0.0380
Blanket curtailment / VBPS	1.228	0.283	0.781	1.930	0.3731

Table 5: reversal of contrasts in Table and expressed as percentage reductions.

Contrast	% reduction	Lower 95% CL	Upper 95% CL
Blanket curtailment/Control	21.8%	-15.5%	47.1%
VBPS/Control	36.3%	2.4%	58.5%
VBPS/Blanket curtailment	18.6%	-28.0%	48.2%

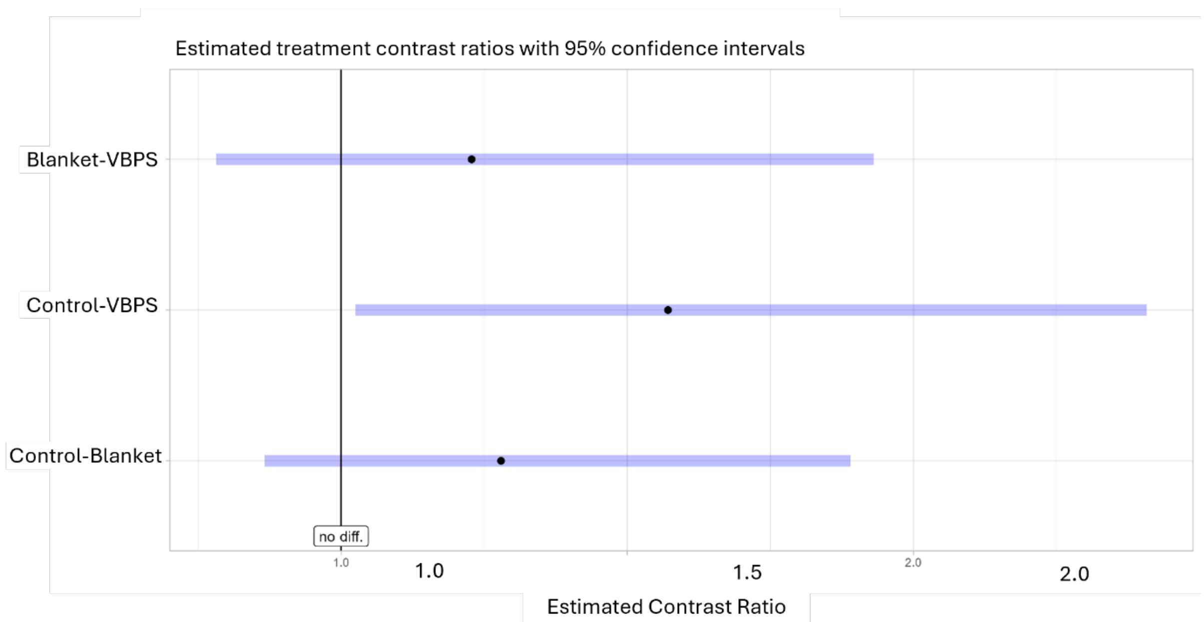


Figure 5: Estimated contrast ratios for fatalities under differing treatments (July and October excluded). Blue bars give 95% confidence intervals for the estimates. The black dots are the mean estimated differences, and a ratio of 1.0 (solid vertical line) indicates there is no difference between the treatments being contrasted..

4.1.3 Summary

Both curtailment systems were found to result in lower fatalities than the control system. On average, each is estimated to reduce fatalities by >30%, but there is substantial uncertainty, meaning the reductions may be as low as nearly 1% or >50%. There was no evidence of differences in fatalities between the VBPS-surrogate rules and blanket curtailment.

Uncertainties in the implementation of the VBPS-surrogate rules motivated two analyses, one for the full study period (July-October) and one for the abbreviated period in which the VBPS-surrogate rules were correctly applied (August-September). Both of which provided similar conclusions with regards to VBPS-surrogate fatalities – whose conclusions were broadly insensitive to these possible errors in the data.

The abbreviated period (August-September) is of primary interest in contrasting the VBPS-surrogate to the other treatments, due to doubts over the VBPS data outside this period. Comparisons between the blanket and control treatments were valid over the entire study period, so those whole-study contrast estimates take precedence.

Using the most reliable data with regards the implementation of the VBPS-surrogate rules (August and September):

1. There were significant reductions in fatalities comparing VBPS to control turbines. These were estimated to be 36% lower (95% CL: (2.4%, 59%)).
2. There was no significant difference observed between the blanket curtailment and the VBPS-surrogate rules in terms of fatalities.

Using the full set of data July-October for which the blanket curtailment and control treatment data are reliable, but where the VBPS-surrogate data is not:

1. There were significant reductions in fatalities comparing VBPS-surrogate rules to control sites. These were estimated to be 32% lower (95% CL: (1%, 53%)).
2. There were significant reductions in fatalities comparing blanket curtailment to control sites. These were estimated to be 31% lower (95% CL: (1%, 52%)).
3. There was no significant difference established between the blanket curtailment and the VBPS-surrogate rules in terms of fatalities.

4.2 Electrical power production

The study has dual objectives of minimizing bat fatalities and estimating the loss of electrical power generation from the curtailments applied. The electrical power generation under the three treatment regimens is contrasted here.

There are several complications that mean simple comparisons of observed electrical power generation under the treatments are insufficient. They are:

- The designed treatment schedule was not implemented as intended. In particular, the VBPS-surrogate rule treatment period was shorter than planned, not starting until 2022-07-05. Given the seasonal/daily dependency on wind-speed, comparisons should only be made at coincident time-points, so data prior to 2022-07-05 are not considered when looking at observed electrical power generation.
- Individual turbines have differing electrical power generation characteristics, i.e., for the same wind input, the electrical power outputs can differ. This has relevance when theoretical comparisons of electrical power generation are calculated.
- The VBPS-surrogate rules recommend curtailment before sunset in some cases, so there is some small amount of electrical power loss unaccounted for in observed electrical power production, as the current data only cover night times.
- The implementation of the VBPS-surrogate rules had marked issues. Incorrect rules were likely applied for July and October, and the logged *a priori* determination of the wind-direction for an evening bore little resemblance to what was observed. For example, the decision log indicates winds within the curtailment wedge were projected to be >50% on most evenings, while in reality, winds were very rarely observed in this region. No stoppages within July would have been required on the actual wind directions observed.

To mitigate against these issues, the treatment effects on electrical power generation are quantified here by:

- Comparisons based directly on observed electrical power generation and the recorded treatment in August and September.
- Modeling of individual turbine electrical power curves, to interpolate over treatment interruptions and reduce operational noise. This also allows estimates of electrical power loss over the entire curtailment season for all turbines.

4.2.1 Data

The data consists of the treatment schedule, the VBPS-surrogate implementation log, the wind-speed observed at turbines in real-time, and the fine-scale turbine operational data. The VBPS-surrogate treatment was delayed, being only applied from 2022-07-05, later than other treatments and different to the design schedule.

Note, the operational data only covers evenings, starting a small period before sunset to slightly beyond sunrise, encompassing any bat curtailment processes. Any comparisons between treatments must be interpreted in this context, e.g., an average 10% percentage loss in electrical power generation between control and treatment applies only to the nightly study times over July to October. In terms of full day or annual electrical power generation, these will be substantially smaller overall losses of electrical power compared to the control, given the bat curtailment only applies to approximately 1/3 of a day, for 1/3 of the year.

Simple summaries of the data suggest daily variability in windspeed dominates differences in treatments – the traces of average daily electrical power output vary markedly, but with relatively little difference between the three treatments within days. Electrical power production under the control is generally higher than the curtailment methods, where VBPS-surrogate rules tend to be lower than blanket curtailment, with some notable days of low production (Figure 3 to 7). The data is further summarized by month (Figure 7) to smooth over daily fluctuations, where the electrical power generation from curtailments is clearly lower than the control. The difference between the two curtailment methods is less distinct when the variability is considered – there is substantive overlap of the plotted ranges of standard errors. The estimated mean electrical power-loss is nonetheless greatest each month for the VBPS-surrogate rules.

Note, the turbines may have different software versions within the windfarm, which provides different electrical power outputs for given wind-speeds. While the treatments are rotated daily across these some of the variability between the treatments will be due to a different mix of turbine types for a given day. The randomized block design will average out the effects of this, and other, sources of turbine individuality over time.

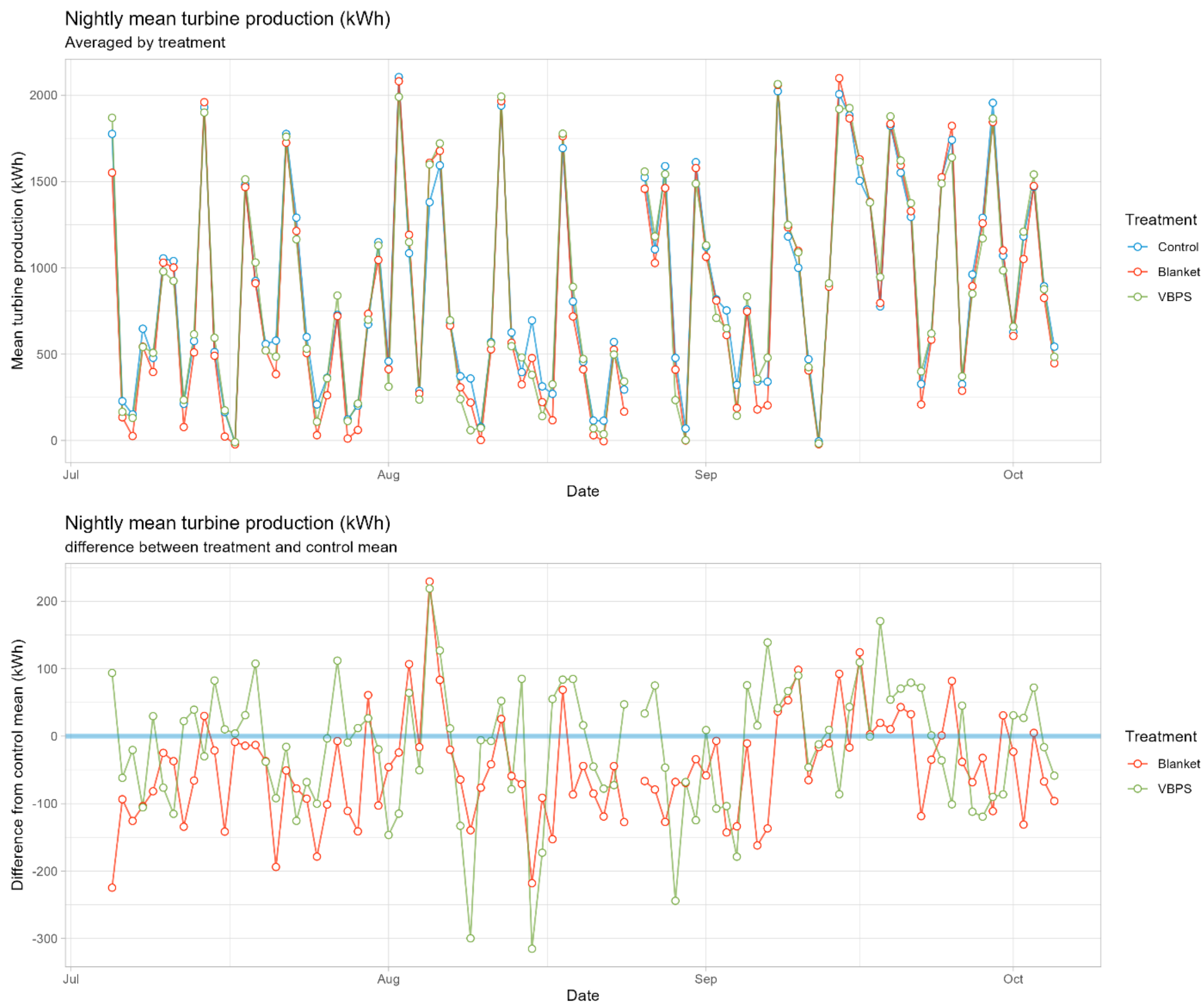


Figure 2: [top] daily mean observed electrical power production for turbines under differing treatments, estimated from 1-minute data, with offline data excluded. [bottom] daily mean observed differences in electrical power production between curtailment systems and the control. Similarly based on 1-minute observed electrical power production.

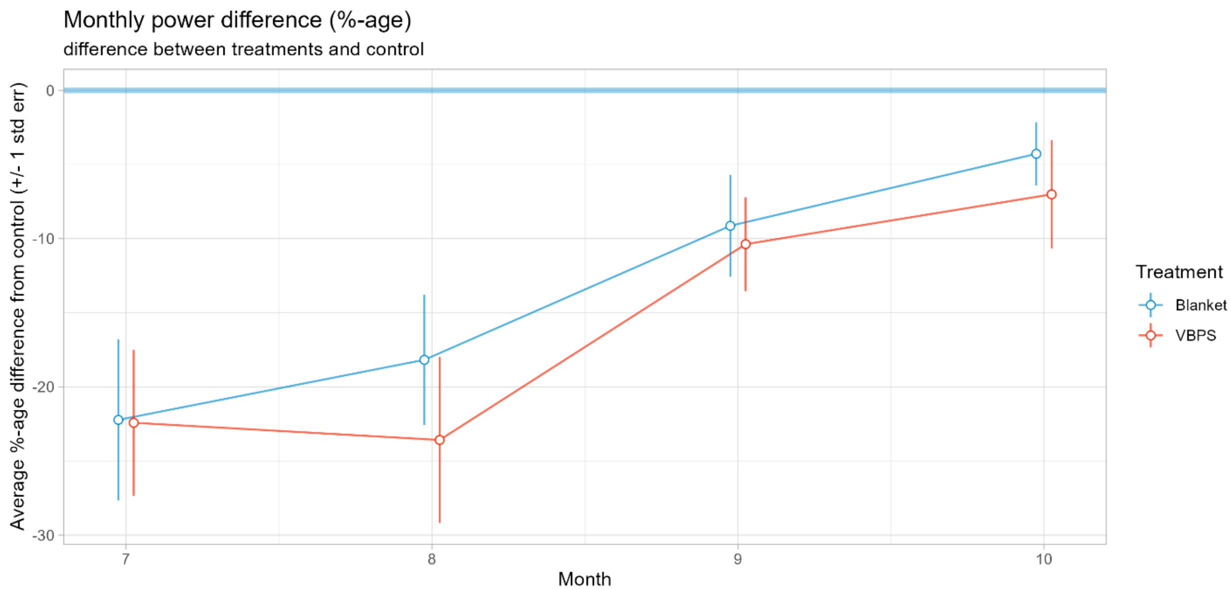


Figure 7: monthly percentage (%-age) differences in electrical power production between the control and curtailment methods, +/- 1 standard error. Refer section 4.2.3 for turbine-level modeling of electrical power generation that avoids incorrect implementation of the VBPS-surrogate rules.

4.2.2 Modeling of empirical electrical power production

Modeling here uses the data with the VBPS-surrogate rules treatment as recorded in the operational logs. However, as previously described, data for July and October deviate markedly from the expected VBPS-surrogate implementation, so do not form a basis for treatment comparison with the observed data. Results in Figure 8 and

Table 6 exclude these data.

There is significantly less electrical power produced under the curtailment methods compared to the control over this period. The control is estimated to produce 7.6% more electrical power than the VBPS-surrogate rules (95% CL (3.6%, 11.8%)) and 6.6% more than blanket curtailment at 5 m/s windspeed (95% CL (1.7%, 10.7%)).

There was no significant difference between the two curtailment systems, with the 95% confidence limit for the difference between blanket curtailment and the VBPS-surrogate rules indicating that the VBPS-surrogate rules could produce between 4.7% less and 2.9% more electrical power than blanket curtailment.

Table 6: estimated ratios contrasting observed electrical power production under different treatments. A ratio of 1 indicates no difference, while a ratio greater than 1 indicates that the treatment in the numerator has more electrical power production than the treatment in the denominator. Grey shading indicates statistical significance at the 5% level.

Contrast	Ratio estimate	Std. Err.	Lower 95% CL	Upper 95% CL	*p*-value
Control / VBPS	1.076	0.018	1.036	1.118	0.0000
Control / Blanket curtailment	1.066	0.017	1.027	1.107	0.0002
VBPS / Blanket curtailment	0.990	0.016	0.953	1.029	0.8296

Table 74: reversal of contrasts in table 6 and expressed as percentage decrease compared to the denominator term. Negative values indicate an increase.

Contrast	% decrease relative to denominator	Lower 95% CL	Upper 95% CL
VBPS/Control	7.1%	3.5%	10.6%
Blanket curtailment/Control	6.2%	2.6%	9.7%
VBPS/Blanket curtailment	-1.0%	-4.9%	2.8%

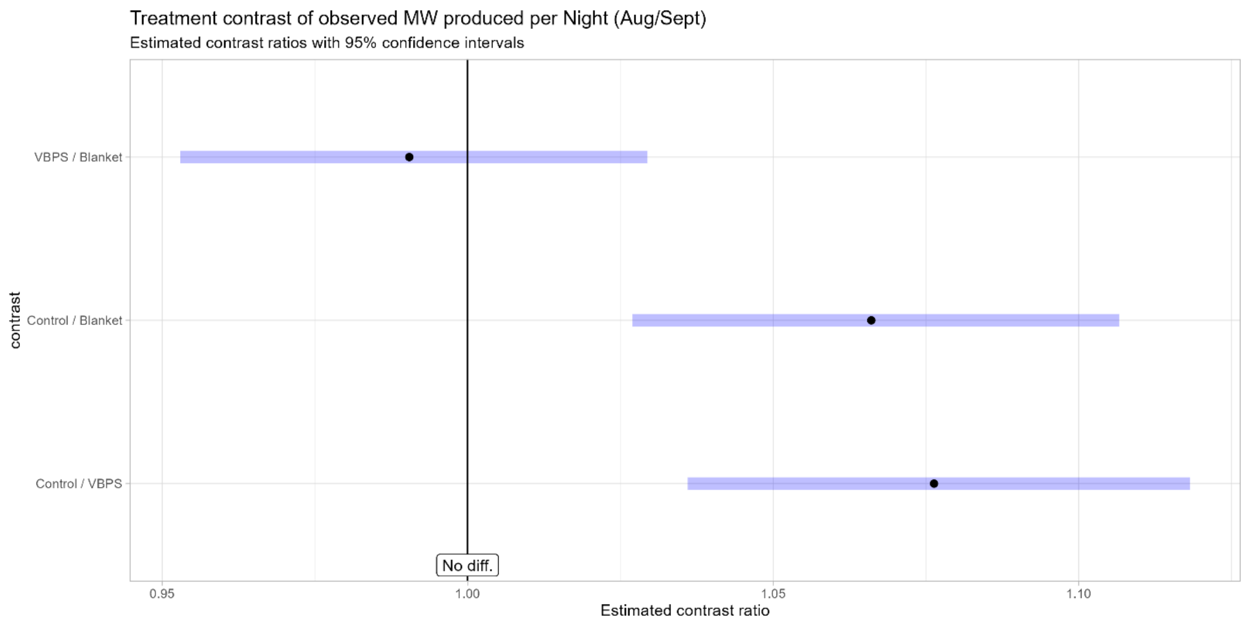


Figure 8: Estimated contrast ratios for observed electrical power production under differing treatments (August-September data). Blue bars give 95% confidence intervals for the estimates. The black dots are the mean estimated differences, and a ratio of 1.0 (solid vertical line) indicates there is no difference between the treatments being contrasted..

4.2.3 Modeling of individual turbines

Models were fitted to each of the 36 turbines to give their characteristic electrical power production curve. This allows simulation of the wind-farms output when curtailment rules for all treatments were applied as intended – as opposed to some instances of VBPS-surrogate rules not being applied as intended. The models were monotonic generalized additive models, where the observed electrical power output was modelled as a function of wind-speed (observed at turbines in real-time). The fine-scale detail of electrical power production for very low wind-speeds is not captured, where turbines may display negative electrical power production. However, this area of the curve is below the lower 3 m/s windspeed threshold where the control turbines fall into the “resource unavailable” category – so is considered irrelevant for the treatment comparisons here.

Example fitted power curves for two turbines are presented in Figure 9. All turbines are physically identical but can be operating with differing versions of control software. This leads to different electrical power generation for the same windspeeds. This is an additional source of error variance when comparing the electrical power generation under different treatments but completely accounted for here by modeling each turbine.

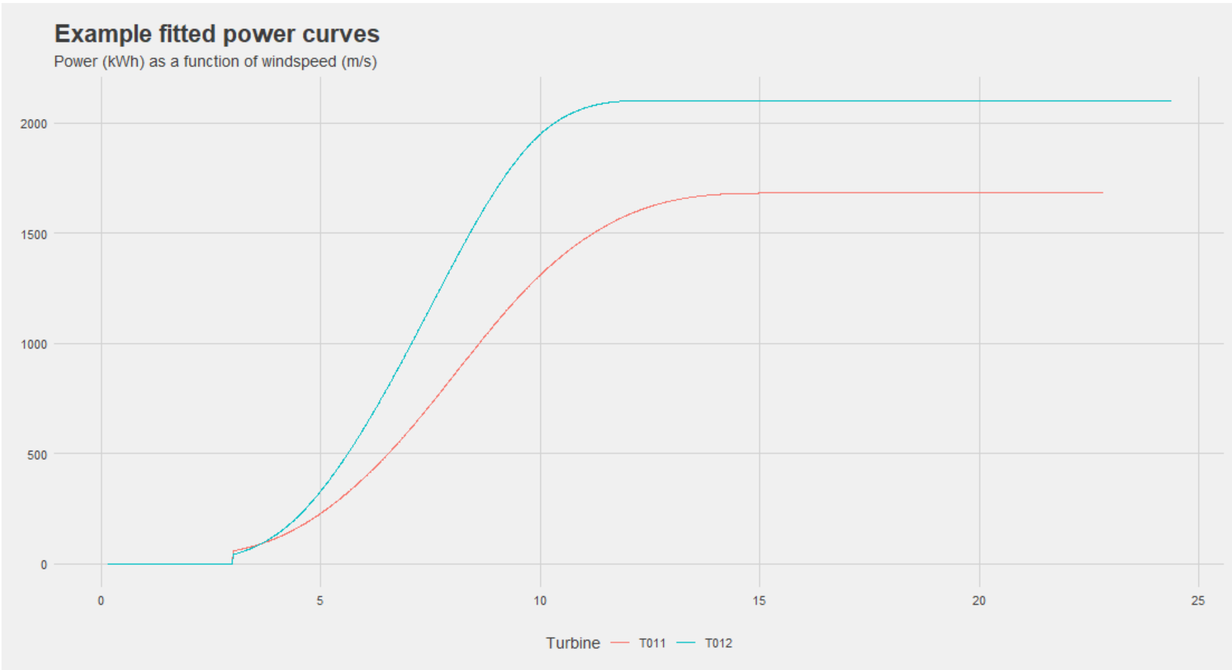


Figure 9: electrical power curves fitted to windspeed and electrical power production data for two turbines (T011 and T012). Models are based on monotonic splines. No turbine at the facility generates electrical power at speeds below 3 m/s, so this serves as a lower operational bound.

Under this approach, data from all 36 turbines can be used throughout the study period for all treatments. The only empirical input required is the windspeed and direction observed at each turbine, as well as times for the start and finish of night. This increases the statistical power markedly through increasing the data available and the removal of demonstrable noise – as well as correcting for suspected errors in the manual implementation of the VBPS-surrogate rules.

Figure 10 & Table 8 present results of modelled contrasts between treatments, based on turbine-level electrical power production models, with turbine-level observed windspeeds at 1-minute resolution. From these, both curtailment systems produce less electrical power than control, with the control producing 9.9% more electrical power than the VBPS-surrogate rules (95% CL: (8.4%, 11.4%)) and 6.8% more electrical power than blanket curtailment (95% CL: (5.4%, 8.2%)). The VBPS-surrogate rules are estimated to produce some 2.8% less electrical power than the blanket curtailment (95% CL: (1.5%, 4.1%)).

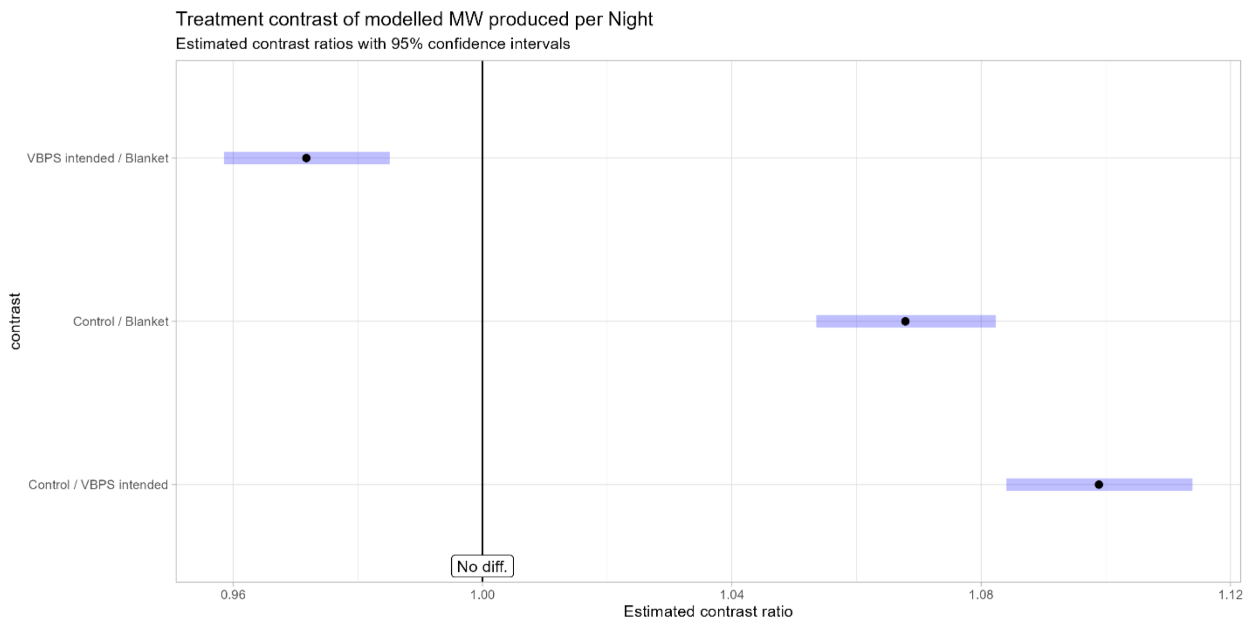


Figure 10: Estimated contrast ratios for modelled electrical power production under differing treatments (August-September data). Blue bars give 95% confidence intervals for the estimates. The black dots are the mean estimated differences, and the a ratio of 1.0 (solid vertical line) indicates there is no difference between the treatments being contrasted..

Table 8: estimated ratios contrasting modelled electrical power production under different treatments. A ratio of 1 indicates no difference, while a ratio greater than 1 indicates that the treatment in the numerator has more power production than the treatment in the denominator. Grey shading indicates statistical significance at the 5% level.

Contrast	Ratio estimate	Std. Err.	Lower 95% CL	Upper 95% CL	*p*-value
Control / VBPS intended	1.099	0.006	1.084	1.114	<0.0001
Control / Blanket curtailment	1.068	0.006	1.054	1.082	<0.0001
VBPS intended / Blanket curtailment	0.972	0.006	0.959	0.985	<0.0001

Table 9: inversion of contrasts in Table 8 and expressed as percentage decrease compared to the denominator term. Negative values indicate an increase.

Contrast	% decrease relative to denominator	Lower 95% CL	Upper 95% CL
VBPS intended/Control	9.0%	7.7%	10.2%
Blanket curtailment/Control	6.4%	5.1%	7.6%
VBPS intended/Blanket curtailment	-2.9%	-4.3%	-1.5%

4.3 Annual production loss estimates

The following section presents the annual production loss figures, following the method outlined in the EPRI report Fitchett & Nasery (2023). Detailed calculations for the figures below are presented in the analysis markdown document – linked here: **AEP loss calculations**. A summary of the approach is given below. Note, for comparability with the EPRI report, calculations are also provided for a hypothetical blanket curtailment below windspeeds of 6.9 m/s.

The calculation process consists of:

- Amendment or removal of abnormal data e.g. power production when below the purported cutoff windspeed; the turbine not producing power for extended periods of time despite favorable windspeeds; negative power production assumed to be zero.
- Any time a treatment turbine was curtailed, the mean production for the control turbines provides contrast for calculating power loss.
- The control turbines at these curtailment times provide estimates of production relative to their rating e.g. an output of 1.8MWh for a 2MWh turbine is 0.9. It is assumed this proportional level of power would have been produced at the treatment turbines if they were not curtailed.
- An average nightly loss is calculated across the treatment turbines. Subsequently summed over the study period, this gives the total average loss for a treatment turbine (see Lost production total, in MWh, Table 6).
- This is balanced against the estimated annual production of a control turbine to give a %-age loss for the year. This annual production is the estimated hourly average for a control turbine, summed over a year – noting the average is weighted to respect the 14-22 split of 2 to 2.2 kWh

turbines in the data. This was calculated to be 9938 MWh – meaning turbines operate on average at roughly 50-60% of their maximum rated output.

Table 5. Summary of Production based un-availabilities (%) for different bat curtailment strategies.

Contrast	Average Annual Power Loss
Control vs. VBPS-surrogate	0.75 %
Control vs. Blanket curtailment (5 m/s)	0.49 %
Control vs. Blanket curtailment (6.9 m/s)	2.25 %

Table 6. Details for production-based unavailability

Treatment	Lost production total	Production-based unavailability	Unavailability percentage (95% CL)
VBPS-surrogate	75 MWh	100 * 75/ 9938	0.75% (+/- 0.0097%)
Blanket Curtailment (5 m/s)	49 MWh	100 * 49/9938	0.49% (+/- 0.0073%)
Blanket Curtailment (6.9 m/s)	224 MWh	100 * 224/9938	2.25% (+/- 0.0279)

4.4 Summary

Looking solely at observed electrical power production over the August-September period where the VBPS-surrogate rules were in correct operation:

- The VBPS-surrogate rules are estimated to produce 7% less electrical power than the control (95% CL: (3.5%, 10.6%)).
- Blanket curtailment of 5 m/s windspeed is estimated to produce 6.2% less electrical power than the control (95% CL: (2.6%, 9.7%)).
- There was no evidence of significant differences between the VBPS-surrogate rules and blanket curtailment electrical power production.

Using turbine-level electrical power production curves (electrical power as a function of windspeed) and observed windspeeds, the following was found for the entire study period (July to October):

- The VBPS-surrogate rules are estimated to produce 9% less electrical power than the control (95% CL: (7.7%, 10.2%)).
- Blanket curtailment of 5 m/s windspeed is estimated to produce 6.4% less electrical power than the control (95% CL: (5.1%, 7.6%)).
- The VBPS-surrogate rules are estimated to produce 2.8% less electrical power than the blanket curtailment (95% CL: (1.5%, 4.1%)).

Based on Annual Energy Production (AEP) calculations, the annual loss for the different treatments compared to normally functioning[5] turbines were:

- 0.75% annual loss for VBPS, when operating over the study period (95% CL: (0.74%, 0.76%)).
- 0.49% annual loss for blanket curtailment for wind-speeds below 5 m/s in the study period (95% CL: (0.48%, 0.50%)).
- 2.25% annual loss for blanket curtailment at wind-speeds below 6.9 m/s in the study period (95% CL: (2.22%, 2.28%)).

5 Discussion

Bat fatalities at wind facilities occur around the world (e.g., Arnett et al. 2008, Baerwald et al. 2011, Camina 2012, Voight et al 2015, Aronson 2021, Bennett et al. 2022), and there is increasing concern regarding the impact these fatalities may have on population viability and species persistence (e.g., Kunz et al. 2007, Frick et al. 2017). Two broad approaches are employed to minimizing bat fatalities at wind facilities. The first approach attempts to limit bat interactions with wind turbines via acoustic deterrents (e.g., Romano et al. 2019, Weaver et al. 2020) or light-based deterrents (e.g., Cryan et al. 2022), avoiding bat mortality by excluding bats from the wind facility or the rotor swept area. The second approach, seeks to alter the wind facilities' operations to minimize bat fatalities rather than trying to modify bat behavior,. This is primarily done through curtailment, which is when turbine blades are temporally slowed or turned off during those periods when they may present the greatest risk to bats. There are two types of curtailment, blanket curtailment, when the ambient wind speed at which turbines begin to generate electricity is increased above the threshold at which energy generation is possible (e.g., Arnett et al. 2011, Arnett et al. 2013), and smart curtailment, which uses relevant variables (e.g., wind speed,

[5] No restrictions on operation other than stopping at wind-speeds < 3m/s

wind direction, temperature, etc.) to make automated decisions to curtail individual turbines when there is the highest estimated risk to bats (e.g., Hayes et al. 2019, Barré et al. 2023).

This study sought to investigate the utility of smart curtailment in reducing bat fatalities, balanced against the potential for decreased electrical power production. To achieve this aim, the experimental data for phase 2 of the VBPS project were analyzed statistically. Three treatments were contrasted: blanket curtailment at 5 m/s windspeed, a control "treatment" with no curtailment, and the VBPS-surrogate which is dynamic over time as a function of windspeed, direction and length of night. These were contrasted in terms of the daily bat fatalities assigned to each turbine, as well as their fine-scale (1-minute) electrical power production.

5.1 Fatality reduction

A synthesis of studies exploring the effectiveness of blanket curtailment found that mean fatality reductions ranged from 4.8-78% across a range of cut-in speeds, with the majority of studies finding at least a 50% reduction when the cut-in speed was increased by 1.5 m/s over the manufacturer's standard (Arnett et al. 2013). A more recent meta-analysis of operational minimization to reduce bat fatalities also found that, , the mean effect size was greater than 35.3% for all but one study included in their analysis (Whitby et al. 2021). Another recent meta-analysis estimated a decrease in bat fatalities of 63% at facilities implementing curtailment regimes with an increase in cut-in speed of 2 m/s of larger (Adams et al. 2021). The results of our analysis are within the range expected from these other studies, if on the lower end of fatality reductions, finding the VBPS-surrogate rules to have reduced bat fatalities by 36.3% (95% CL: (2.4%, 58.5%)). While there was not a statistically significant difference between blanket curtailment and the control when only considering the months of August and September (21.8%, 95% CL: (-15.5%, 47.1%)), this is likely due to a lack of statistical power given the truncated period in which the VBPS-surrogate rules were applied correctly. This is further evidenced by the fact that when the data from the entire 108-day study period was analyzed, providing greater statistical power to detect differences between treatments, blanket curtailment at 5 m/s (2 m/s above the manufacturer's standard) was found to have reduced bat fatalities by 31.2% (95% CL: (1.3%, 52.0%)). Neither analysis found a statistically significant difference between blanket curtailment and the VBPS-surrogate rules, indicating a similar level of effectiveness in reducing bat fatalities.

Although some treatment differences were statistically significant, precision was generally low, with the reduction in fatalities potentially ranging from a few percentage points to >50%. there are some areas within this design that would contribute to low statistical power, including limits on the number of turbines and days. More notably however, there was some potentially significant loss of data through VBPS-surrogate rule implementation issues, which meant that the VBPS-surrogate rule efficacy in reducing fatalities couldn't be reliably quantified for July and October. A large loss of precision stemmed from the determination of usable bat carcasses. The treatments are on daily rotation, so the aging of carcasses, and hence allocation of these to turbines/treatments must be accurate to this level. While 740 carcasses were recovered, we determined that only 224 were able to be allocated accurately by treatment, having an important effect on the statistical power of the analysis.

5.2 Electrical power loss within the study period

While both blanket and smart curtailment can be effective in reducing bat fatalities (e.g., Arnett et al. 2011, Arnett et al. 2013, Hayes et al. 2019), there is an associated loss of electrical power production. However, the loss in annual energy production is generally small, with five facilities across 11 operational minimization comparisons reporting annual losses ranging from 0.06% to 3.2% (Whitby et al. 2021). The highest annual loss in production, 3.2%, was reported from a smart curtailment system based on the acoustic detection of bats (Hayes et al. 2019) and is almost three times the next largest annualized percent lost electrical power (1.2%) (Whitby et al. 2021). This is particularly interesting, as one of the aims in developing smart curtailment systems is to have the same or greater reductions in bat fatalities as blanket curtailment, but with lower loss of electrical power production. While numerous models have demonstrated the potential for turbine specific curtailment algorithms to outperform blanket curtailment in terms of the reduction in bat fatalities and loss of electrical power (Behr et al. 2017, Hayes et al. 2019, Berré et al. 2023) there has been little testing of these algorithms in the field.

When considering the loss of electrical power production within the current study, uncertainties in the application of the VBPS-surrogate rules, and the associated reductions in statistical power, meant the contrasting of electrical power production under treatments was subject to two types of analysis: the observed electrical power production for each turbine under treatment in the months of August and September, and comparison from modelled electrical power outputs based solely on observed windspeeds and the operational rules of the treatments for the full study period (July-October).

Under both types of analysis, it was clear that curtailment systems reduce the electrical power output compared to controls. These analyses put the average total electrical power loss during the experimental periods due to curtailments as roughly 6-9%, although these may be as varied as approximately 3% to 11%. Based on the empirical data from August and September, there was no evidence of significant differences between the VBPS and blanket curtailment electrical power production (-1.0%, 95% CL: (-4.9%, 2.8%)). In contrast, when modeling the individual turbine power curves to interpolate over treatment interruptions and reduce operational noise, the VBPS-surrogate rules are anticipated to produce approximately 2%-4% less total electrical power on average than blanket curtailment for the July-October study period. Note this applies only to the experimental periods – approximately 1/3 of the year, and only nights, being roughly 1/3 of a daily turbine operation.

A full annual production loss estimation was conducted, based on methodology in Fitchett & Nasery (2023). This finds the production loss for a turbine operating VBPS, versus not, to be 0.75% per annum (95% CL: (0.74%, 0.76%)). In contrast, blanket curtailment at 5 m/s windspeed had an estimated production loss of 0.49% (95% CL: (0.48%, 0.50%)).

5.3 Comparison to VBPS phase 1 results

The VBPS-surrogate rules implemented within phase 2 was a distillation of results from the phase 1 modeling exercise of this study. Those models suggested that a set of curtailment rules that were dynamic over time and reactive to wind-direction, times of dawn/dusk, and windspeed, could reduce bat fatalities compared to blanket curtailment, whilst sacrificing less power production.

The operational rules determined in phase 1 were associated with reductions in fatalities of 10-20% and for electrical power reductions of 1-3% over the study months, when compared to blanket curtailment. The electrical power losses estimated in this experimental phase were consistent with those expectations.

There was not a significant difference in the fatalities between the VBPS-surrogate rules and blanket curtailment established here. The VBPS-surrogate rules versus blanket curtailment for August-September (when the VBPS-surrogate rules were correctly implemented) was from 28% lower to 48% higher fatality, with the VBPS-surrogate rules having a mean reduction of 19% in fatalities relative to blanket curtailment. In contrast, phase 1 rules for this period were selected to provide projected reductions of 22% and 17%. While the experimentally observed fatalities this year were similar to expectation, substantial uncertainty makes this inconclusive – the similarity might be a chance occurrence with markedly different outcomes for future operation.

5.4 Conclusions

The results of the phase 2 analysis found that a coarse approximation of the intended smart curtailment was as effective at reducing bat fatalities as blanket curtailment, with only a small additional reduction in electrical power loss. This serves as an indication for the potential of the actual implementation of the smart curtailment to further reduce bat fatalities at wind facilities, with no or little additional loss of electrical power production compared to blanket curtailment. When only considering the months of August and September, when the VBPS-surrogate rules were implemented correctly, this method of curtailment reduced bat fatalities by 36.3% (95% CL: (2.4%, 58.5%)), with a 7.1% (95% CL: (3.5%, 10.6%)) reduction in electrical power production compared to the control. The empirical data on electrical power production provided no evidence for additional loss of electrical power production compared to blanket curtailment (-1.0%, 95% CL: (-4.9%, 2.8%)), whose estimated bat fatalities were not statistically significantly different from the control (21.8%, 95% CL: (-15.5%, 47.1%)) or the VBPS-surrogate rules (18.6%, 95% CL: (18.6%, 48.2%)), during this time period.

While these results indicate the utility of the VBPS-surrogate rules, they do not serve as a full validation of their effectiveness. When using characteristic electrical power production curves to simulate the wind facility's electrical power production over the full study period (July-October), assuming curtailment rules for all treatments were applied as intended, the VBPS-surrogate rule resulted in 9% (95% CL: (7.7%, 10.2%)) less electrical power production than the control, a -2.9% (95% CL: (-4.3%, -1.5%)) reduction in electrical power production compared to blanket curtailment. However, the current study does not allow the assessment of whether the simulated potential additional loss of electrical power production is offset by a greater reduction in bat fatalities, since the VBPS-surrogate rules were not implemented correctly for July and October. Therefore, while the electrical power production simulation represents the potential cost of the VBPS-surrogate rules, there is no equivalent estimate of potential benefits.

A major limitation of this study was the software/hardware constraints that meant the Vestas system was unable to operate in real-time. This led to the development of the manually imputed VBPS-surrogate rules that are a rough approximation of the bat fatality risk model that was meant to be integrated into the SCADA system for Vestas turbines. Not only was this approximation coarse, but it was dependent on weather predictions instead of real-time data provided by sensors installed on the individual turbines. The manual implementation also provided greater opportunity for human error to affect the implementation of the smart-curtailment, as demonstrated by the VBPS-surrogate rules being incorrectly applied in July and October. The resulting abbreviated study period also led to a loss of statistical power, further exacerbated by the limited number of fresh bat carcasses observed at the study site, resulting in a lack of precision around the estimates of the treatment effects. Yet despite these limitations, the VBPS-surrogate rules still resulted in a statistically significant reduction of bat fatalities and electrical power production equivalent to that observed for blanket curtailment, warranting further exploration of the effectiveness of this approach to smart curtailment.

In addition to the automated, real-time implementation of the VBPS system, there are further refinements to the bat fatality risk model that, in time, could lead to further reductions in bat fatalities. The effectiveness of different deterrents can vary by species (e.g., Weaver et al. 2020), as can curtailment (e.g., Barré et al. 2023), especially for species such as the Brazilian free-tailed bat (*Tadarida brasiliensis*), which are known to fly at heights and wind speeds greater than those associated with many of the bat species most frequently killed at North American wind facilities (Arnett et al. 2013). Sample size limitations in this study meant that species-specific bat fatality risk models could not be developed in phase 1 and the species-specific relative effectiveness of the VBPS-surrogate rules for reducing fatalities in phase 2 could not be assessed. Furthermore, COVID-19 created difficulties in obtaining certain sensors during phase 1, so that data on some relevant environmental covariates, such as precipitation (e.g., Behr et al. 2017, Barré et al. 2023) and barometric pressure (e.g., Bender and Hartman 2015), could not be collected. Additional studies focused on specific species, as well as different habitat types and locations, along with continued environmental data collection, could address these current gaps, further improving the VBPS system over time.

Given the success of this study in demonstrating the effectiveness of the VBPS-surrogate rules in reducing bat fatalities, the next steps for future research should focus on validating the actual VBPS system once the software/hardware constraints that prevented its automated, real-time implementation have been resolved. This will provide a more accurate assessment of the system's ability to reduce bat fatalities and the associated reduction in electrical power production. Once this has been achieved, ideally with a multi-year study to capture any potential effects of annual variation in bat activity and weather conditions, it will be better possible to evaluate which of the further refinements to the VBPS system should be pursued.

6 References

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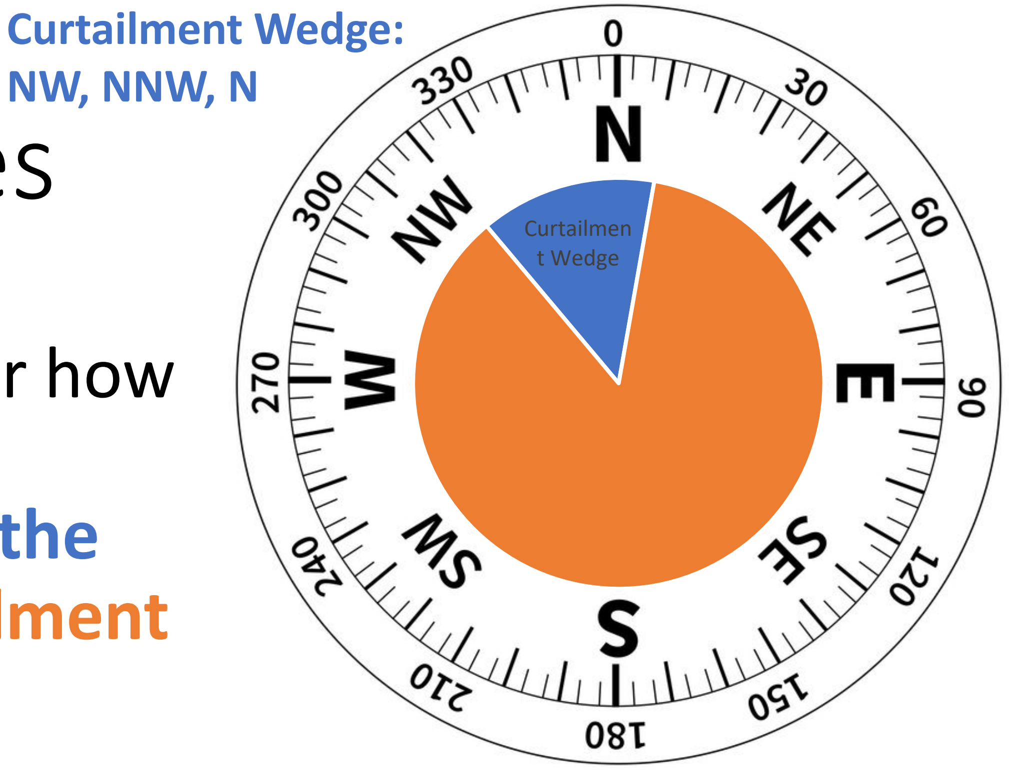
Attachment 3: VBPS Curtailment Guidelines

VBPS Curtailment Guidelines

- There are 9 turbines operating under VBPS software every night, though these turbines rotate nightly within the 36 study turbines.
- Curtailment Time Window: time relative to sunset/sunrise when curtailment may occur; changes monthly
- Windspeed Curtailment Threshold: Within the curtailment time window, VBPS turbines may be curtailed below a specified cut-in speed/threshold; changes monthly
- Wind Direction: VBPS implementation changes based on the forecasted wind direction each night. See the next two slides for details.

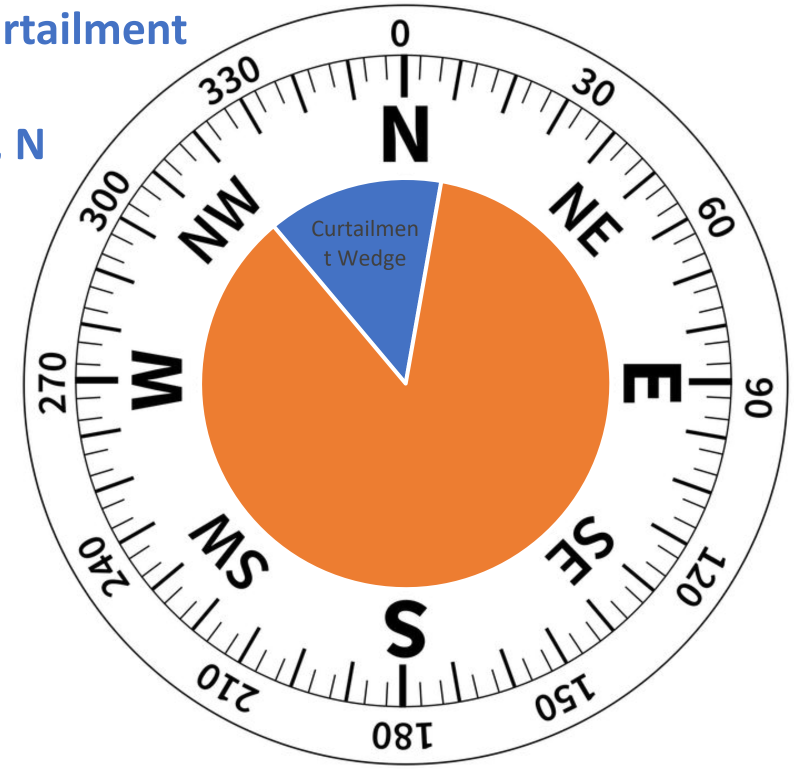
VBPS Curtailment Guidelines



- For each month, there are instructions for how to operate the VBPS turbines, based on whether the wind is coming from **within the curtailment wedge** or **outside the curtailment wedge** for the majority of the night.
- Potential Implementation instructions include:
  - **Increase cut in speed for that night to 10.0 mps**
  - Curtail VBPS turbines when wind speed is below the threshold (i.e. operate the VBPS curtailment schedule)
  - **DO NOT CURTAIL – VBPS Turbines generate power all night**

VBPS Curtailment Guidelines

Sample Curtailment Wedge: NW, NNW, N



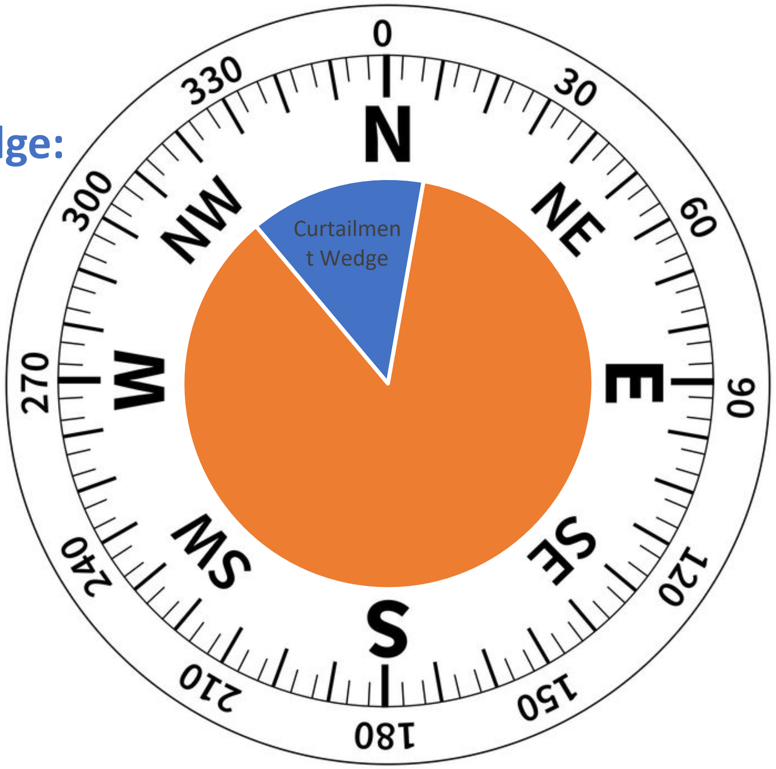
- Wind direction "Curtailment Wedge" range: Each month has a range of wind directions shown **in blue** where curtailment will increase.
- The curtailment wedge is also defined as a range of directions in the format of both degrees on a compass [e.g. 320 (NW)– 10 (N)], and a range of cardinal directions [e.g. NW, NNW, N]
- Every afternoon, a Vestas staff member will check the forecast for wind direction and determine whether the wind direction will come from **within the curtailment wedge**, or **outside the curtailment wedge** for >50% of the time during the Curtailment Time Window

Record Keeping

- Each afternoon, Vestas staff should record in the provided spreadsheet:
  - Wind Forecast:
    - The forecasted wind directions for the night
    - Whether the wind is forecast to come from **within the Curtailment Wedge**; or B. **Outside the Curtailment Wedge** for >50% of the night
  - Implementation: Based on the current month's instructions and whether the wind is forecast to come from **within** or **outside** of the curtailment wedge for >50% of the night, record which of the following options was implemented:
    - **Increase cut-in speed for that night to 10.0 mps**
    - Curtail VBPS turbines when wind speed is below the monthly threshold
    - **DO NOT CURTAIL – VBPS Turbines generate power all night**

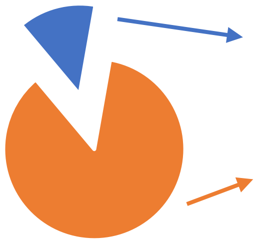
July

Curtailment Wedge: NW, NNW, N



- Curtailment Time Window:
  - Begin: 11 minutes before sunset
  - End: 73 minutes before sunrise
- Windspeed Curtailment Threshold: 5.3 mps
- Wind direction "Curtailment Wedge" range:

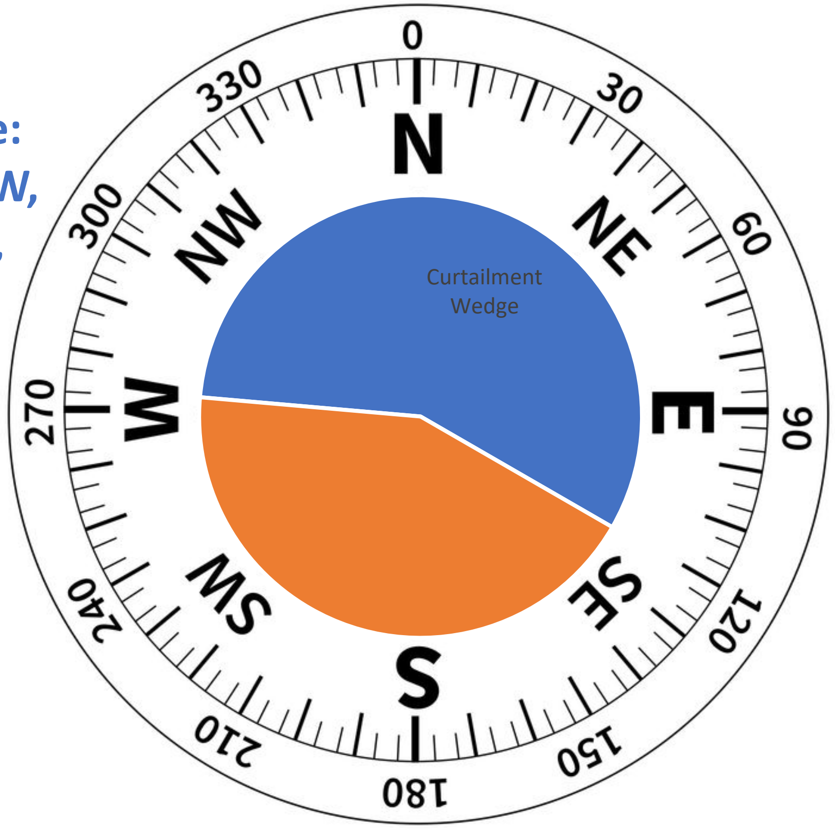
  320° (NW) – 10° (N)
- Implementation:



  - If wind direction is forecast to come from the **curtailment wedge** ≥50% of the night: **increase cut-in speed for that night to 10.0 mps**
  - If wind direction is forecast to come from **OUTSIDE the curtailment wedge** >50% of the night: Curtail VBPS turbines when wind speed is below the threshold

August

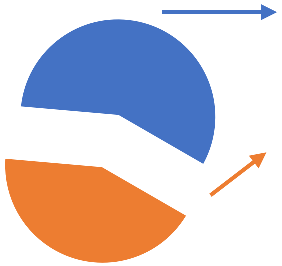
Curtailment Wedge: W, WWN, NW, NNW, N, NNE, NE, NEE, E, ESE



- Curtailment Time Window:
  - Begin: 20 minutes after sunset
  - End: 58 minutes before sunrise
- Windspeed Curtailment Threshold: 6.1 mps
- Wind direction “Curtailment Wedge” range:

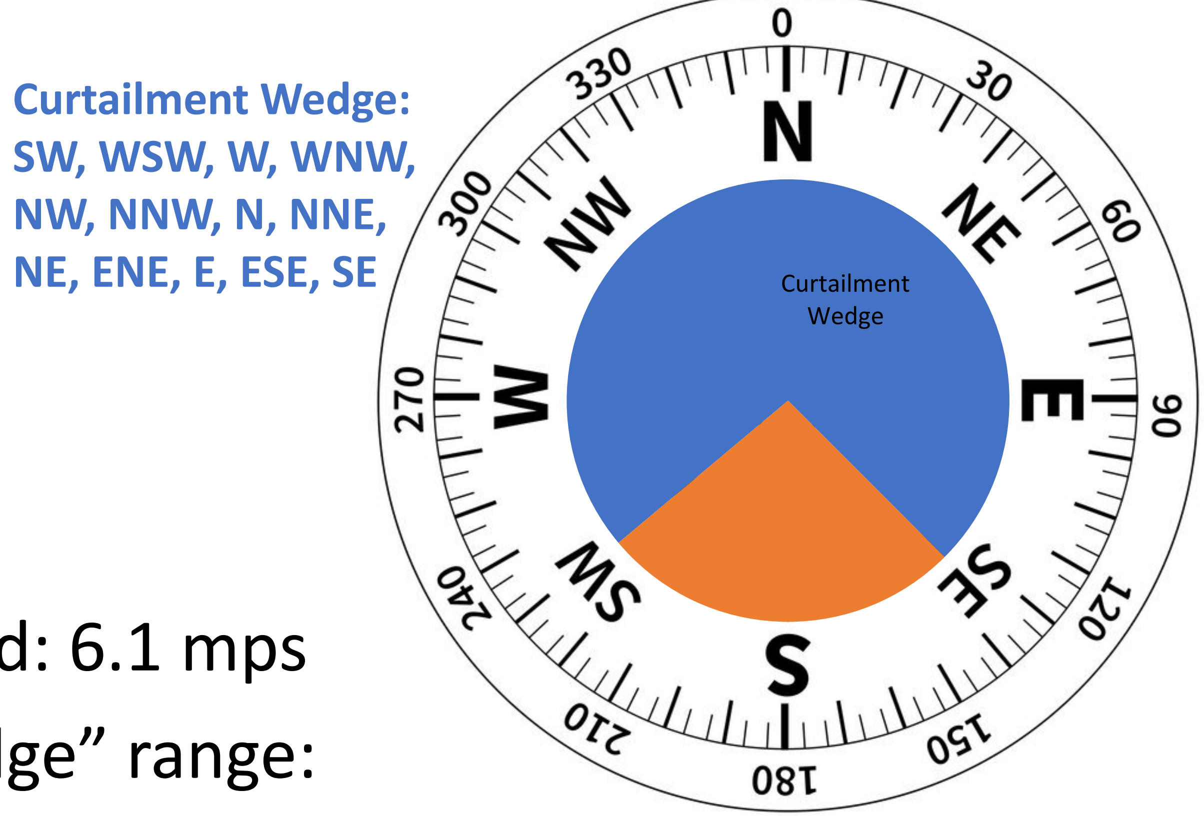
  275° (W) – 120° (ESE)

- Implementation:



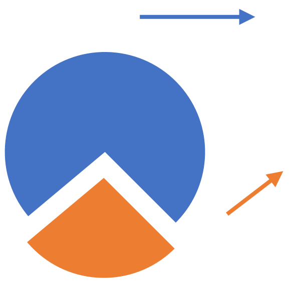
  - If wind direction is forecast to come from the **curtailment wedge** ≥50% of the night: curtail VBPS turbines when wind speed is below the threshold
  - If wind direction is forecast to come from **OUTSIDE the curtailment wedge** >50% of the night: **DO NOT CURTAIL – VBPS Turbines generate power all night**

September



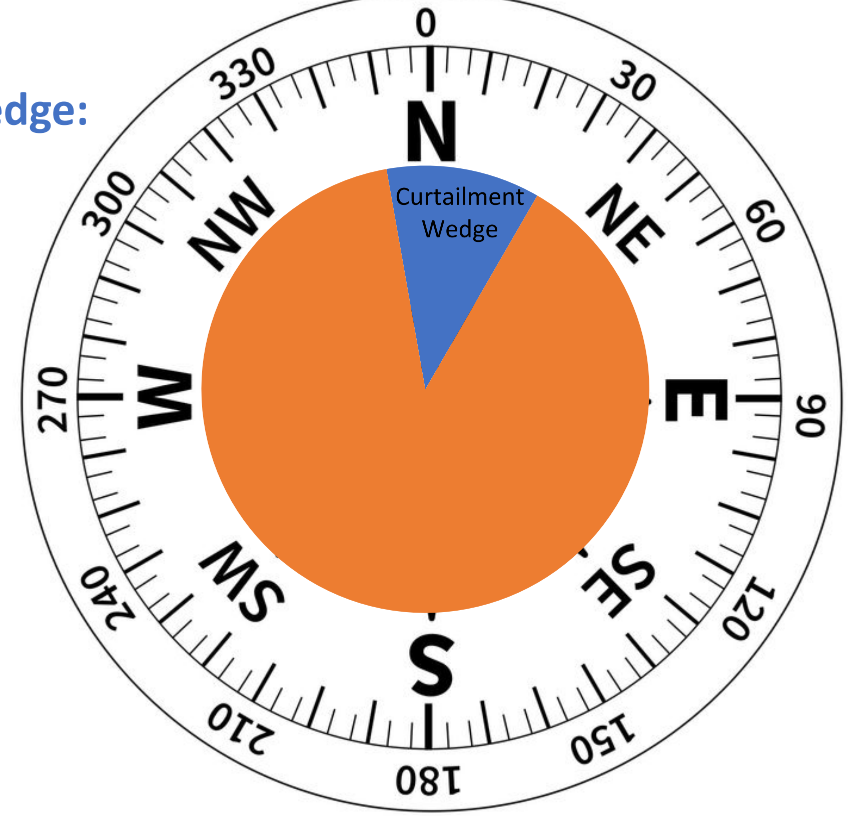
- Curtailment Time Window:
  - Begin: 21 minutes after sunset
  - End: 120 minutes before sunrise
- Windspeed Curtailment Threshold: 6.1 mps
- Wind direction "Curtailment Wedge" range:

  230° (SW) – 135° (SE)
- Implementation:



  - If wind direction is forecast to come from the **curtailment wedge** ≥50% of the night: curtail VBPS turbines when wind speed is below the threshold
  - If wind direction is forecast to come from **OUTSIDE the curtailment wedge** >50% of the night: **DO NOT CURTAIL – VBPS Turbines generate power all night**

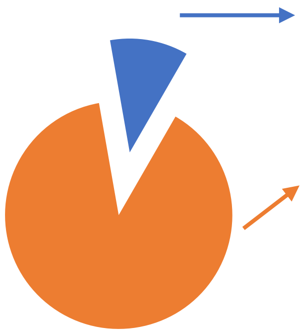
October



- Curtailment Time Window:
  - Begin: 23 minutes after sunset
  - End: 160 minutes before sunrise
- Windspeed Curtailment Threshold: 5.4 mps
- Wind direction "Curtailment Wedge" range:

  350° (N) – 30° (NE)

- Implementation:
  - If wind direction is forecast to come from the **curtailment wedge** ≥50% of the night: **increase cut-in speed for that night to 10.0 mps**
  - If wind direction is forecast to come from **OUTSIDE the curtailment wedge** >50% of the night: curtail VBPS turbines when wind speed is below the threshold



Attachment 4: Annual Energy Production Methodology

Evaluation of the Turbine Integrated Mortality Reduction (TIMR) Technology as a Smart Curtailment

Lost Power Production Analysis

1. Introduction

As part of DOE sponsored research, the goal of this analysis is to quantify wind turbine lost power production due to smart curtailment in general. The following describes how the analysis will be applied to TIMR (EPRI Award EE0008727). The production loss analysis proposed is for an experiment consisting of 18 wind turbines in three groups of six turbines per treatment. Attached as an Appendix is the Evaluation of the Turbine Integrated Mortality Reduction (TIMR) Technology as a Smart Curtailment Approach: Study Plan (February 2020). It provides an overview and rationale to the approach. The start of the study has been delayed because Covid-19 concerns. As a result, the study will likely be moved to adjacent wind farm and the tests could be done on different types of turbines. Regardless, study is designed to compare the following three treatments applied from official sunset to sunrise during each of two testing periods (summer and fall of Year 1 (126 days) and Year 2 (118 days)):

- **The TIMR system (TIMR).** During the testing periods, TIMR will shut down turbines when a threshold of $\geq$1 bat call(s) is recorded at nacelle height from any of four acoustic monitors and the wind speed is $\leq$6.9 m/s. For this study, this will be called *high risk*. Turbines will be curtailed for 30 minutes following those conditions being met. If the risk is still high during the final 10-minute increment of the initial 30 minutes shut-down (Note: not on a rolling time basis, but fixed 10-minute intervals), the shut-down will continue for an additional 10 minutes until the conditions are no longer high risk. Normal operation will resume once a risk condition changes from high risk.
- **Blanket curtailment (Blanket).** Turbines will remain shut down up to 5.0 m/s wind speed (instead of typical cut-in of 3.0 m/s) on a calendar and time-of-day schedule.
- **Control.** No change in turbine operation. Normal operation includes manufacturer's cut-in speed of about 3.0 m/s

2. Lost Power Production Analysis Data Needs

Table 1 provides a list of the types of data in ten-minute increments requested from the host company, MidAmerican Energy Company (MEC), for each study turbine and/or for the group of study turbines. The data request is for the overall study (e.g., biological as well as power production). Some of them are critical for the power production analysis described below but others will be used to build relationships between bat fatalities and treatments and to verify that the prescribed treatments/operational controls were implemented

Table 1: Host Company Data Requests

Description	Unit/Description	Biological Analysis	Techno-Economic Analysis
Timestamp (every 10min)	specify time zone, daylight savings time	R	R

Brandon Fitchett bfitchett@epri.com

Description	Unit/Description	Biological Analysis	Techno-Economic Analysis
Active Power (avg, max, min, stddev)	kW		R
Nacelle wind speed (primary anemometer) (avg, max, min, stddev)	m/s	R	R
Nacelle orientation (avg, max, min, stddev)	° (degrees)	R	D
Ambient Temperature	[C°]	R	R
Ambient Barometric Air Pressure	kPa	D	R
Rotor Speed (avg, max, min, stddev)	rpm	R	R
Blade Pitch Angle (avg, max, min, stddev)	° (degrees)	D	R
Wind Direction (avg, max, min, stddev)	° (degrees)	R	D
Generator Speed (avg, max, min, stddev)	rpm	R	R
Operating State (avg, max, min, stddev)	ENUM	R	R
Derate signal (avg, max, min, stddev)	If available as a separate tag	D	R
Bat Curtailment SCADA tag	Bat(s) Detected	R	R

R= Required for analysis, D=Desired for QA/QC purposes or as potential Covariate

3. Methods to Estimate Lost Production

The production loss methods, summarized in Table 2, follow closely with an IEC 61400-26-1 standard for production-based availability, but can be highly simplified to measure only losses due to bat-related curtailment. According to IEC [1] Annex E.1, two different philosophies are typical to determine potential energy production of a wind turbine when the turbine is not operating in “Full Performance” or, for purposes of this experiment, when a turbine is offline for bat-related curtailment:

- Methods based on windspeed and reference power curves. (W)
- Production based methods. (P)

During this study, we will focus on a production-based method (P2 in Table 2) that uses nearby control turbines as indicators of potential production for times that test turbines are offline due to bat-related curtailment. Since the energy production of neighboring turbines is used, there is no need for wind speed correction related to air density, pressure and temperature or power curves for look-up. This method is less sensitive to seasonality, wind turbine aging, deterioration and wake effects.

Table 2: Summary of IEC Recommended Methods for Assessing Production Loss

Method	Description	Accuracy
W1	Reference Power Curve and Nacelle Anemometer	Medium

Method	Description	Accuracy
W2	Reference Power Curve and average of nacelle anemometer windspeed from neighboring turbines	Medium
W3	Reference power curve and average of nacelle anemometer windspeed from all turbines	Medium
W4	Reference power curve and site meteorological mast wind speed	Low
W5	Reference power curve and external windspeed source	Low
P1	Average production of 'normally' operating neighboring turbines	High
P2	Average production of all other turbines 'normally' operating	High

Method W1: According to [1] Annex E.2.2 this method requires a site-specific power curve for every turbine at the windfarm. The wind turbine's nacelle anemometer windspeed will be used to look up power production values when the turbine will be unavailable.

Method W2: [1] Annex E.3.5 states that, the average nacelle anemometer wind speed readings of neighboring turbines or turbine with similar conditions to the test turbine can be used with site-specific power curve to extract power when the test turbine was unavailable. This method address the issue of the wind turbine offline nacelle anemometer bias which due to inaccurate windspeed readings may impact quantification of lost production. One drawback of the method is to group the neighboring turbines for each turbine. Since the set of curtailment experiment keep revolving this adds complexity to the analysis.

Method W3: According to [1] Annex E.3.5, the average windspeed of all the turbines of the wind turbine farm along with site-specific power curves is used to estimate lost production.

Method W4: Meteorological tower windspeed measurements with a correction factor along with site-specific OEM power curve is used to estimate lost production when the turbine is offline instead of wind turbine nacelle anemometer ([1] Annex E.2.4). The MET tower is not equi-distant from all turbines. Hence depending upon the distance and other site conditions a "correction factor" is applied to MET tower wind speed reading which better fits the turbine's conditions. The measured windspeed values and corelated windspeed values from MET can experience loss of accuracy because dynamic nature of wind.

Method W5: This method involves using an external windspeed source with reference power curve to determine lost production when the turbine was unavailable.

Method P1: This method involves using the average of production data of 'normally' operating neighboring turbines to account for lost production of an offline test turbines ([1] Annex E.3.3).

Method P2: Involves using average production of all normally operating turbines on the site. In this experiment, we will use as many as possible, but have chosen a minimum of six. The following will describe how method P2 would be applied. ([1] Annex E.3.2).

4. Chosen Methodology and Additional Data Q/A:

The chosen method for this project is P2, as it has been quantified as highly accurate and stable [2]. For simplicity, we are only considering lost production for the time period when the turbine was down due to bat-related curtailment. Other curtailment due to internal or external factors will be considered as normal operation for this experiment as the goal here is to quantify production lost due to bat-related curtailment. The bat activity should be able to be detected from a SCADA point/flag and can be used to flag a time period for lost production due to bats.

IEC Annex E.3.2 [1] assumes that other turbines in the same operational treatment will have equivalent production. The potential power production of the test turbine for that 10-min timestamp is the product of the nominal power of the proxy wind turbines in consideration and the average production factor of all the proxy wind turbines operating 'normally' within that timestamp. ([1] Annex E.3.2) Proxy turbine will only be considered if it is operating "normally" it will not be considered if the turbine is curtailed or unavailable.

$$Average\ Production\ Factor\ (Fave) = 1/n * \sum_{1}^{n} F(i) = 1/n * \sum_{1}^{n} (PpAve(i)/Pr(i))$$

Equation 1: Average Production Factor (Fave) [1] Annex E.3.2

Where,

F(i) = Production Factor of Wind Turbine i

Pr(i) = Rated Power of Wind Turbine i

PpAve(i) = Average produced power of Wind Turbine i

n = Number of turbines operating normally.

The lost power of the test turbine can be calculated in the following way.

$$Power\ Lost = (Fave) * Pr - Pa$$

Equation 2: Power Lost [1] Annex E.3.2

Where,

Pr = Rated Power of the test turbine

Pa = Actual Power of the test turbine

This method is suitable for windfarm with more than one wind turbine. No windspeed data or correction for site condition is required. Average across more turbines reduces sensitivity.

Some additional checks to method P2 to ensure it reaches accuracy and repeatability as measured in [2], as the IEC standard does not account for local variation in wind conditions or different production from the neighboring turbines. This relative production will, however, be checked. The 'normally' operating proxy turbines which are used to estimate lost production for the test turbine will be checked to see if they historically fall between +/- 5% production values of the test turbines. If not, the outlying turbines can be excluded from the analysis.

5% is a good threshold to check if the historic production of a proxy turbine aligns with the test turbine. The number can be increased/decreased depending upon the application. Minimum historic data would be 6 months.

To consider any control turbine to estimate lost production for test turbine following steps are followed.

- Historical data is filtered for time-period when both the turbines are available. All shutdown and curtailment events are filtered out.
- Sum the raw 10-min average power production values for both the test turbine and the proxy turbine.
- Divide the raw sum of 10-min average power values by 6 to get (MWh) values.
- Calculate eligibility ratio (z).

$$Eligiblity\ Ratio\ (z)(\%) = \frac{Turbine(Proxy)\ (MWh) - Turbine(Test)(MWh)}{Turbine(Test)\ (MWh)}$$

Equation 3: Eligibility Ratio (z)

If Eligibility Ratio (z) falls between +/- 5%, then that turbine can be used as a proxy to estimate lost production for test turbine.

4.1 - Data Analysis on 10-min interval data point

The timeseries data will be in 10-min frequency. Each test turbine will go through this process individually. Lost production is calculated for test turbines only when a test turbine is offline due to bat-related curtailment.

1. Using the bat curtailment SCADA tag (When Bat Activity Tag [max] = 1 or Bat curtailment Tag [avg] >0), count all data when the test turbine is completely or partially unavailable due to bats
2. If the bat curtailment SCADA tag is active, but there is some other overriding reason the turbine is down (E.g. Turbine-Specific Grid Curtailment or Component Fault/Alarm), that 10-min timestamp will not be accounted for lost production and can be filtered out
3. Considering all turbines at the site are of same OEM, model and rating, the lost production for every test turbine during bat curtailment event at each 10-min timestamp can be simplified as:

$$Lost\ Power(t) = P\_Proxy\_Avg(t) - P\_test(t)$$

Equation 4: Simplified Equation to Estimate Lost Power

Where,

P_Proxy_Avg = Average Power Production of all proxy group turbine at timestamp (t)

P_test = Actual Power Production of test turbine at timestamp (t)

Note: *P_test* will typically be negative, except when the bat curtailment tag was active for only a portion of the time-stamp. For sake of simplicity during this project, small negative values can be considered as zero.

4. The lost power (MW) 10-min values are summed and divided by 6 to convert to an energy (MW-h) value. That value will be the lost energy production due to bat curtailment ("Lost Production") for the period of the analysis/experiment.

5. If available, actual measured and averaged AEP for the proxy turbines will be used for the AEP estimate (denominator) of the production based un-availability equation (Equation 5) for each test turbine. This actual AEP will be averaged from SCADA power or energy data for at least one 12 month period that includes the test. If individual turbine AEP is not available, use the total site AEP and divide by the number of turbines at site. If insufficient production data exists, use long-term AEP estimates for each test turbine from the site assessment report for the denominator of the Production Based Un-availability equation.
6. Calculate production-based un-availability due to bat curtailment for the test turbine:

$$\textbf{Production Based Un} - \textbf{Availability} = \frac{\textbf{Lost Production (MWh)}}{\textbf{Actual AEP of an average turbine (MWh)}}$$

Equation 5: Production Based Un-Availability

4.2 - AEP Estimates for Production Based Un-Availability Equation

The host site is fairly new and hence not all seasonal variation will be captured in the historic SCADA data. **The pre-construction site assessment report** is likely the best option for long-term expected AEP values for each turbine and the site as a whole. Typically, such a report can provide the following information:

- AEP in a long-term average sense on a turbine-by-turbine level
- AEP expectations for the site
- Monthly full site production expectations
- Wind resource characteristics, Wind speed Weibull distribution, site air density, etc.

The turbine-by-turbine and site-level expected AEP allows for lost production % calculation at turbine level and site level. This Lost Production % is a critical project metric to publish and benchmark, while specific site MW-h production numbers can remain confidential if required. The site assessment report will also allow a comparison of the test months' actual site production with "average" expectations for those months and ensure we're not testing during an abnormal season and, if so, we could calibrate or caveat the results.

If the site assessment report cannot be made available, then two years of actual turbine and site production data may be used as an estimate for expected AEP in Equation 5.

If site production data is not available or biased in some way by abnormal operational or wind conditions during the collection period, NREL's Wind Toolkit and Wind Prospector can be used to estimate production of any host site given the site's location.

Estimating the site AEP within a few percent should be sufficient for the purposes of this study, as the gross site production is not as important as the lost production *percentage*, expected to be in the range of 0.5-3% of total site AEP.

Example: If lost production is measured as 2% of total AEP, and total AEP itself has an error of 5% (likely much less using any of the above methods), then the lost production percentage will have an error of 5% of 2%, or 0.1% of total site AEP.

4.3 - Potential Considerations While Analyzing 10-min Data

- If a proxy turbine historically falls within +/- 5% production of the test turbine and other proxy turbines using Equation (3), but it has 24+ consecutive hours of under-performance, it can be flagged to the site, investigated, and/or eliminated as a "proxy" turbine.
- Negative power values are typical for an offline wind turbine due to power consumption and will be considered as zero for simplicity.
- Turbines offline due to bats for less than 10 minutes during a 10-minute time stamp will be handled the same as any other offline for bats. They will likely have less average power produced during that 10-minute time-stamp.
- Verify that wind regime during study period is representative of prior years and long-term average projections from pre-construction estimates:
    - Wind speeds during study period resembles expectations for wind resource during the same time of year
    - Wind direction (wind rose) comparison during study period matches expectations for the months of the study
        - Verify wind direction does not linger in directions causing undue, long-sustained wakes on proxy turbines during bat-related shut-downs of test turbines

References:

[1] IEC, "Wind energy generation systems – Part 26-1: Availability for wind energy generation systems", IEC 61400-26-1:2019, Published May 2019.

[2] http://www.ewea.org/events/workshops/wp-content/uploads/Tech16a-PO-033.pdf

Appendix: Evaluation of the Turbine Integrated Mortality Reduction (TIMR) Technology as a Smart Curtailment Approach: Study Plan (February 2020)

- This is the study plan was written assuming the field season would start in 2020 but it has been delayed because of Covid-19 concerns.
- It will start in 2021 and likely at a site called Southern Hills adjacent to Orient which has been verbally described by Mid-American (MEC) as “another phase” of Orient.
- The overall site conditions are expected to the same.
- The type of turbines could be different but the design of the study will be the same.

Brandon Fitchett bfitchett@epri.com

Attachment 5: AEP Analysis Details

VBPS lost production analysis

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Overview

The following provides a fully transparent calculation of the lost power production estimates following the methodology outlined in the EPRI report for the DOE *"DRAFT: Evaluation of the Turbine Integrated Mortality Reduction (TIMR) Technology as a Smart Curtailment Approach Lost Power Analysis DE-EE0008727"* (*pers. comm.* C. Newman, document DOE TIMR_Lost Production Analysis_11-28-23_DRAFT.docx) - hereafter *Fitchett & Nasery (2024).*

Analysis is conducted on data provided by M. Whitby (Jan 2023), and relevant for this analysis consists of:

- `OperationsData_2022` (CSV and RDS) - various turbine-level data at one minute resolution. Of particular relevance here are the time-stamps, power outputs and wind-speeds. Power outputs and windspeeds are provided both on minute scale, and as a rolling 10-minute average, which is in keeping with the temporal resolution that turbine operating decisions are made. This data is restricted to night-time hours and the study period.
- `TreatmentAssignment2022.csv` - the pre-defined treatment schedule over the study period. Nightly allocations of the four treatment groups. The treatments are:
    - Control: normal operations where operation is curtailed with wind-speeds <3m/s (based on 10-minute averages)
    - TIMR: treatment relating to another smart curtailment system, not considered here.
    - VBPS: the Vestas Bat Protection System, which is a set of rules based on phase 1 analysis, where curtailment is a monthly-varying function of time relative to sunrise/sunset, wind-direction and wind-speed.
    - Blanket curtailment: the usual curtailment speed of the control turbines has been increased to 5m/s

Supplementing this in order to determine the operational status of turbines under the VBPS system, the following are used/required:

- Operational rules as outlined in the VBPS report *"Experimental evaluation VPBS project Project Title: Developing and Evaluating a Smart Curtailment Strategy Integrated with a Wind Turbine Manufacturer Platform Award Number: DE-EE0008729.0000"* (July 7, 2023).

EPRI power loss calculations

The approach in the EPRI report by Fitchett & Nasery (2024) is emulated here. This is principally based on the textual description within their report, example calculations therein, and some personal communication. Their code has not been seen, nor is the data identical. There is not complete agreement between analysis here and equivalent figures published within the EPRI report, which is understandable for multiple reasons - not least of which, the data here is 1-minute resolution vs 10-minute for the EPRI analysis. The final section of this document addresses this.

In the first instance, the data needs treatment to remove potential errors and uninformative observations e.g. where turbines were not operating correctly:

(*pers. comm.* P. Nasery 21/11/23)

For TIMR turbines,

i. For each night, data for each turbine (each case) was filtered for "curtail" state and the maximum power was listed in each case. The cases for which the maximum power was >200 kW, the timeseries of power was checked. If more than 50 % of data shows turbine not curtailed during the "curtail" command, then that case is considered faulty and is eliminated.
ii. For each case, the turbine was filtered for states other than "curtail" and the maximum power was listed in each case. The cases for which the maximum power was < 200 kW, the power curves were checked. If more than 50 % of data shows turbine curtailed during the non-curtail commands, then that case is considered faulty and is eliminated.

> ⓘ NB
>
> The threshold adopted here for irregular output is 200kW - it should be less than this if purportedly off, or greater than this if operating.

Data preparation

There has been extensive analysis of the data for the VPBS reports, with considerable cleaning and manipulation required for its modelling. For comparability with the EPRI approach, analysis here progresses from the initial data provided, which has had no alterations from the VPBS project team.

```
# original operation data provided from M. Whitby
powerData <- readRDS(here::here("data/VBPS_share/OperationsData_2022.rds"))
```

```
# add preplanned treatment schedule
treatmentTable <-
read_csv(here::here("data/VBPS_share/TreatmentAssignment2022.csv")) %>%
  mutate(BatNight_DT = mdy(Date),
         Treatment = ifelse(Treatment == "Curtail_5.0", "Curtail 5 m/s",
Treatment),
         Treatment = ifelse(Treatment == "NormalOps", "Control", Treatment),
         ) %>%
  select(-StudyDay, -Date)

Rows: 4572 Columns: 4
── Column specification
────────────────────────────────────────────────────────
Delimiter: ","
chr (4): StudyDay, Date, Turbine, Treatment

ℹ Use `spec()` to retrieve the full column specification for this data.
ℹ Specify the column types or set `show_col_types = FALSE` to quiet this
message.

# different turbine versions from the EPRI report
turbineVersion <- readRDS(here::here("data/TurbineVersionTable.rds"))

# restrict to relevant fields - note using the 10-minute average data "TM XX"
being Ten Minute
# remove TIMR data and lower bound power to 0 as per EPRI
workingPower <- powerData %>%
  left_join(treatmentTable, by = c("BatNight_DT", "Turbine")) %>%
  left_join(turbineVersion) %>%
  filter(Treatment != "TIMR") %>%
  select(-`TM Active Power`) %>%
  rename(`TM Active Power` = `Active Power`) %>%
  select(Turbine, Version, Status, dt_local, `TM Windspeed Average`, `TM
Active Power`, Treatment, BatNight_DT) %>%
  mutate(`TM Active Power` = ifelse(`TM Active Power` < 0 , 0, `TM Active
Power`)) %>%
  na.omit()

Joining with `by = join_by(Turbine)`
```

VBPS curtail information

Note this is calculated and quite complex, so use previously constructed data for the time-flags for VBPS operation (from VBPS report analysis). The only data used is the VBPS on/off variable, which is merged by time and turbine. Apply the EPRI filters with regards data validity: respecting the 3m/s cutoff and where the turbine appears to be functioning for at least 50% of the night.

```
VBPSDataFlag <- readRDS(here::here("data/powerModellingData.rds"))
```

```r
VBPSDataFlag <- VBPSDataFlag %>%
  filter(Treatment == "VBPS") %>%
  select(Turbine, dt_local, calcVBPSCurtail)

VBPSData <- workingPower %>%
  filter(Treatment == "VBPS") %>%
  left_join(VBPSDataFlag) %>%
   mutate(Error = if_else(`TM Windspeed Average` <= 3 & `TM Active Power` >
200, T, F)) %>%
  na.omit()
```

```
Joining with `by = join_by(Turbine, dt_local)`
```

```r
VBPSData %>%
  group_by(Turbine, BatNight_DT) %>%
  summarise(propError = sum(Error)/n()) %>%
  filter(propError > 0.5)
```

```
`summarise()` has grouped output by 'Turbine'. You can override using the
`.groups` argument.
```

```
# A tibble: 0 × 3
# Groups:   Turbine [0]
# ℹ 3 variables: Turbine <chr>, BatNight_DT <date>, propError <dbl>
```

Blanket curtailment

From the Fitchett & Nasery (2024) description:

> For blanket curtailment turbines,
>
> i. Data for each turbine (each case) was filtered for wind speed < = 5 and the maximum power was listed in each case. The cases for which the maximum power was >200 kW, the timeseries of power was checked. If more than 50 % of data (wind speed <= 5) shows turbine not curtailed, then that case is considered faulty and is eliminated.
> ii. For each case, the turbine was filtered for wind speed > 5 and the maximum power was listed in each case. The cases for which the maximum power was < 200 kW, the power curves were checked. If more than 50 % of data shows turbine curtailed during wind speeds beyond 5 m/s, then that case is considered faulty and is eliminated.

Examination of data shows it is common to have low wind-speeds but the power be > 200 kW

```r
workingPower %>%
  filter(Treatment == "Curtail 5 m/s" & `TM Windspeed Average` <= 5) %>%
  group_by(Turbine, BatNight_DT) %>%
  summarise(maxPower = max(`TM Active Power`)) %>%
  filter(maxPower > 200) %>%
  nrow()
```

```
`summarise()` has grouped output by 'Turbine'. You can override using the
`.groups` argument.

[1] 557

blanketData <- workingPower %>%
  filter(Treatment == "Curtail 5 m/s" ) %>%
  mutate(Error = if_else(`TM Windspeed Average` <= 5 & `TM Active Power` >
200, T, F),
         Error = if_else(`TM Windspeed Average` > 5 & `TM Active Power` <
200, T, Error))


blanketData %>%
  group_by(Turbine, BatNight_DT) %>%
  summarise(propError = sum(Error)/n()) %>%
  filter(propError > 0.5)

`summarise()` has grouped output by 'Turbine'. You can override using the
`.groups` argument.

# A tibble: 23 × 3
# Groups:   Turbine [12]
   Turbine BatNight_DT propError
   <chr>   <date>          <dbl>
 1 T013    2022-09-25      0.788
 2 T015    2022-07-31      0.982
 3 T015    2022-08-27      0.844
 4 T015    2022-08-28      0.922
 5 T020    2022-06-28      1
 6 T020    2022-08-29      0.619
 7 T020    2022-08-31      1
 8 T020    2022-09-10      1
 9 T020    2022-09-11      0.692
10 T035    2022-09-10      1
# ℹ 13 more rows
```

Normal operations (control)

From the Fitchett & Nasery (2024) description:

> For normal operation turbines,

i. Data for each turbine (each case) was taken and the maximum power was listed in each case. The cases for which the maximum power was < 200 kW, the power curves were checked. This helped in identifying turbine offline for the entire night (even if wind speeds are beyond cut-in). Those cases were considered faulty and were eliminated.

From the site, it was known that some turbines were offline for several nights. The data for each night is taken for these turbines and power curves are studied, in order to find out and eliminate those cases.

We observe here that there are several instances where the turbines appear to be non-functioning.

```
workingPower %>%
  filter(Treatment == "Control" & `TM Windspeed Average` <= 3) %>%
  group_by(Turbine, BatNight_DT) %>%
  summarise(maxPower = max(`TM Active Power`)) %>%
  filter(maxPower > 200) %>%
  nrow()
```

```
`summarise()` has grouped output by 'Turbine'. You can override using the
`.groups` argument.

[1] 68
```

```
workingPower %>%
  filter(Treatment == "Control" & `TM Windspeed Average` > 3) %>%
  group_by(Turbine, BatNight_DT) %>%
  summarise(maxPower = max(`TM Active Power`)) %>%
  filter(maxPower < 200)
```

```
`summarise()` has grouped output by 'Turbine'. You can override using the
`.groups` argument.

# A tibble: 30 × 3
# Groups:   Turbine [18]
   Turbine BatNight_DT maxPower
   <chr>   <date>         <dbl>
 1 T010    2022-06-21         0
 2 T013    2022-07-08         0
 3 T013    2022-07-17       100
 4 T013    2022-09-12         0
 5 T013    2022-09-29         0
 6 T014    2022-07-17        51
 7 T014    2022-08-04        76
 8 T015    2022-09-12       164
 9 T020    2022-08-23         0
10 T020    2022-09-01         0
# ℹ 20 more rows
```

```
controlData <- workingPower %>%
  filter(Treatment == "Control" ) %>%
  mutate(Error = if_else(`TM Windspeed Average` <= 3 & `TM Active Power` >
200, T, F),
         Error = if_else(`TM Windspeed Average` > 3 & `TM Active Power` <
200, T, Error))
```

```
controlData %>%
  group_by(Turbine, BatNight_DT) %>%
  summarise(propError = sum(Error)/n()) %>%
  filter(propError > 0.5)

`summarise()` has grouped output by 'Turbine'. You can override using the
`.groups` argument.

# A tibble: 69 × 3
# Groups:   Turbine [28]
   Turbine BatNight_DT propError
   <chr>   <date>          <dbl>
 1 T010    2022-06-21      0.979
 2 T010    2022-07-16      0.531
 3 T010    2022-08-22      0.785
 4 T013    2022-07-08      1
 5 T013    2022-08-21      0.562
 6 T013    2022-09-29      1
 7 T014    2022-07-06      0.545
 8 T014    2022-07-25      0.640
 9 T014    2022-08-04      1
10 T014    2022-08-16      0.514
# ℹ 59 more rows
```

Generate cleaned data

The suspect data as defined in Fitchett & Nasery (2024) is removed, and further modifications made. First the removal of a night's data where the turbine's functioning was suspect for >50% of the time.

```
cleanData <- controlData %>%
  bind_rows(blanketData, VBPSData) %>%
  mutate(calcVBPSCurtail = if_else(is.na(calcVBPSCurtail), F,
calcVBPSCurtail))



keepTurbNights <- cleanData %>%
  group_by(Turbine, BatNight_DT) %>%
  summarise(propError = sum(Error)/n()) %>%
  filter(propError < 0.5)

`summarise()` has grouped output by 'Turbine'. You can override using the
`.groups` argument.

cleanData <- cleanData %>%
  right_join(keepTurbNights) %>%
  arrange(Turbine, dt_local) %>%
  filter(!Error)

Joining with `by = join_by(Turbine, BatNight_DT)`
```

As per Fitchett & Nasery (2024), we remove times where turbines are idle from low wind:

6. Eliminate those timestamps where at least one turbine experiences wind speed below cut-in speed

```
timeRetain <- cleanData %>%
  filter(`TM Windspeed Average` > 3) %>%
  select(Turbine, dt_local)

cleanData <- cleanData %>%
  right_join(timeRetain)

Joining with `by = join_by(Turbine, dt_local)`
```

Data imputation

Fitchett & Nasery (2024) allude to data imputation.

7. Replace zeros with NaN or missing values and backfill these missing values with values from neighboring turbines

> ⓘ Imputation
>
> Data interpolation for the EPRI report was using the python functiondataframe.ffill(axis=1) (*pers. comm.* Nasery 2024). This interpolates across rows, collecting the left value. The supposition is they have a time-by-turbine matrix of power productions. Ordering of the columns is likely alphabetical, could (ought to) be blocked by turbine version.

An equivalent is the `fill` function in the tidyverse - with ordering by turbine within turbine-type. This was experimented with several logical permutations, all of which gave data that diverged markedly from the figures in the EPRI report. There are extensive potential issues with data imputation, the definition of "neighboring" is sufficiently vague that the imputations were not implemented here.

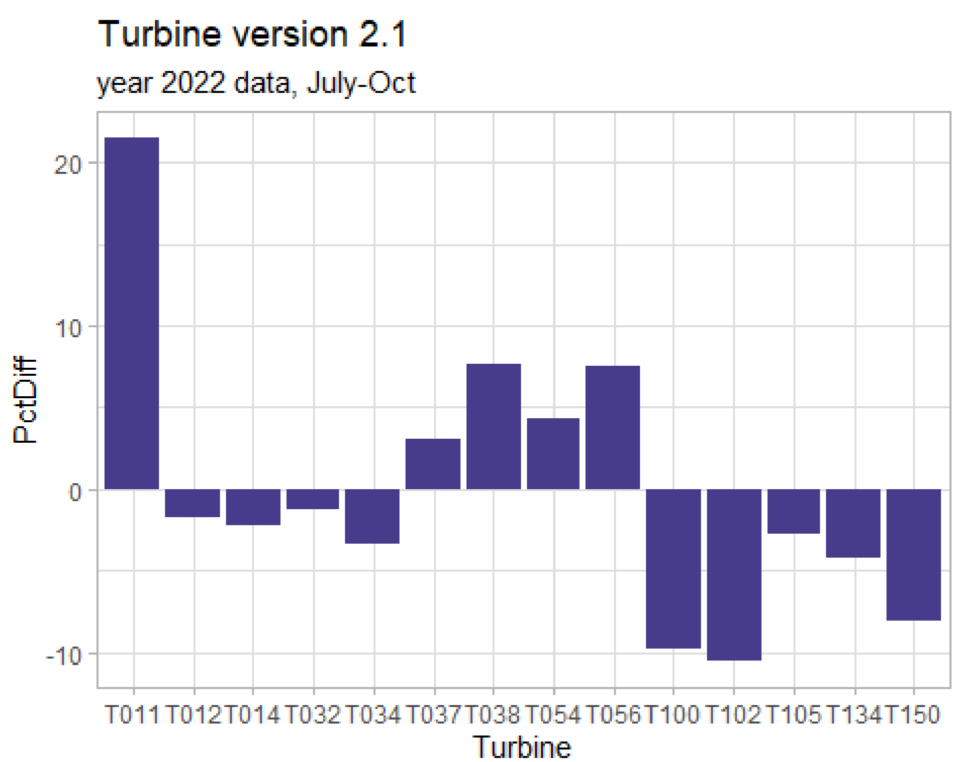
```
# imputation not done - the most logical from the description and
dataframe.ffill would be:
cleanData <- cleanData %>%
  arrange(Version, Turbine, BatNight_DT) %>%
  mutate(
    `TM Active Power` = ifelse(`TM Active Power` == 0, NA, `TM Active
Power`)) %>%
  group_by(Version, dt_local) %>%
    fill(`TM Active Power`, .direction = "down")
```

Exploratory plots

Plots mirroring that of EPRI report. Firstly for the 2MWh turbines ("Version 2.1")

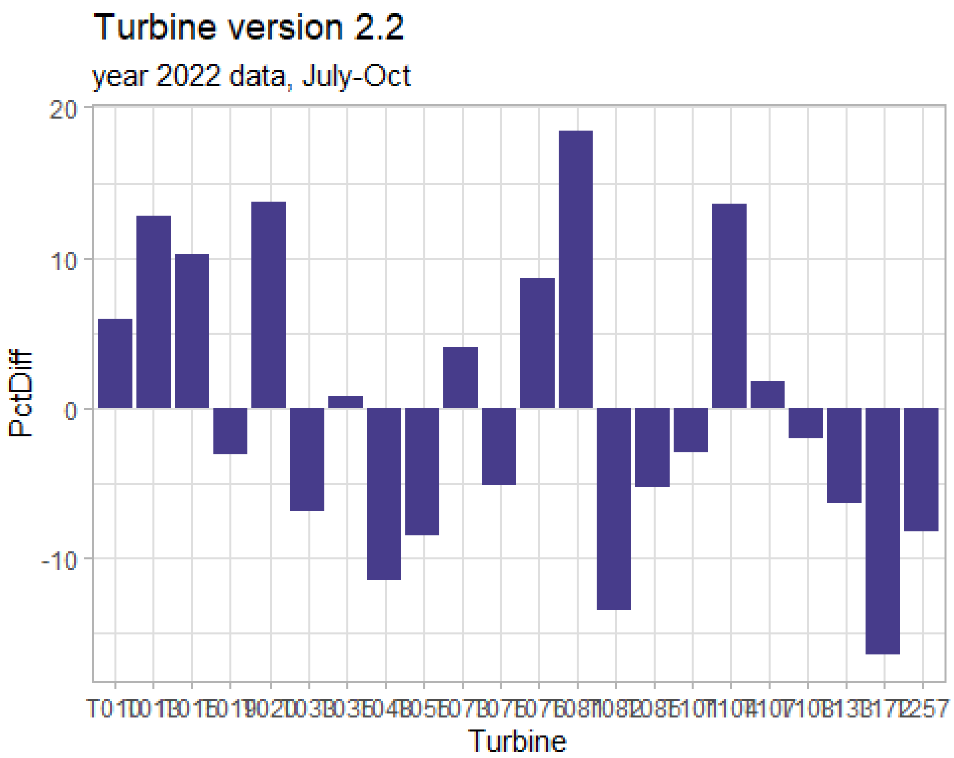
```
# generate for the %-age diff from average within versions
```

```
pctTurbData <- cleanData %>%
  group_by(Version, Turbine) %>%
  summarise(TurbineSumPower = sum(`TM Active Power`, na.rm = T)) %>%
  group_by(Version) %>%
  mutate(VersionMean = mean(TurbineSumPower, na.rm = T),
         VersionDiff = TurbineSumPower - VersionMean,
         PctDiff = -VersionDiff/VersionMean*100) # note plots in DOE report
have losses as +ve

`summarise()` has grouped output by 'Version'. You can override using the
`.groups` argument.

pctTurbData %>%
  filter(Version == "V2.1") %>%
ggplot() +
  geom_col(aes(Turbine, PctDiff), fill = 'slateblue4') +
  ggtitle("Turbine version 2.1", "year 2022 data, July-Oct") +
  theme_light()
```



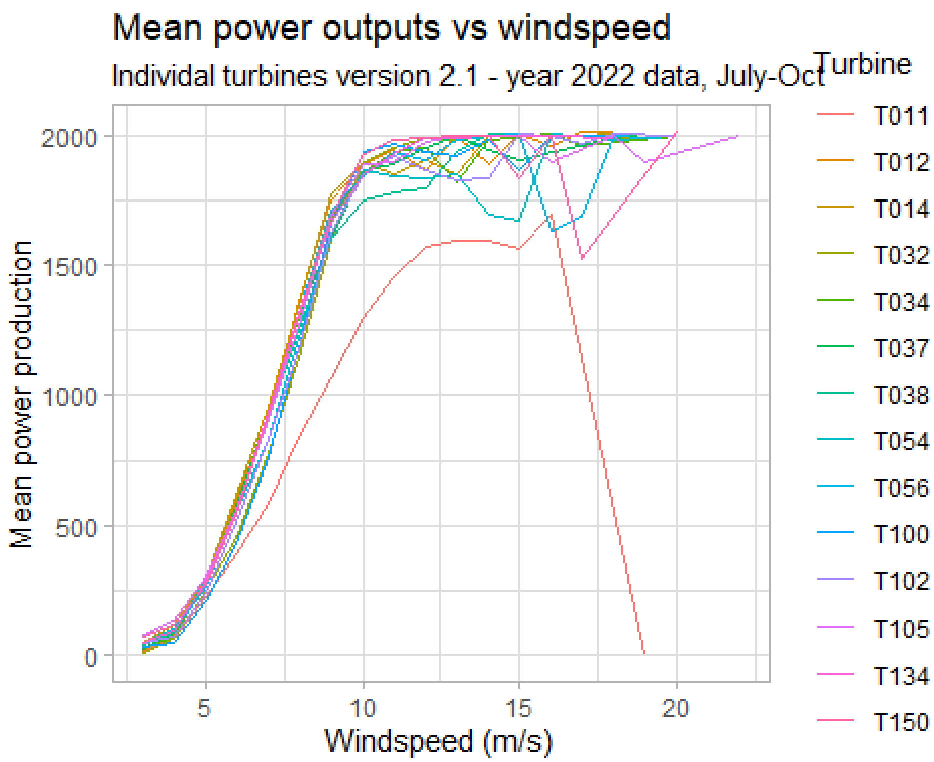
Similar for the 2.2MWh turbines ("Version 2.2")

```
pctTurbData %>%
  filter(Version == "V2.2") %>%
ggplot() +
  geom_col(aes(Turbine, PctDiff), fill = 'slateblue4') +
  ggtitle("Turbine version 2.2", "year 2022 data, July-Oct") +
  theme_light()
```

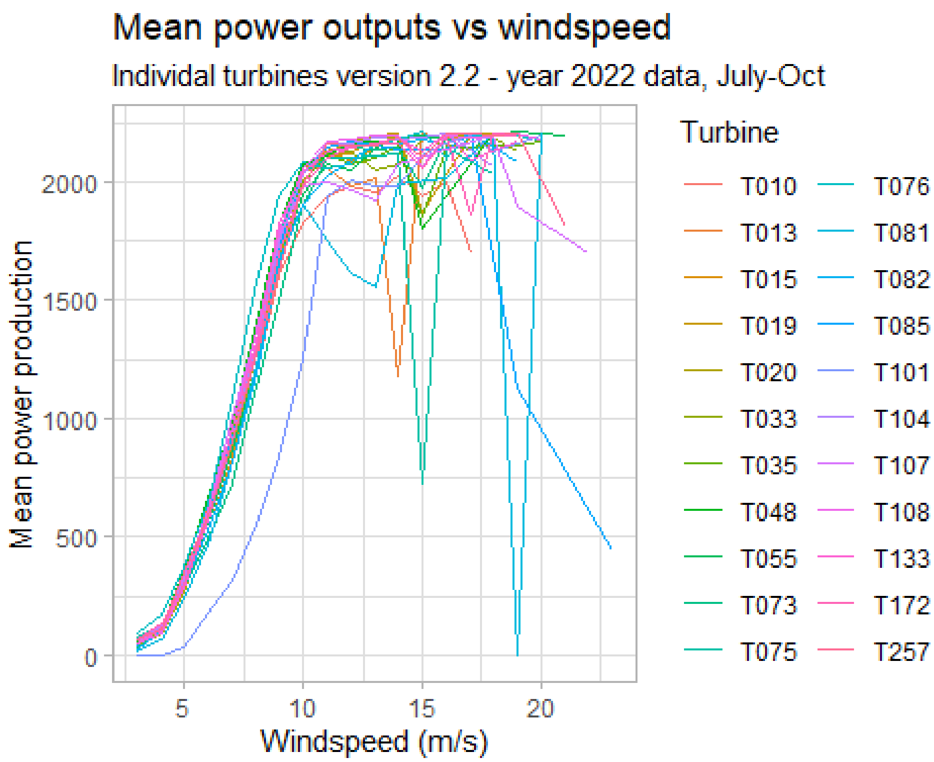


It’s unclear about the data manipulations required for the plots in the EPRI report, but some averaging is required. Here we take the mean for integer rounded values. There are clear anomolies in the data that would warrant investigation, but these are largely consistent with the EPRI report, so are retained in the current state for comparability.

```
cleanDataBinned <- cleanData %>%
  mutate(windBinned = round(`TM Windspeed Average`, 0)) %>%
  group_by(Turbine, windBinned) %>%
  summarise(Version = Version[1], meanPowerBin = mean(`TM Active Power`,
na.rm = T))

`summarise()` has grouped output by 'Turbine'. You can override using the
`.groups` argument.

cleanDataBinned %>%
  filter(Version == "V2.1") %>%
  ggplot() +
  geom_line(aes(windBinned, meanPowerBin, group = Turbine, col = Turbine)) +
  ggtitle("Mean power outputs vs windspeed", "Individal turbines version 2.1
- year 2022 data, July-Oct") +
  xlab("Windspeed (m/s)") +
  ylab("Mean power production") +
  theme_light()
```




```
cleanDataBinned %>%
  filter(meanPowerBin < 100 & windBinned > 5 & Version == "V2.1")

# A tibble: 1 × 4
# Groups:   Turbine [1]
  Turbine windBinned Version meanPowerBin
  <chr>        <dbl> <chr>          <dbl>
1 T011            19 V2.1               0

cleanDataBinned %>%
  filter(Version == "V2.2") %>%
  ggplot() +
  geom_line(aes(windBinned, meanPowerBin, group = Turbine, col = Turbine)) +
  ggtitle("Mean power outputs vs windspeed", "Individual turbines version 2.2
- year 2022 data, July-Oct") +
  xlab("Windspeed (m/s)") +
  ylab("Mean power production") +
  theme_light()
```



Annual production loss calculations

First determine the amount of power produced by the control turbines for every time point. The difference between these and when the treatment turbines are curtailed, is the basis of power loss estimates. Each of the treatments are considered in turn on this basis. For comparability with the EPRI analysis, a cutoff at windspeeds of 6.9 m/s is also considered.

```
# Determine the average control turbine production at each time point
cleanData <- cleanData %>%
  mutate(rating = if_else(Version == "V2.1", 2000, 2200))

aveControlProduction <- cleanData %>%
  mutate(propPower = `TM Active Power`/rating) %>%
  filter(Treatment == "Control") %>%
  group_by(dt_local) %>%
  summarise(controlMeanProp = mean(propPower, na.rm = T)) %>%
  select(dt_local, controlMeanProp)
```

VBPS

Determine when the VBPS allocated turbines were curtailed based on the rules defined from phase 1. Note these were determined in previous VBPS calculations, so the boolean for its operation has been carried over to analysis here.

```
# restrict to VBPS curtailed instances
# Determine the mean proportion of rating achieved by controls
```

```
# Sum losses for each turbine each night
# Take mean of these: gives the mean nightly loss for a turbine due to
treatment
VBPSCurtailed <- cleanData %>%
  left_join(aveControlProduction) %>%
  filter(Treatment == "VBPS" & calcVBPSCurtail == T) %>%
  na.omit() %>%
  mutate(loss = controlMeanProp * rating) %>%
  group_by(BatNight_DT, Turbine) %>%
  summarise(turbineSumLoss = sum(loss)/60) %>% # covert to hour-scale cf
EPRI, which was 10-min to hour
  group_by(BatNight_DT) %>%
  summarise(mean = mean(turbineSumLoss))

Joining with `by = join_by(dt_local)`
`summarise()` has grouped output by 'BatNight_DT'. You can override using the
`.groups` argument.

# sum for the study period and give as MWh
studyVBPSLoss <- sum(VBPSCurtailed$mean)/1000
```

The average turbine-level loss over the course of the study, due to VBPS curtailment, is estimated to be 75 MWh. To put this in perspective, we need the estimated annual energy production for a control turbine. This is estimated in a similar fashion: determine the average hourly production for a turbine operating normally, and scaling to the year. As per the EPRI report, this needs to be a weighted average of the two versions of the turbine used in the study.

```
# the average production for a turbine, based on mean proportion of rating
the controls operate at
versionProduction <- cleanData %>%
  left_join(aveControlProduction) %>%
  filter(Treatment == "Control") %>%
  na.omit() %>%
  mutate(production = controlMeanProp * rating) %>%
  group_by(Version) %>%
  summarise(sumProduction = mean(production))

Joining with `by = join_by(dt_local)`

# scaled to yearly for the two version typs
meanAnnual2000 <- versionProduction$sumProduction[1]*24*365
meanAnnual2200 <- versionProduction$sumProduction[2]*24*365

# conversion to hourly and MWh
VBPSPctLoss <- studyVBPSLoss/((meanAnnual2000*14 + meanAnnual2200*22)/36000)
* 100
```

This translates to a 0.75% loss over the year for a VBPS turbine, compared to the normal/control turbines.

Blanket curtailment at 5 m/s

```
# restrict to blanket 5 m/s curtailed instances
# Determine the mean proportion of rating achieved by controls
# Sum losses for each turbine each night
# Take mean of these: gives the mean nightly loss for a turbine due to
treatment

blank5Curtailed <- cleanData %>%
  left_join(aveControlProduction) %>%
  filter(Treatment == "Curtail 5 m/s" & `TM Windspeed Average` < 5) %>%
  na.omit() %>%
  mutate(loss = controlMeanProp * rating) %>%
  group_by(BatNight_DT, Turbine) %>%
  summarise(turbineSumLoss = sum(loss)/60) %>%
  group_by(BatNight_DT) %>%
  summarise(mean = mean(turbineSumLoss))

Joining with `by = join_by(dt_local)`
`summarise()` has grouped output by 'BatNight_DT'. You can override using the
`.groups` argument.

meanBlank5Loss <- sum(blank5Curtailed$mean)/1000
```

The estimated loss of power due to blanket curtailment at 5 m/s, over the course of the study for an individual turbine was 49 MWh.

```
blank5PctLoss <-
meanBlank5Loss/((versionProduction$sumProduction[1]*24*365*14 +
versionProduction$sumProduction[2]*24*365*22)/36000) * 100
```

Put into context against the annual production of an average control turbine, we get an estimated 0.49%.

Blanket curtailment at 6.9 m/s windspeed

```
# restrict to blanket 6.9 m/s curtailed instances
# Determine the mean proportion of rating achieved by controls
# Sum losses for each turbine each night
# Take mean of these: gives the mean nightly loss for a turbine due to
treatment

blank6Curtailed <- cleanData %>%
  left_join(aveControlProduction) %>%
  filter(Treatment == "Curtail 5 m/s" & `TM Windspeed Average` < 6.9) %>% #
use the 5 m/s turbines, but at 6.9 m/s
  na.omit() %>%
  mutate(loss = controlMeanProp * rating) %>%
  group_by(BatNight_DT, Turbine) %>%
  summarise(turbineSumLoss = sum(loss)/60) %>%
  group_by(BatNight_DT) %>%
  summarise(mean = mean(turbineSumLoss))
```

```
Joining with `by = join_by(dt_local)`
`summarise()` has grouped output by 'BatNight_DT'. You can override using the
`.groups` argument.

meanBlank6Loss <- sum(blank6Curtailed$mean)/1000
```

The estimated loss of power due to blanket curtailment at 6.9 m/s, over the course of the study for an individual turbine was 224 MWh.

```
blank6PctLoss <-
meanBlank6Loss/((versionProduction$sumProduction[1]*24*365*14 +
versionProduction $sumProduction[2]*24*365*22)/36000) * 100
```

Put into context against the annual production of an average control turbine, we get an estimated 2.25%.

Confidence intervals

The EPRI report outlines calculations for the precision of their power loss estimates. This is followed here, but it should be noted that there is no clear rationale for their calculations and the statistical inference is unclear and very non-standard. There is also reference to tabulated values for their calculation, but not what sort of tables these are. Hence, some figures are necessarily carried over for analysis here. It is noteworthy that the calculations incorporate the number of repeated measures used, but must assume some level of independence in the calculations - this is unlikely to be true and typically under-estimates variances.

VBPS

```
# determine the range at each time point, then average
VBPSCurtailed <- cleanData %>%
  left_join(aveControlProduction) %>%
  filter(Treatment == "VBPS" & calcVBPSCurtail == T) %>%
  na.omit()

Joining with `by = join_by(dt_local)`

# EPRI "n" is the number of 10 minute time-stamps, here minutes but appears
to translate
nVBPS <- length(unique(VBPSCurtailed$dt_local))

VBPSCurtailed <- VBPSCurtailed %>%
  mutate(loss = controlMeanProp * rating) %>%
  group_by(BatNight_DT, Turbine) %>%
  summarise(turbineSumLoss = sum(loss)/60) %>% # covert to hour-scale cf
EPRI, which was 10-min to hour
  group_by(BatNight_DT) %>%
  summarise(range = max(turbineSumLoss) - min(turbineSumLoss))

`summarise()` has grouped output by 'BatNight_DT'. You can override using the
`.groups` argument.
```

```
# in MWh
EPRI_sd <- sqrt(nVBPS * (mean(VBPSCurtailed$range)/2.970)^2)/60000

VBPSPctUncert <- EPRI_sd/((meanAnnual2000*14 + meanAnnual2200*22)/36000) *
100
```

Providing a VBPS "CI" of +/- 0.0097.

Blanket curtailment at 5 m/s

```
# determine the range at each time point, then average
blank5Curtailed <- cleanData %>%
  left_join(aveControlProduction) %>%
  filter(Treatment == "Curtail 5 m/s" & `TM Windspeed Average` < 5) %>%
  na.omit()

Joining with `by = join_by(dt_local)`

# EPRI "n" is the number of 10 minute time-stamps, here minutes but appears
to translate
nBlank5 <- length(unique(blank5Curtailed$dt_local))

blank5Curtailed <- blank5Curtailed %>%
  mutate(loss = controlMeanProp * rating) %>%
  group_by(BatNight_DT, Turbine) %>%
  summarise(turbineSumLoss = sum(loss)/60) %>% # covert to hour-scale cf
EPRI, which was 10-min to hour
  group_by(BatNight_DT) %>%
  summarise(range = max(turbineSumLoss) - min(turbineSumLoss))

`summarise()` has grouped output by 'BatNight_DT'. You can override using the
`.groups` argument.

# in MWh
EPRI_sd <- sqrt(nBlank5 * (mean(blank5Curtailed$range)/2.970)^2)/60000

blank5PctUncert <- EPRI_sd/((meanAnnual2000*14 + meanAnnual2200*22)/36000) *
100
```

Providing a blanket curtailment (5 m/s) "CI" of +/- 0.0073.

Blanket curtailment at 6.9 m/s

```
# determine the range at each time point, then average
blank6Curtailed <- cleanData %>%
  left_join(aveControlProduction) %>%
  filter(Treatment == "Curtail 5 m/s" & `TM Windspeed Average` < 6.9) %>%
  na.omit()

Joining with `by = join_by(dt_local)`

# EPRI "n" is the number of 10 minute time-stamps, here minutes but appears
to translate
```

```
nblank6 <- length(unique(blank6Curtailed$dt_local))

blank6Curtailed <- blank6Curtailed %>%
  mutate(loss = controlMeanProp * rating) %>%
  group_by(BatNight_DT, Turbine) %>%
  summarise(turbineSumLoss = sum(loss)/60) %>% # covert to hour-scale cf
EPRI, which was 10-min to hour
  group_by(BatNight_DT) %>%
  summarise(range = max(turbineSumLoss) - min(turbineSumLoss))

`summarise()` has grouped output by 'BatNight_DT'. You can override using the
`.groups` argument.

# in MWh
EPRI_sd <- sqrt(nblank6 * (mean(blank6Curtailed$range)/2.970)^2)/60000

blank6PctUncert <- EPRI_sd/((meanAnnual2000*14 + meanAnnual2200*22)/36000) *
100
```

Providing a blanket curtailment (6.9 m/s) "CI" of +/- 0.0279.

Reproducibility

Reproducibility of the results in the DOE report can't be achieved for several reasons:

- A common dataset is not available for analysis. Analysis here is based on the dataset indicated above, whereas the DOE report data is demonstrably different, being explicitly on 10-minute resolution versus 1-min here, albeit with 10-min rolling averages where appropriate. Analysis is based on the 10-min rolling average information for greater comparability.
- The analysis description is textual, which leaves substantial ambiguity and scope for deviation e.g. imputation is suggested and would be dependent on data ordering.
- Our analysis is in light of the VBPS experiment, which ultimately operated over a time time period that for the TIMR study described in the DOE report.

Generation of summary statistics for the data in hand, following the description in the DOE report, are markedly different in some instances. Nonetheless, the rationale described in the DOE report is reproduced here for the data preparation and power loss calculations.