A silver-haired bat. *Photo by Cris Hein, National Renewable Energy Laboratory*

Summary of Bats and Land-Based Wind Energy Development in the United States and Canada

Bat Species Impacted by Wind Energy Development

Deployment of wind energy over the past 20 years has increased renewable energy generation, but also raised concerns regarding the impact of wind turbine collisions on certain bat species (Friedenberg and Frick 2021). In 2012, the estimated number of bat fatalities from wind energy development in the United States and Canada ranged from 196,190 to 395,886 (Arnett and Baerwald 2013). The installed capacity across the two countries at the time was approximately 66,000 megawatts. Since then, the installed capacity of wind energy has more than doubled (Rand et al. 2020); therefore, the number of annual bat fatalities has likely increased as well.

A total of 22 species of bats have been reported as fatalities at wind energy facilities in the United States and Canada (American Wind Wildlife Institute 2020). Migratory tree-roosting species, including the hoary bat (*Lasiurus cinereus*), eastern red bat (*Lasiurus borealis*), and silver-haired bat (*Lasionycteris noctivagans*), constitute approximately 72% of bat carcasses reported, but other species, such as the Brazilian free-tailed bat (*Tadarida brasiliensis*), can make up a significant portion of fatalities in the southern United States (Arnett and Baerwald 2013; Zimmerling and Francis 2016; American Wind Wildlife Institute 2020; Weaver et al. 2020). Wind turbines are also known to cause fatalities of federally endangered species including the Indiana bat (*Myotis sodalis*), northeastern myotis (*Myotis septentrionalis*), and Hawaiian hoary bat (*Lasiurus semotus*), but occurrences are relatively rare (Erickson et al. 2016; Gorresen et al. 2020). Differences in behavior, abundance, and other factors likely contribute to the variability in fatality rates among bat species.

Data on relative age and sex of individual carcasses is inconclusive as it is difficult to determine this information from many of the carcasses that are recovered during searches (Korstian et al. 2013; Nelson et al. 2018; Chipps et al. 2020). The lack of demographic data for many bat species makes it difficult to assess the potential population-level impacts of wind turbines. Given that many species have a small population and slow growth rate, it has become increasingly important to better understand the long-term impact of wind energy on certain species of bats (Barclay and Harder 2003; Kunz et al. 2007; Russell et al. 2014; Frick et al. 2017; Friedenberg and Frick 2021).

Interactions Between Bats and Wind Turbines

In the northern hemisphere, consistent patterns of bat activity and fatalities at wind energy facilities have been observed with peaks occurring between mid-July and October (Arnett and Baerwald 2013; American Wind Wildlife Institute 2020), which coincides with the mating season and autumn migration of many bat species (Hedenstrom 2009; Cryan et al. 2012). Within this period, high fatalities occur on nights with relatively low and less variable wind speeds (Arnett and Baerwald 2013; Hein and Schirmacher 2016). Bat activity patterns relative to wind speeds may be related to energetic constraints on bats or a reduction in insect activity as wind speed increases (Jong et al. 2021).

Studies using thermal video cameras provide insight into how bats approach and interact with wind turbines, including the tower, nacelle, and blades, and demonstrate that risky behavior around wind turbines increases during late summer and early autumn

A hoary bat. *Photo by Cris Hein, National Renewable Energy Laboratory*

(Horn et al. 2008; Cryan et al. 2014; Goldenberg et al. 2021). Several hypotheses indicate that some species of bats may be attracted to wind turbines. Potential attractant(s) include noise, roost sites, foraging and water, mating behavior, lights, and scent-marking (Kunz et al. 2007; Cryan and Barclay 2009; Guest et al. 2022). These hypotheses have been explored to varying degrees, but there is no consensus, primarily because of the difficulties in assessing and differentiating species-specific bat behavior at wind turbines (Guest et al. 2022). How and why bats respond to wind energy facilities or even individual wind turbines likely varies among species and can also vary with local habitat features, insect activity, weather conditions, or a combination of these and other factors (Hein and Hale 2019; Johannsen et al. In Press).

Fatalities are predominately caused by blunt force trauma resulting from bats being struck by wind turbine blades. There is speculation that some individual bats may succumb to injuries resulting from barotrauma (i.e., rapid pressure change causing internal bleeding or damage to internal organs; Baerwald et al. 2008). However, there is insufficient data demonstrating barotrauma as a common cause of bat fatality at wind turbines. Moreover, the pressure variation likely to cause barotrauma is so close to the surface of wind turbine blades that there is a higher probability of direct contact with the blades than of solely experiencing barotrauma (Lawson et al. 2020).

Minimizing Bat Fatality at Wind Turbines

Several minimization strategies to reduce bat fatalities at wind energy facilities have been explored. Curtailing involves adjusting the operation of wind turbines, such as raising the cut-in speed above normal operations, to slow turbine blade rotations when bats are at risk. The cut-in speed is the wind speed at which wind turbines begin generating electricity-for many wind turbines the cut-in speed is 3.0 or 3.5 meters per second (m/s). Curtailment based on wind speed and time of year is often referred to as "blanket curtailment" and has been shown to significantly reduce bat fatality (Adams et al. 2021; Whitby et al. 2021). For example, when the cut-in speed is raised to 5.0 m/s, fatalities may be reduced by 24%–64% for hoary bats, 42–74% for eastern red bats, and 30%–66% for silver-haired bats (Whitby et al. 2021). The financial and energy production impacts vary from site to site and are influenced by factors such as curtailment scenario (e.g., 5.0 m/s vs 6.0 m/s cut-in speed), wind speed conditions, energy markets, and wind turbine specifications (Maclaurin et al. 2022).

Although blanket curtailment is based on a relatively narrow set of conditions (i.e., at night, under low wind speed conditions, and across a 2-to-3-month period), it limits power production, making it financially unsustainable for some wind energy facilities. As a result, researchers have explored incorporating additional variables, which is often referred to as "smart curtailment." For example, because bat activity and risk vary at night and across seasons, specific weather variables (e.g., temperature, wind direction, precipitation) can be applied to further reduce the amount of times wind turbines are nonoperational (e.g., Martin et al. 2017). Acoustic bat activity data can also be used, either in real time (e.g., Hayes et al. 2019) or to develop models that inform curtailment decisions (e.g., Behr et al. 2017; Peterson et al. 2021). For example, using these data, Hayes et al. (2019) reported an overall 84.5% reduction in bat fatality while decreasing curtailment time by 48% relative to wind turbines operating under a blanket curtailment scenario. Several studies are underway to verify that smart curtailment offers a cost-effective conservation strategy.

An alternative minimization strategy, which allows wind turbines to operate normally, is to emit ultrasound (i.e., high frequency sound above normal human hearing) similar to that used by bats during echolocation. The intent is to create a disorienting or uncomfortable airspace to dissuade bats from approaching or spending time near wind turbines. This approach involves installing ultrasonic deterrents on wind turbine structures to reduce bat activity in the rotor-swept area. Some studies have shown a reduction in overall bat activity and fatalities when these devices have been deployed on operational wind turbines (Arnett et al. 2013; Romano et al. 2019; Gilmour et al. 2020; Weaver et al. 2020), but results vary by location and species (Romano et al. 2019; Weaver et al. 2020). One of the challenges with emitting ultrasound is that higher frequency signals rapidly attenuate, or lose intensity, as the distance from the source increases. For example, a 20-kilohertz signal may be loud enough to influence bat behavior out to nearly 70 meters, but a 50-kilohertz signal may lose the necessary intensity by 35 meters (Weaver et al. 2020). To date, deterrent devices have only been installed on the nacelle or tower of wind turbines. Given the length of modern turbine blades, which can reach nearly 100 meters for land-based wind turbines, it is unlikely that some ultrasonic frequencies will reach the blade tip or beyond. A potential solution to this limitation is to install deterrent devices on the blades, but this will require research and development to ensure the devices do not impact the blade integrity or performance. Additional questions to address for deterrents are: 1) How do different species respond to various audio (e.g., constant sound, pulses, or frequency sweeps) or visual (e.g., ultraviolet light) stimuli? 2) Do bats habituate to the stimuli? 3) Where are the best locations to deploy deterrent devices on wind turbines?

Research Gaps

Research over the past 20 years has helped researchers better understand the impacts of wind energy development on bats, but many questions remain (Hein and Hale 2019), including:

- What are the population status and trends for bat species at risk of wind turbine collisions?
- What are the behavioral and physiological factors that result in bat and wind turbine interactions?
- What new species may be impacted as wind energy deployment expands to different regions, such as the southeastern and southwestern United States?
- Are there alternative approaches to monitoring bat fatality that are more cost-effective?
- What level of minimization (e.g., a 50% reduction in bat fatalities) is required to sustain bat populations?
- How can existing minimization strategies be improved or new approaches developed to reduce bat fatality while maximizing wind energy production?

Conclusion

A better understanding of bat population status and trends will help put existing and future fatality rates into context and may help provide goals for minimization. Greater knowledge of the behavioral and physiological mechanisms behind bat interactions with wind turbines may improve existing minimization strategies or lead to new, more cost-effective approaches. Given the variability across species (e.g., behavior, abundance, fatality rates) and wind energy facilities (e.g., wind turbine dimensions, operational characteristics), the solution to reducing impacts while meeting renewable energy production goals will require flexibility among stakeholders and a combination of mitigation approaches that includes avoidance, minimization, and compensation.

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References

Adams, E. M., J. Gulka, and K. A. Williams. 2021. "A review of the effectiveness of operational curtailment for reducing bat fatalities at terrestrial wind farms in North America." *PLoS ONE* 16: e0256382. https://doi.org/10.1371/journal.pone.0256782.

American Wind Wildlife Institute. 2020. "Summary of Bat Fatality Monitoring Data Contained in AWWIC (2nd Edition)." American Wind Wildlife Information Center. https://awwi.org/resources/awwic-bat-technical-report/. Accessed April 13, 2022.

Arnett, E. B., and E. F. Baerwald. 2013. "Impacts of Wind Energy Development on Bats: Implications for Conservation." In: Adams, R., and S. Pedersen (eds.) *Bat Evolution, Ecology, and Conservation*. Springer, New York, NY. https://doi.org/10.1007/978-1-4614-7397-8_21.

Arnett, E. B., C. D. Hein, M. R. Schirmacher, M. M. P. Huso, and J. M. Szewczak. 2013. "Evaluating the Effectiveness of an Ultrasonic Acoustic Deterrent for Reducing Bat Fatalities at Wind Turbines." *PLoS ONE* 8:1–8. https://doi.org/10.1371/journal.pone.0065794.

Baerwald, E. F., G. H. D'Amours, B. J. Klug, and R. M. R. Barclay. 2008. "Barotrauma is a significant cause of bat fatalities at wind turbines." *Current Biology* 18: R695–R696. https://doi.org/10.1016/j.cub.2008.06.029.

Barclay, R. M. R., and L. D. Harder. 2003. *Life Histories of Bats: Life in the Slow Lane*. Pp. 209–253 in Bat Ecology (T. H. Kunz and M. B. Fenton, eds.). The University of Chicago Press. https://tethys.pnnl.gov/publications/life-histories-bats-life-slow-lane.

Behr, O., R. Brinkmann, K. Hochradel, J Mages, F Korner-Nievergelt, I. Niermann, M. Reich, R. Simon, N. Weber, and M. Nagy. 2017. "Mitigating Bat Mortality with Turbine-Specific Curtailment Algorithms: A Model Based Approach." In: Koppel, J. (ed) *Wind Energy and Wildlife Interactions*. Springer, Cham. https://doi.org/10.1007/978-3-319-51272-3_8.

Chipps, A. S., A. M. Hale, S. P. Weaver, and D. A. Williams. 2020. "Genetic Approaches Are Necessary to Accurately Understand Bat-Wind Turbine Impacts." *Diversity* 12:1–11. https://doi.org/10.3390/d12060236.

Cryan, P. M., and R. M. R. Barclay. 2009. "Causes of bat fatalities at wind turbines: hypotheses and predictions." *Journal of Mammalogy* 90: 1330–1340.

Cryan, P. M., P. M. Gorresen, C. D. Hein, M. R. Schirmacher, R. H. Diehl, M. M. Huso, D. T. S. Hayman, P. D. Fricker, F. J. Bonaccorso, D. H. Johnson, K. Heist, and D. C. Dalton. 2014. "Behavior of bats at wind turbines." Proceedings of the National Academy of Sciences of the United States of America 111:15126–15131. https://doi.org/10.1073/pnas.1406672111.

Erickson, R. A., W. E. Thogmartin, J. E. Diffendorfer, R. E. Russell, and J. A. Szymanski. 2016. "Effects of wind energy generation and white-nose syndrome on the viability of the Indiana bat." *PeerJ* 4:e2830 https://doi.org/10.7717/peerj.2830.

Frick, W. F., T. L. Cheng, K. E. Langwig, J. R. Hoyt, A. F. Janicki, K. L. Parise, J. T. Foster, and A. M. Kilpatrick. 2017. "Pathogen dynamics during invasion and establishment of white-nose syndrome explain mechanisms of host persistence." *Ecology* 98:624–631. https://doi.org/10.1002/ecy.1706.

Friedenberg, N. A., and W. F. Frick. 2021. "Assessing fatality minimization for hoary bats amid continued wind energy development." *Biological Conservation* 262:109309. https://doi.org/10.1016/j.biocon.2021.109309.

Gilmour, L. R. V., M. W. Holderied, S. P. C. Pickering, and G. Jones. 2020. "Comparing acoustic and radar deterrence methods as mitigation measures to reduce human-bat impacts and conservation conflicts." *PLoS ONE* 15(2):e0228668. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0228668.

Goldenberg, S. Z., P. M. Cryan, P. M. Gorresen, and L. J. Fingersh. 2021. "Behavioral patterns of bats at a wind turbine confirm seasonality of fatality risk." *Ecology and Evolution* 11:4843–4853. DOI: 10.1002/ece3.7388. https://onlinelibrary.wiley.com/doi/10.1002/ece3.7388.

Gorresen, P. M., P. M. Cryan, and G. Tredinnick. 2020. *Hawaiian hoary bat (Lasiurus cinereus semotus) behavior at wind turbines on Maui*. https://pubs.er.usgs.gov/publication/70216926.

Guest, E. E., B. F. Stamps, N. D. Durish, A. M. Hale, C. D. Hein, B. P. Morton, S. P. Weaver, and S. R. Fritts. 2022. "An Updated Review of Hypotheses Regarding Bat Attraction to Wind Turbines." *Animals* 12(3):343. https://doi.org/10.3390/ani12030343.

Hayes, M., L. Hooton, K. Gilland, C. Grandgent, T. Smith, S. Lindsay, J. Collins, S. Schumacher, P. Rabie, J. Gruver, and J. Goodrich-Mahoney. 2019. "A smart curtailment approach for reducing bat fatalities and curtailment time at wind energy facilities." *Ecological Applications*. *https://doi.org/10.1002/eap.1881*.

Hedenström, A. 2009. "Optimal Migration Strategies in Bats." *Journal of Mammalogy* 90: 1298–1309. https://academic.oup.com/jmammal/article/90/6/1298/898078.

Hein, C. D., and M. R. Schirmacher. 2016. "Impact of Wind Energy on Bats: a Summary of our Current Knowledge." *Human-Wildlife Interactions* 10:19–27. https://doi.org/10.26077/x7ew-6349.

Hein C. D., And A. M. Hale. 2019. "Wind Energy and Bats in Renewable Energy and Wildlife Conservation." C Moorman, S Grodsky, S Rupp, eds. John Hopkins University Press: Baltimore, MD, pp. 122–145.

Horn, J. W., E. B. Arnett, and T. H. Kunz. 2008. "Behavioral Responses of Bats to Operating Wind Turbines." *Journal of Wildlife Management* 72:123–132. DOI: 10.2193/2006-465. https://bioone.org/journals/journal-of-wildlife-management/volume-72/issue-1/2006-465/Behavioral-Responses-of-Bats-to-Operating-Wind-Turbines/10.2193/2006-465.short.

Johannsen et al. In Press.

Jong, J., L. Millon, O. Hastad, and J. Victorsson. 2021. "Activity Pattern and Correlation between Bat and Insect Abundance at Wind Turbines in South Sweden." *Animals* 11:3269 DOI: 10.3390/ani11113269. https://www.mdpi.com/2076-2615/11/11/3269.

Korstian, J. M., A. M. Hale, V. J. Bennett, and D. A. Williams. 2013. "Advances in sex determination in bats and its utility in wind-wildlife studies." *Molecular Ecology Resources* 13:776–780. https://doi.org/10.1111/1755-0998.12118.

Kunz, T. H., E. B. Arnett, B. M. Cooper, W. P. Erickson, R. P. Larkin, T. Mabee, M. L. Morrison, M. D. Strickland, and J. M. Szewczak. 2007. "Assessing Impacts of Wind-Energy Development on Nocturnally Active Birds and Bats: A Guidance Document." *Journal of Wildlife Management* 71:2449–2486. https://doi.org/10.2193/2007-270.

Lawson, M., D. Jenne, R. Thresher, D. Houck, J. Wimsatt, and B. Straw. 2020. "An investigation into the potential for wind turbines to cause barotrauma in bats." *PLoS ONE*. https://doi.org/10.1371/journal.pone.0242485.

Martin, C. M., E. B. Arnett, R. D. Stevens, and M. C. Wallace. 2017. "Reducing bat fatalities at wind facilities while improving the economic efficiency of operational mitigation." *Journal of Mammalogy* 98(2):378–385. https://doi.org/10.1093/jmammal/gyx005.

Maclaurin, G., C. Hein, T. Williams, O. Roberts, E. Lantz, G. Buster, and A. Lopez. 2022. "Nation-scale impacts on wind energy production under curtailment scenarios to reduce bat fatalities." *Wind Energy*. https://doi.org/10.1002/we.2741.

Nelson, D. M., J. Nagel, R. Trott, C. J. Campbell, L. Pruitt, R. E. Good, G. Iskali, and P. F. Gugger. 2018. "Carcass age and searcher identity affect morphological assessment of sex of bats." *Journal of Wildlife Management* 82(8):1582–1587. https://doi.org/10.1002/jwmg.21544.

Peterson, T. S., B. McGill, C. D. Hein, and A. Rusk. 2021. "Acoustic exposure to turbine operation quantifies risk to bats at commercial wind energy facilities." *Wildlife Society Bulletin* DOI: 10.1002/wsb.1236.

Rand, J. T., L. A. Kramer, C. P. Garrity, B. D. Hoen, J. E. Diffendorfer, H. E. Hunt, and M. Spears. 2020. "A continuously updated, geospatially rectified database of utility-scale wind turbines in the United States." *Scientific Data* 7:1–12. DOI:10.1038/s41597-020-0353-6. https://www.nature.com/articles/s41597-020-0353-6.

Romano, W. B., J. R. Skalski, R. L. Townsend, K. W. Kinzie, K. D. Coppinger, and M. F. Miller. 2019. "Evaluation of an acoustic deterrent to reduce bat mortalities at an Illinois wind farm." *Wildlife Society Bulletin* 43:608–618. https://doi.org/10.1002/wsb.1025.

Russell, R. E., K. Tinsley, R. A. Erickson, W. E. Thogmartin, and J. Szymanski. 2014. "Estimating the spatial distribution of wintering little brown bat populations in the eastern United States." *Ecology and Evolution* 4(19):3746–3754. DOI: 10.1002/ece3.1215. https://onlinelibrary.wiley.com/doi/full/10.1002/ece3.1215.

Weaver, S. P., C. D. Hein, T. R. Simpson, J. W. Evans, and I. Castro-Arellano. 2020. "Ultrasonic acoustic deterrents significantly reduce bat fatalities at wind turbines." *Global Ecology and Conservation* 24:e01099. https://doi.org/10.1016/j.gecco.2020.e01099.

Whitby, M. D., M. R. Schirmacher, and W. F. Frick. 2021. *The state of the science on operational minimization to reduce bat fatality at wind energy facilities.* A report submitted to the National Renewable Energy Laboratory by Bat Conservation International, Austin, TX.

Zimmerling, J. R., and C. M. Francis. 2016. "Bat mortality due to wind turbines in Canada." *Journal of Wildlife Management* 80:1360–1369. https://doi.org/10.1002/jwmg.21128.

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