Bat Behavior in Relation to Wind Turbines: Attraction Hypotheses and Avoidance Behaviors

SUMMARY

Several studies have documented bats exhibiting either attraction or avoidance behaviors near wind farms or wind turbines. In some cases, bats frequently approach wind turbines, possibly to investigate structures such as the tower or blades. While multiple hypotheses exist based on behaviors such as foraging, roosting, or mating, no single explanation fits all species or conditions. Environmental factors like prey availability, habitat type, and wind conditions also shape behavioral responses. For example, the common noctules (*Nyctalus noctula*) and hoary bat (*Lasiurus cinereus*) may perceive turbines as potential roosting sites, foraging areas, or locations for mating or other social interactions, increasing collision risk. In contrast, several species of Myotis and the brown long-eared bat (*Plecotus auritus*) may avoid wind turbines because of habitat changes or operational noise. Understanding these patterns is vital for developing mitigation strategies that support both bat conservation and renewable energy goals.

INTRODUCTION

Bats provide critical ecosystem services, but collision risk and habitat loss resulting from the global development of wind energy have raised conservation concerns. Initial research emphasized attraction mechanisms [1,2], but recent studies show that some species, particularly those adapted to forest habitats, may avoid wind farms [3–5]. Species-specific sensory traits—hearing, vision, and echolocation—play a key role in shaping these behaviors and should inform wind farm planning [6].

UNDERSTANDING BAT BEHAVIOR RELATED TO ATTRACTION HYPOTHESES

Several species of bats may be attracted to wind farms or wind turbines, and the attractants may vary by species, environmental conditions, landscape features, and wind turbine characteristics. Moreover, the available research on these hypotheses may offer both supporting and opposing results, which complicate our understanding of how and why bats interact with wind turbines. Guest et al. [7] reviewed the existing literature on the major attraction hypotheses, including foraging, light, roosting, noise, and mating. Most of these studies focused on observing bat behavior at wind farm and non-wind-farm sites. Few studies attempted to relate behavioral observations with mortality. The following is a summary of the leading hypotheses with comments on the strength of the evidence supporting each.

Hoary bat (*Lasiurus cinereus*). *Photo by Cris Hein, NREL*

Insect foraging (moderate support): A leading hypothesis is that insects cluster near wind turbines, creating foraging opportunities. Factors like heat emissions from the nacelle, artificial lighting within wind farms, and altered airflow may increase insect density near wind turbines. Echolocation calls associated with foraging (i.e., feeding buzzes) and aerial hunting maneuvers have been observed near wind turbines [7–10]. In addition, bat carcasses with full or partially full stomachs were collected underneath wind turbines, suggesting they were foraging at the time of the collision event [3].

Artificial light (limited support): Artificial lighting can attract bats, but the attraction varies by species, color of light (wavelength), and whether the light is a point source or diffuse [11–14]. Some species may increase their activity and/or foraging at lit sources (e.g., *Lasiurus* spp.) [15,16]. In other instances, lights may have no influence on or may decrease bat activity [17]. There remains no evidence that lighting increases attraction or mortality of bats at wind farms. Seewagen et al. [18] observed no effect of lighting on eastern red bats and hoary bats. Studies investigating the relationship between mortality and wind turbine lighting reported no increase in mortality at wind turbines with aviation lighting [19].

Water surface misinterpretation (limited support): The smooth surfaces of wind turbines present similar reflective echolocation signatures as water, which may confuse bats and prompt close investigative approaches [20,21].

Roost and landmark hypothesis (moderate support): Wind turbines may serve as landmarks in open habitats (e.g., agricultural landscapes, offshore) or potential roost sites. This hypothesis may be more relevant for long-distance migratory tree-roosting bats, including hoary bats and common noctules, that might orient on conspicuous features, especially in poor weather conditions [22]. In addition, the development of wind farms in forests creates gaps and edge habitat, which may attract some species. There are several unpublished accounts of bats roosting in wind turbines. Bennett et al. [23] observed bat guano on door slats, suggesting bats were roosting in the wind turbine, a hypothesis also suggested by Brabant et al. [24].

Bat specimens that were sighted on offshore wind farms (OWFs) in spring 2019. Left picture: bat sp. roosting in the grate floor of a turbine in the Belgian Nobelwind OWF (8 April 2019); right picture: bat sp. roosting on the foundation of a turbine in the Belgian C-Power OWF (30 April 2019). *Photos from Parkwind (left) and C-Power (right)*

Social aggregations (limited support): Wind turbines might be used as social aggregation points during migration or mating. Observations of *Lasiurus* spp. mating near turbines suggest this possibility [25], though overall support remains limited [2].

Olfactory cues (speculative): Some bats may be attracted by the odor of insect carcasses on the blades of wind turbines or odors from social scent-marking behaviors (i.e., the scents left by individuals making contact with a structure; see [7]). This hypothesis has been considered for hoary bats and Brazilian free-tailed bats, though direct evidence remains scarce [6] and has been met with skepticism. Clerc et al. [26] suggest that it is unlikely that scent markings on wind turbines could attract bats from more than a few meters away.

EMERGING EVIDENCE OF BAT AVOIDANCE BEHAVIOR

While attraction mechanisms can increase collision risk, emerging evidence shows that some species exhibit avoidance behavior. Several recent studies indicate reduced bat activity at varying distances from wind turbines, including 1,000 m [27], 600 m [28], 400 m [29], 300 m [30], and 200 m [31]. Potential avoidance mechanisms include:

Noise and vibration (moderate support): Operational noise and vibrations from wind turbines may cause distress or disorientation, particularly for species dependent on echolocation in forested habitats. Echolocation-reliant species such as *Myotis* spp. and western barbastelle (*Barbastella barbastellus*) may avoid wind turbines because of the noise generated during operation [32].

Habitat loss (moderate support): The removal of natural habitat during construction may result in abandonment of the area by some species [33,34]. Forest species, such as brown long-eared bats and Natterer's bats (*Myotis nattereri*), may abandon areas where wind turbines replace mature forest cover. Even after regrowth, simplified vegetation structures may be unsuitable for these species [31,33].

Visual disturbance (limited support): The presence of newly constructed wind turbines and associated infrastructure may trigger aversion by species not adapted to anthropogenic infrastructure [8]. To date, there are no field studies examining the visual effects of wind turbines on bats.

UNTANGLING THESE BEHAVIORS

There is no single hypothesis that explains either attraction or avoidance of wind turbines by bats. It is not surprising to see contradictory results given how complex these interactions are and how variable the circumstances can be. Sensory perception, echolocation characteristics, flight ecology, intensity and distance of stimuli, and habitat type can influence how bats respond to the presence of wind farms [6]. Understanding the driving factors that influence how bats perceive and navigate their environments may help explain attraction and avoidance behaviors and reduce risk. Key factors include:

Species-specific flight ecology: Fast, open-air foragers, such as *Nyctalus* spp., *Pipistrellus* spp., *Lasiurus* spp., and *Tadarida* spp., make up most bat fatalities in Europe and North America [35–37]. There is evidence that these species approach and spend time flying around wind turbines, including multiple passes across the rotor-swept area [8,38]. Conversely, fatalities of slower, more maneuverable bats such as *Myotis* spp., *Plecotus* spp., and *Barbastella* spp. are relatively rare. Their lower flight altitude, foraging near vegetative surfaces, and reduced activity in high-wind conditions may reduce their exposure to operating wind turbines. Ellerbrok et al. [32] further suggest that bat activity near wind turbines is lower during operation compared to periods when wind turbines are idle, even under comparable wind conditions.

Habitat configuration: Clearings in forest habitat created by developing wind farms may attract edge and open-air foragers but reduce the occurrence of by interior-forest foragers [39]. In agricultural landscapes, hedgerows and riparian areas are important foraging and commuting habitats for bats [40–42]. The placement of wind turbines near these features can influence activity. For example, when comparing activity at hedgerows with and without wind turbines, bat activity decreased near hedgerows when turbines were within 10–43 m, but no changes were observed when wind turbines were placed 100–283 m away [43].

Wind conditions and wake effects: Wind speed and direction can also influence bat interactions with wind turbines. A study by Cryan et al. [8] found that tree-roosting bats most often approached wind turbines from the downwind side, with higher activity observed at lower wind speeds. Leroux et al. [44] found that common pipistrelles avoided turbulent wake zones downwind of wind turbines, likely due to elevated flight costs and reduced maneuverability. These behavioral patterns are consistent with aerodynamic studies showing that wind turbines generate complex wake zones with increased turbulence and variable shear [45].

Wind testing facility at Sandia National Laboratories. *Photo from Sandia National Laboratories, NREL 38920*

IMPLICATIONS AND RISK MANAGEMENT MEASURES

Understanding both attraction and avoidance behaviors and the factors that influence them is crucial for effective risk management in wind energy development. However, translating these findings into clear recommendations remains challenging due to the complexity of the interactions involved. Key risk management strategies include:

Responsible siting of wind farms: Wind turbines should be sited more than 200–300 m from high-quality bat habitats such as mature forests, wetlands, roosting trees, and hedgerow networks to reduce risk [8,46]. Avoidance of known migratory corridors and landscape features used for navigation (e.g., ridgelines, river valleys) is also recommended [47]. Lower-risk areas include intensively farmed agricultural zones with large parcel sizes and sparse linear vegetation [5]. Within forested regions, clustering wind turbines in existing clearings and minimizing the number of new access roads may reduce habitat fragmentation.

Common noctule bat. *Photo from Roziline, Adobe Stock 248844381*

Turbine design and configuration: Maximizing clearance between wind turbine blades and the ground may help reduce interactions with species, such as hoary bats [48]. In addition, reducing wind turbine density can reduce risk for species that often fly at heights within the rotor-swept zones of wind turbines, including the common noctule [27,44].

Wind speed and wake effects: Aerodynamic wake effects and turbulent wind zones can shape bat activity patterns tens to hundreds of meters away from wind turbines, particularly downwind where increased flight costs may lead to avoidance by some species [44,45]. To minimize these impacts, wind turbine siting should consider local wind patterns and avoid configurations that concentrate wake turbulence near high-use bat habitats or movement corridors.

Adaptive management: Because preconstruction acoustic surveys often fail to predict actual bat activity [49], adaptive strategies are essential. Post-construction acoustic monitoring can allow for real-time data collection and wind turbine control adjustments to reduce fatalities [50,51]. Curtailment, or temporarily slowing blade rotation during periods of high risk, has proven effective [52–54] and can be optimized using smart systems that integrate weather data and bat presence [55].

Lighting: Reducing unnecessary lighting near wind turbines may reduce insect abundance and activity, thus lowering potential attraction by bats. Using security lighting that is triggered by human activity and shielding direct light downward can help mitigate risk for visually sensitive species.

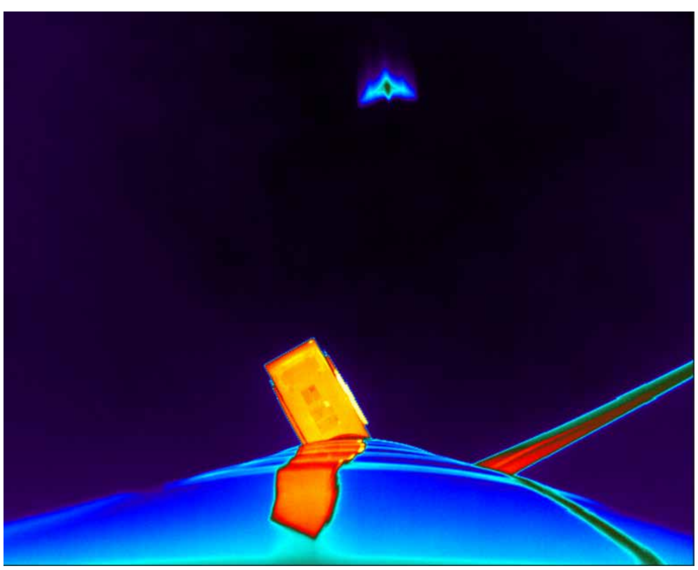
Habitat compensation: In cases of unavoidable habitat loss, offset measures should aim to restore similar habitat types nearby or enhance existing natural areas. Improving forest connectivity, preserving water sources, and managing linear features like hedgerows can all support displaced bat populations [27,29,56].

BEHAVIORAL RESEARCH GAPS

Despite significant advances, several critical knowledge gaps remain in understanding bat interactions with wind turbines. The following are suggestions for addressing these research gaps:

Species-specific behavioral data: There are few studies on the behavioral and physiological responses of bats that are most vulnerable to wind energy development. More research is needed to assess flight altitude, maneuverability, perception, and foraging strategies for species that commonly interact with wind turbines.

Spatio-temporal activity patterns: Bats exhibit complex movement behaviors across daily, seasonal, and migratory timescales. Understanding when and where bats interact with wind turbines requires long-term, fine-scale data collection. Technologies like passive acoustic monitoring, radio telemetry, GPS tracking, radar, and thermal imaging—especially when integrated with machine learning—can reveal patterns of wind turbine interactions and avoidance across habitats, landscapes, and weather conditions.



Thermal image of a bat flying near a wind turbine. *Photo from Sara Weaver, Texas State University*

Predictive tools and species risk profiles: Developing tools that predict collision risk under varying environmental and design conditions requires robust, species-specific inputs. This includes data on morphology, sensory traits, habitat preferences, and known behavioral responses. Species-level profiles can inform dynamic siting decisions and support adaptive mitigation planning.

Post-construction responses and habitat use: Many studies emphasize preconstruction risk assessment, but less is known about how bat communities respond over time to wind farm development. Long-term monitoring is needed to understand shifts in habitat use, delayed effects on reproduction or survival, and the potential for cumulative or landscape-scale impacts on populations.

Ecosystem and multi-taxa trade-offs: Solutions to reduce bat fatalities, such as changes to wind turbine design, configuration, and curtailment, may have unintended effects on other taxa or reduce energy production. Research should explore cross-taxa impacts and seek strategies that balance renewable energy goals with broader ecological outcomes [56].

CONCLUSION

Understanding the behavioral ecology of bats in relation to wind farms is fundamental to designing effective mitigation measures to reduce the negative impacts that wind energy may have on bats. Bats respond to wind turbines in highly species-specific and context-dependent ways, influenced by factors such as habitat type, wind turbine characterization and configuration, weather conditions, and sensory ecology.

Moving forward, integrating detailed bat behavioral data into wind turbine siting and design, improving monitoring protocols, and developing smart adaptive mitigation strategies will be key to reducing impacts to bats. Research efforts should focus on long-term behavioral responses, cumulative ecological impacts, and trade-offs with other conservation and energy goals. Tools such as species-specific risk profiles, machine-learning-based monitoring and minimization strategies, and cross-taxa impact assessment will support a holistic approach.

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