Supporting Information

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SI Methods

Recording Supplemental Near-Infrared Video Imagery. In addition to thermal imagery, we used near-infrared (NIR) video cameras (Model KP-E500, Hitachi; Model GX1920, Allied Vision Technologies) and NIR illuminators (Model T90A42, Axis Communications; Model Mark 40, Luma Scientific; Model ALS-40, Sofradir EC) to gather concurrent, supplemental imagery of bats at turbines. It is difficult to see visual details or judge depth of field from thermal imagery alone (1), and NIR imagery helped us identify targets detected, judge spatial relationships between flying targets and the turbines, and gather additional details about behaviors of bats interacting with the turbine towers, nacelles, and blades. These NIR cameras and illuminators operate at wavelengths of light ranging from 700 to 1,000 nm, which fall outside the visible spectrum of bats (2–5). NIR cameras were positioned at 30 m from the base of each turbine and NIR illuminators were positioned at 12 m and 60 m from the turbine and aimed at the nacelle.

Acoustic Monitoring for Bat Echolocation Calls on Top of Turbines. We used frequency division acoustic detectors (Model Anabat II; Titley Electronics) to monitor the airspace around turbines for bat echolocation calls. These detectors were mounted on top of each nacelle at the back, with their microphones pointed into the airspace directly behind the nacelle and away from the turbine blades. Detector microphones were housed in a 50-mm-diameter curved PVC tubes that faced upward at an angle of 45°. Detectors were programmed to record calls each night from 1 h before sunset to 1 h after sunrise for the duration of the study.

We analyzed bat-call data with sound analysis software (Analook, www.hoarybat.com) as described previously (6). All extraneous noise was visually filtered from the data before summary and analysis. We divided echolocation passes into two phonic groups based on minimum frequency of the call, in part because bats using different ranges of frequencies to echolocate may differ in their behaviors around turbines and in their responses to environmental factors. We manually classified bat passes as being produced by either high-frequency bats (≥33 kHz average minimum frequency) or low-frequency bats (<30 kHz average minimum frequency). High-frequency species of bats included *Myotis* spp., tricolored bats (*Perimyotis subflavus*), evening bats (*Nycticeius humeralis*), and eastern red bats (*Lasiurus borealis*). Low-frequency species include big brown bats (*Eptesicus fuscus*), silver-haired bats (*Lasionycteris noctivagans*), and hoary bats (*Lasiurus cinereus*). We also identified passes of hoary bats as a third phonic subgroup (a subset of low-frequency bats) using a customized filter in Analook derived from those developed by Britzke and Murray (7) with a "Smoothness" setting of 12, a "Bodyover" setting of 110, a "MinFmin" setting of 14, a "MaxFmin" setting of 21, and a "CallNum" setting of 1. We specifically categorized the passes of hoary bats, because this species is particularly vulnerable to wind turbines (8) and because, unlike most other species present at the study site, their echolocation sequences are relatively easy to distinguish from those made by other bats. To assess whether or not bats were interacting with the turbines and potentially feeding, we examined calls with sound analysis software (Songscope 3.4, Wildlife Acoustics) and classified them as approach phase or terminal phase ["feeding buzz" (9)]. We defined the approach phase as frequency modulated call sequences with intervals between pulses lasting from 0.01 to 0.05 ms and the terminal phase as frequency modulated call sequences with <0.01 ms between pulses.

Radar Monitoring of Airspace Surrounding Wind Turbines. We used an all-weather, 25-kW, x-band (3.19-cm wavelength) vehicle-mounted portable radar unit (Furuno 2127BB, Furuno Electric) to collect data on flying animals at the wind facility. The radar runs on 120-V alternating current supplied by a low-noise, regulated generator, and the radar was refitted with a 1.2-m diameter, high-gain parabolic antenna with a greater range of detection and some height estimating capability not available with the original equipment manufacturer's open-array antenna. The radar's beam is shaped by antenna characteristics (parabolic, 38.8-dB gain), the radar cross-section of targets, wavelength, and other factors (see, for example, ref. 10) that resulted in a ∼3.3° wide beam for this study. The antenna was continuously rotated in azimuth through 360° every 2.5 s, updating animal locations with each rotation. The elevation angles used in this study, between 2.75° and 3.50° above the horizon, were not changed during operation and were as low as possible to avoid clutter while simultaneously monitoring as much of the rotor-swept areas of turbines as possible. However, it was not possible to detect flying animals within the immediate vicinity (area monitored by video cameras) of the wind turbines monitored because of electronic clutter created by the radar beam reflecting off the monopoles, nacelles, and blades. The resulting 2D circular display showed radar tracks of animal detections. Maximum range of detection in this study was capped at 3 km. We positioned the radar unit such that the detection area overlapped as much as possible the rotor-swept areas of the three turbines simultaneously monitored by video. The radar was moved among these three turbines according to a schedule such that all turbines were monitored regularly: one turbine was visited every other day and the other every fourth day. For this report, analysis focused on one of the turbines located along the periphery of the turbine array where there was less ground clutter, which can obscure radar echoes from flying animals.

We sited the radar about 2-km away from each turbine that was the primary focus of monitoring that night to optimize coverage of the rotor-swept area. Radar data were recorded for ∼11.5 h each night, beginning 30 min before local civil sunset. The radar recorded animal movement data as raster imagery during each update of the radar display using a programmable frame-capture card (Accustream 170 Express, Foresight Imaging). The locations from which focal turbines were monitored varied somewhat in response to changes in vegetation as seasonal harvest of crops progressed in this highly agricultural landscape. Despite these changes, effort was made to maintain the 2-km distance to focal turbines.

Radar-determined locations of flying animals within carefully chosen subsets of radar coverage areas were extracted manually to ensure data were as free as possible of noise and other unwanted artifacts. Observations were drawn uniformly across all ranges (i.e., heights) within the radar coverage area out to 3 km. These observations were then processed using R statistical software to estimate flight parameters and perform statistical analyses. Data from invertebrates can corrupt analyses, so we attempted to remove these by setting a threshold based on target airspeed. We estimated target airspeed using radar-determined ground velocities and local wind data, and these airspeeds were used to classify targets as either "vertebrate" ($\geq 7\ \mathrm{m \cdot s^{-1}}$) or "invertebrate" (11). Currently, no method exists to distinguish bird from bat targets detected on portable radar (12). We computed metrics on each extracted radar target, including speed, direction, height, and location with respect to the radar. Knowing the antenna elevation and radar coverage area allowed us to compute height distributions of vertebrate and invertebrate targets.

Fatality Monitoring on Ground Beneath Turbines. We searched beneath all three turbines daily during the study period, weather permitting. We established 80-m-radius plots cleared of vegetation and centered on each turbine with parallel transect lines within each circular plot spaced 4-m apart. We searched 2 m on each side of the transect line to increase the potential of finding fresh carcasses (i.e., bat fatalities from the previous night). Searchers were paired at each turbine, and each searcher walked half of a plot. To minimize potential searcher bias, searchers switched sides and walking direction each time a turbine was searched. Searchers walked at a rate of ∼40 m/min along each transect. We began searches within 15 min of sunrise and searches ended before sunset. When a dead bat was found, we recorded the species, sex, age (where possible), condition of carcass (entire, partial, or scavenged), and estimated time of death (for example, <1 d, <2 d). In this analysis we only included data on fresh (determined by round, fluid-filled eyes and smell) fatalities estimated to have died the night before when thermal cameras recorded imagery.

SI Results

Acoustic Monitoring for Bat Echolocation Calls on Top of Turbines. We recorded 695 bat call sequences on nacelle-mounted acoustic detectors during nights the thermal cameras were deployed and the majority of calls were consistent with the parameters of those made by species of migratory tree bats: 19% (n = 131) of the recorded calls were identified as those of hoary bats; 39% (n = 271) were low-frequency calls similar to those of hoary bats and silver-haired bats, although a small proportion were likely made by big brown bats; and 42% (n = 293) were high-frequency calls characteristic of eastern red bats, tricolored bats, and evening bats. Calls unambiguously characteristic of species of *Myotis* were not detected.

Bat calls were detected during only 218 (22%) of the 993 events in which bats were observed on video, likely because if incomplete overlap in the detection areas of acoustic detectors (mostly above the nacelle) and video cameras (mostly below the nacelle). Of the video detections with associated acoustics, 9% involved bats passing in direct flight without any apparent response to the turbine and 91% involved bats exhibiting focal behaviors. Of the 258 video detections of bats active around the nacelle near the acoustic detectors where they might have been recorded had they been echolocating and within the zone of reception of the acoustic detector (45° upward angle from top and back of nacelle), only 49% had associated acoustic detections, suggesting that bats might sometimes forego echolocation while flying close to wind turbines.

Acoustic calls did not indicate that bats were frequently capturing prey on or near the turbines monitored. Of 883 call sequences recorded from the top of the three turbines between July 13 and October 4, 2012 (about 2 wk longer than video monitoring period), only 8.8% were characteristic of bats closely approaching prey or structures, and none were terminal phase calls ["feeding buzz" (9)] characteristic of bats homing in on insect prey. We observed concurrent insect activity in only 7% of the video detections of bats, suggesting a lack of correlation between obvious insect abundance and bat activity at the turbines monitored. There were only a few video observations of bats feeding around turbines in typical ways known to be associated with the pursuit and capture of insects, and those events, confirmed with wider-view NIR imagery, mostly occurred nearer to the ground and were not centered on the turbine.

Radar Monitoring of Airspace Surrounding Wind Turbines. We recorded nearly 642 h of radar data during 56 nights of data collection. The final dataset comprised over 920,000 raster images. We estimate that the radar recorded the tracks of 3–4 million flying animals during the course of the study. This was far more information than could be analyzed, so a subset of data (n = 3,458 radar tracks) was selected for further examination in relation to height distribution, which ranged from 0 to 207 m above ground level (AGL). Of those results, further screening based on airspeed eliminated 42.3% of tracks as likely to be those of invertebrates, leaving 1,995 vertebrate tracks. These were strongly skewed in favor of low flight heights, with a modal height of ∼20 m AGL. Although radar was unable to detect animals flying within the areas close to turbines imaged by video cameras, 42.4% of vertebrate radar targets moving past the turbines flew at heights within the range swept by turbine blades (∼50–120 m AGL).

Fatality Monitoring on Ground Beneath Turbines. We completed daily fatality searches after all but 5 (3%) of the 163 camera nights during which thermal imagery was gathered. We found a total of 12 fresh bat carcasses under the three turbines during fatality searches after camera nights. Tree bats composed 92% (n = 11) of fatalities, represented by eight eastern red bats (six adult female, two adult male), two silver-haired bats (both adult female), and one adult-female Seminole bat (*Lasiurus seminolus*), whereas one juvenile male big brown bat (*E. fuscus*) represented a species not considered a tree bat.

SI Discussion

We do not believe the lower observed activity at high rotation speeds represents detection bias caused by the fast-moving blades; the process for detecting bats in video imagery analyzed single video frames in which detection-area differences among frames with moving and nonmoving turbine blades were negligible (Fig. 1). It may be that tree bats have trouble flying upwind into the strong turbulence of turbines with fast-moving blades. However, our occasional observation of windward and upwind flight at high wind speeds (Movie S11) suggests that, like other animals exhibiting rheotaxis (persistent upstream orientation for the purpose of maintaining a position within a flow) (13), tree bats are capable of flying upwind against considerable airflow. It is also possible that bats visually or acoustically perceive and avoid fast-moving blades, yet we observed multiple instances in which bats flew on direct flight paths through blades rotating at full speed (from both upwind, downwind, and sometimes both directions), and in most cases they did not seem to alter course or respond to the blades until after they had passed through the plane of the moving blades (Movie S12). After such events, bats at times repeatedly returned to the areas of close encounters with blades, sometimes to be struck or displaced in the airspace again. We would not expect such returns if bats were visually or acoustically perceiving and actively avoiding the fast-moving blades, which can have tip speeds >55 m/s (200 kph). Similarly, if bats were visually perceiving and avoiding the moving blades we might expect fewer bats to occur near turbines when blades are turning on brightly moonlit nights than on dark nights, which was not the pattern we observed. Considered together, our evidence indicates that tree bats sometimes approach turbines in high winds when the blades are turning rapidly, but that they are less likely to do so than when the blades are not turning or are moving slowly, and that they may be unable to perceive fast-spinning blades.

1. Horn JW, Arnett EB, Kunz TH (2008) Behavioral responses of bats to working wind turbines. *J Wildl Manage* 72(1):123–132.
2. Hope GM, Bhatnagar KP (1979) Electrical response of bat retina to spectral stimulation: Comparison of four microhiropteran species. *Experientia* 35(9):1189–1191.
3. Mistry S, McCracken GF (1990) Behavioural response of the Mexican free-tailed bat, *Tadarida brasiliensis*, to visible and infra-red light. *Anim Behav* 39(3):598–599.
4. Müller B, et al. (2009) Bat eyes have ultraviolet-sensitive cone photoreceptors. *PLoS ONE* 4(7):e6390.

5. Winter Y, López J, Von Helversen O (2003) Ultraviolet vision in a bat. *Nature* 425(6958):612–614.
6. Hein CD, Schirmacher MR, Arnett EB, Huso MMP (2011) *Patterns of Pre-Construction Bat Activity at the Proposed Resolute Wind Energy Project, Wyoming, 2009–2010. A Final Project Report Submitted to the Bats and Wind Energy Cooperative* (Bat Conservation International, Austin, TX).
7. Britzke ER, Murray KL (2000) A quantitative method for selection of identifiable search-phase calls using the Anabat system. *Bat Res. News* 41(2):33–36.
8. Arnett EB, et al. (2008) Patterns of bat fatalities at wind energy facilities in North America. *J Wildl Manage* 71(1):61–78.
9. Griffin DR (1958) *Listening in the Dark: The Acoustic Orientation of Bats and Men* (Yale Univ Press, New Haven, CT).
10. Schmaljohann H, Liechti F, Bachler E, Steuri T, Bruderer B (2008) Quantification of bird migration by radar—A detection probability problem. *Ibis* 150(2):342–355.
11. Larkin RP (1991) Flight speeds observed with radar, a correction: Slow "birds" are insects. *Behav Ecol Sociobiol* 29(3):221–224.
12. Cryan PM, Diehl RH (2009) Analyzing bat migration. *Ecological and Behavioral Methods for the Study of Bats*, eds Kunz TH, Parsons S (Johns Hopkins Univ Press, Baltimore), 2nd Ed, pp 477–488.
13. Chapman JW, et al. (2011) Animal orientation strategies for movement in flows. *Curr Biol* 21(20):R861–R870.

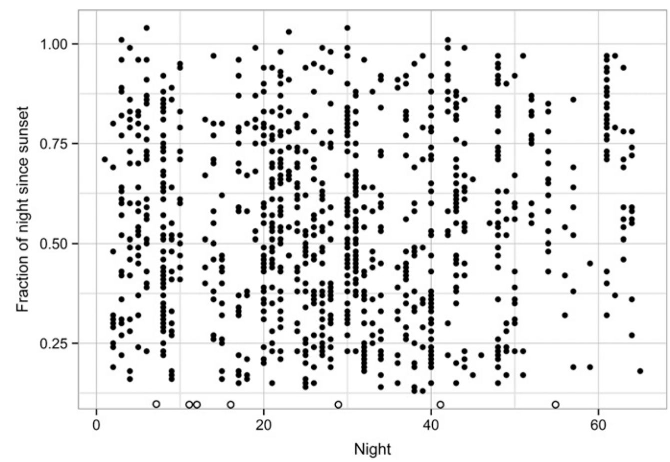


Fig. S1. Video detections of bats relative to time since sunset and survey night (night 1 = July 29, 2012) for all three wind turbines monitored. For comparability over the survey period, time since sunset is standardized as fraction of time of night to account for the seasonal change in night duration. Hollow points on the *x* axis indicate nights with no thermal camera recordings.

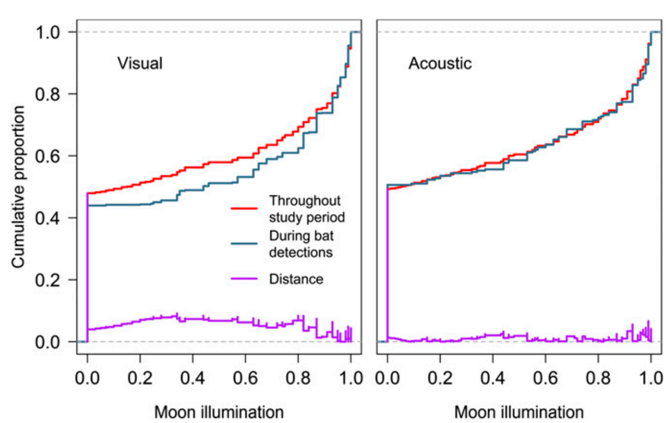


Fig. S2. Cumulative distribution functions of moon illumination during bat detections relative to that recorded throughout the study period for both visual (video) and acoustic detectors. Illumination was recorded as the proportion of lunar disk lit while visible above the horizon. Increasing values of distance (the absolute difference at any interval between the pair of functions for each of the two samples) indicate illumination levels at which bats were detected less frequently than expected; decreasing values indicate more frequent observations than expected. For visual and acoustic detections, the Kolmogorov–Smirnov test statistics were $D = 0.0822$ ($P < 0.0001$) and $D = 0.0341$ ($P = 0.9466$), respectively.

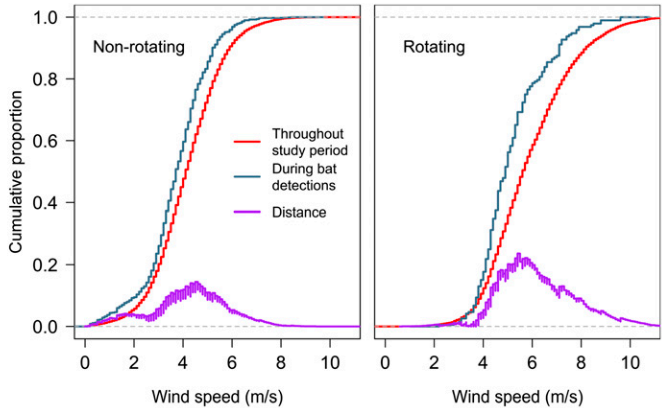
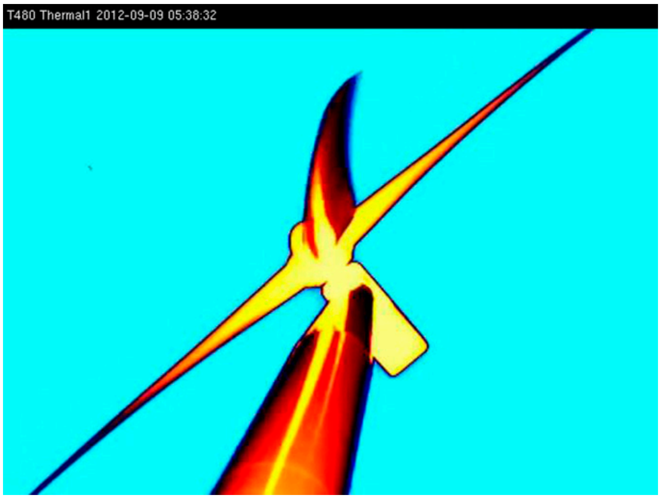


Fig. S3. Cumulative distribution functions of wind speed during bat detections relative to that recorded at night throughout the study period for both nonrotating and rotating turbine blades. Increasing values of distance (the absolute difference at any interval between the pair of functions for each of the two samples) indicate wind speeds at which bats were detected more frequently than expected; decreasing values indicate fewer than expected observations. For nonrotating and rotating turbine blades, the Kolmogorov–Smirnov test statistics were $D = 0.1444$ ($P < 0.0001$) and $D = 0.2365$ ($P < 0.0001$), respectively.

Table S1. Behaviors of bats seen altering course toward wind turbines during video monitoring, from 872 detections of "focal" behaviors

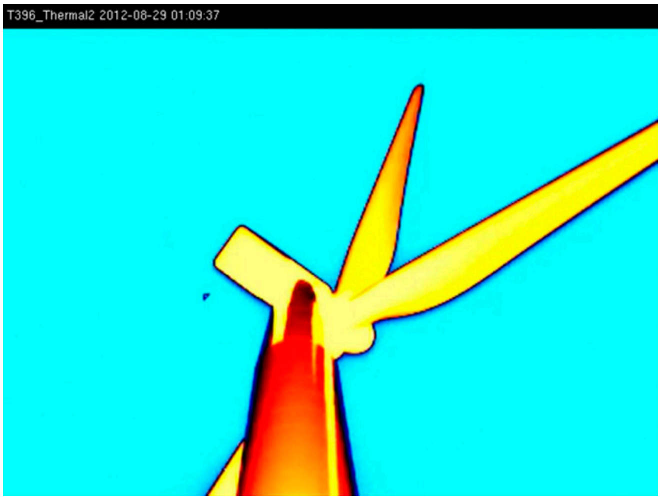
Behavior	Description
Single approach* ($n = 630$; 72%)	Alters course and approaches turbine only once before moving on (Movie S1)
Multiple looping approaches (239; 27%)	Approaches then loops outward in airspace away from turbine before returning one or more times toward monopole, nacelle, or blades (Movie S2)
Close approaches: nacelle* (258; 30%)	Flying very close (<2 m) to turbine nacelle (Movies S3 and S4)
Close approaches: monopole* (110; 13%)	Flying very close (<2 m) to turbine monopole (Movie S5)
Close approaches: blades* (55; 6%)	Closely approaches or follows turbine blade (Movie S6)
Chasing/following (14; 2%)	Chasing or following other individuals in airspace close to turbine (Movie S7)
Hovering flight (7; <1%)	Flapping flight that does not involve a clear directional component for ≥1 s (Movie S3)
Air-braking (5; <1%)	Abruptly stops forward motion of flight in midair (Movie S3)
Displacement returns (3; <1%)	Returns to turbine after being moved through airspace by blade turbulence (Movie S8)
Serpentine flight (2; <1%)	Flying on a serpentine (winding) course (Movie S9)

Values in parentheses indicate the number of times each behavior was noted, as well its proportional occurrence (%) among focal behaviors. Categories of behavior are not mutually exclusive. Those marked with an asterisk had been previously reported (13).



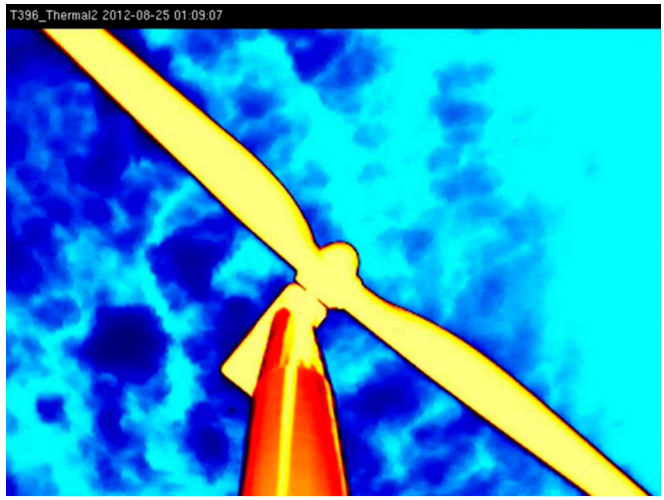
Movie S1. Bat making a single directed approach toward a turbine before changing course and flying away at ∼0530 hours on September 9, 2012. Blade rotation 14 rpm, wind out of the southwest (225°) at 4.4 m/s, and 44% moon illumination.

Movie S1



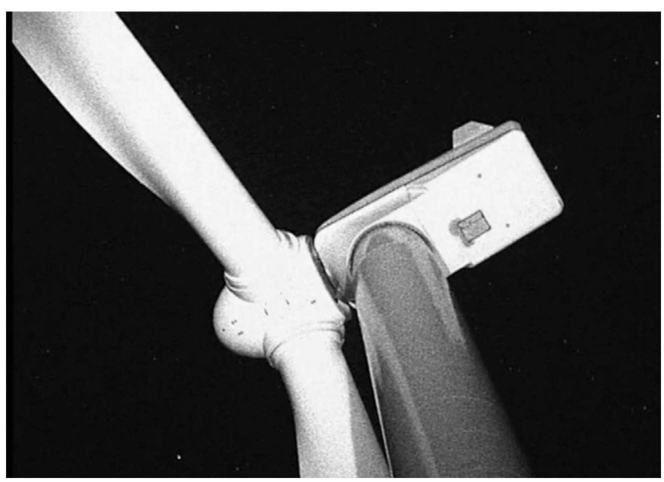
Movie S2. Bat making repeated looping approaches to leeward side of wind turbine at ∼0109 hours on August 29, 2012. Blade rotation <1 rpm, wind out of the east-northeast (58°) at 5.4 m/s, and 93% moon illumination.

Movie S2



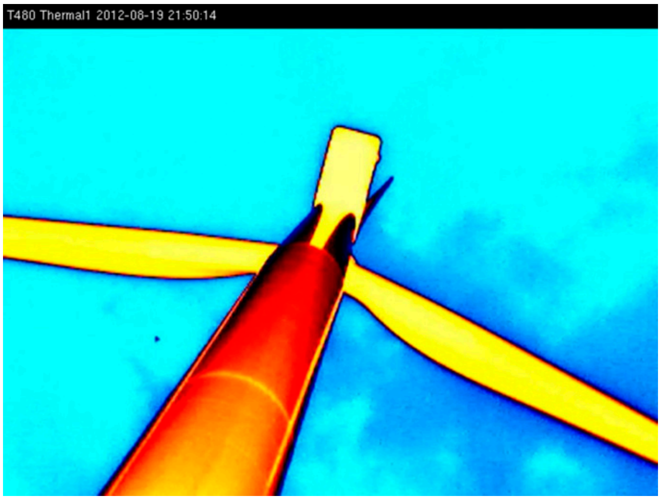
Movie S3. A hoary bat (*Lasiurus cinereus*; identified acoustically) air-brakes, hovers, and then makes repeated approaches after flying downwind past a wind turbine with curtailed blades at ~0100 hours on August 25, 2012. Blade rotation <1 rpm, wind out of the southeast (131°) at 7.2 m/s, and no moon illumination.

Movie S3



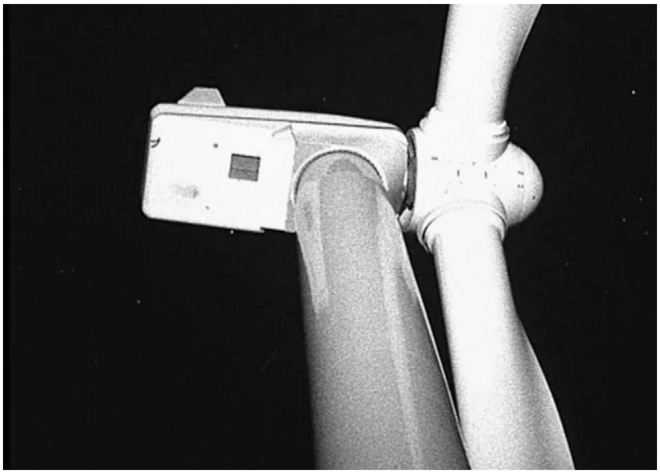
Movie S4. Near-infrared, close-up video of a bat closely approaching and investigating the upper parts of a turbine at ~0430 hours on September 19, 2013. Blade rotation <1 rpm, wind out of the west-southwest (257°) at 2.7 m/s, and no moon illumination.

Movie S4



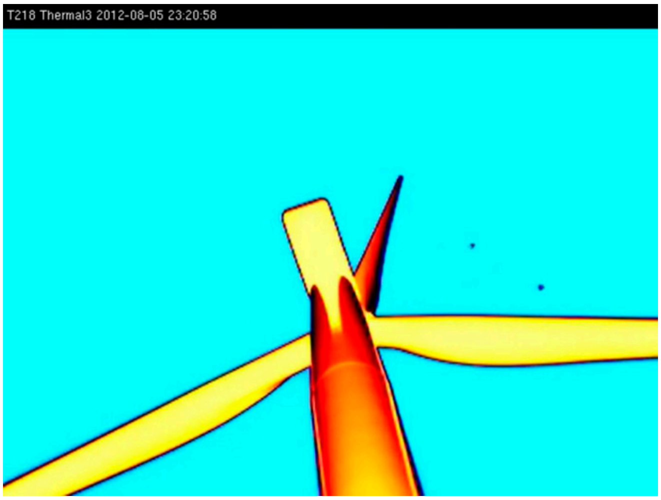
Movie S5. Bat making repeated close approaches to a turbine monopole at ~2150 hours on August 19, 2012. No blade rotation, wind out of the north-northwest (330°) at 0.4 m/s, and no moon illumination.

[Movie S5](#)



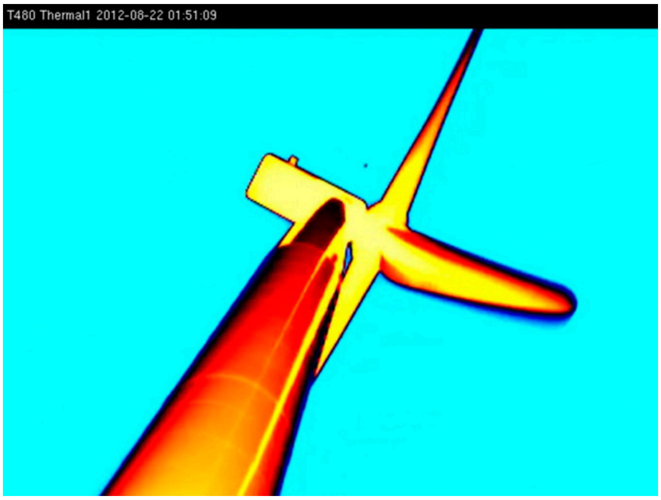
Movie S6. Near-infrared, close-up video of a bat closely following a slow moving turbine blade (shadowed on far side of monopole) at ~0240 hours on July 19, 2013 (before monitoring with thermal cameras began). Blade rotation <1 rpm, wind out of the east-northeast (70°) at 7.5 m/s, and no moon illumination.

[Movie S6](#)



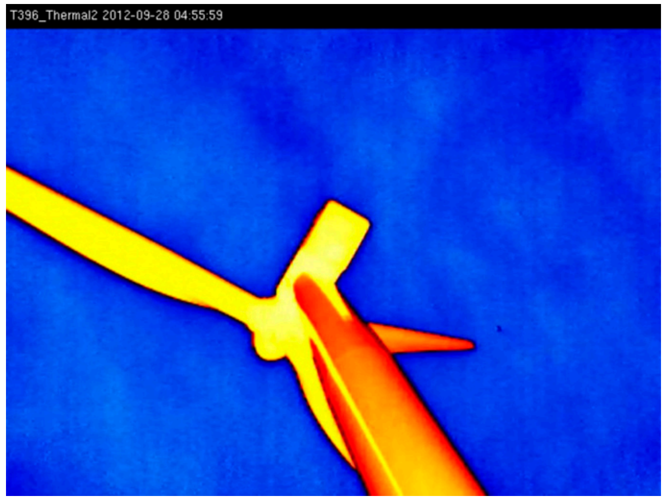
Movie S7. Two bats chasing each other near wind turbine at ~2320 hours on August 5, 2012. No blade rotation, wind out of the north-northwest (321°) at 4.6 m/s, and no moon illumination.

Movie S7



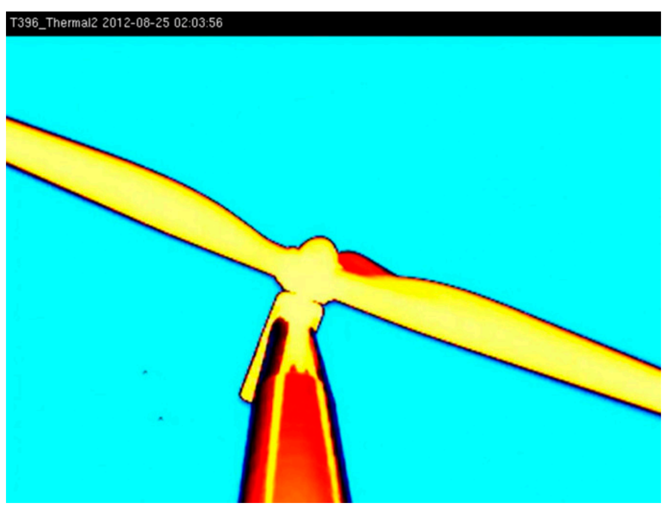
Movie S8. Bat repeatedly returning to turbine after close encounters with spinning blades at ~0150 hours on August 22, 2012. Blade rotation 14 rpm, wind out of the east (93°) at 8.0 m/s, and no moon illumination.

Movie S8



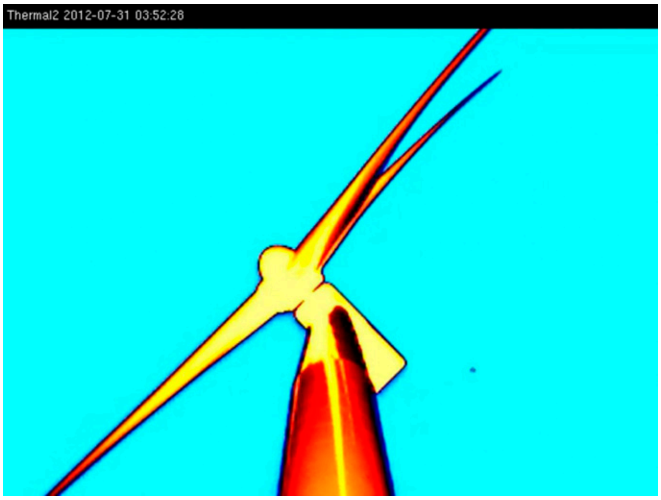
Movie S9. Bat exhibiting serpentine flight in lee of wind turbine monopole and blades at ~0500 hours on September 29, 2012. No blade rotation, wind out of the northeast (315°) at 5.8 m/s, and 96% moon illumination.

Movie S9



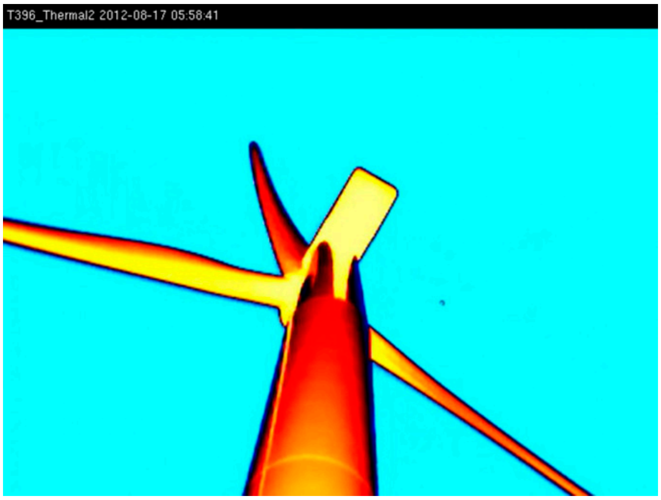
Movie S10. Two hoary bats (*Lasiurus cinereus*) interacting in midair on the leeward side of a wind turbine at ~0200 hours on August 25, 2012. The species identification was made from concurrent acoustic calls recorded from the turbine nacelle, in which navigation and social calls characteristic of this species were heard during the close midair approaches. No blade rotation, wind out of the south-southeast (157°) at 8.3 m/s, and no moon illumination.

Movie S10



Movie S11. Bat flying upwind to investigate leeward areas of a wind turbine with blades rotating at full speed at ~0350 hours on July 31, 2012. Bat makes several upwind passes through the moving blades of the turbine without clear indication that it perceives and avoids the fast-moving blades before moving through their plane of motion. Blade rotation speed 14 rpm, wind out of the southwest (228°) at 7.2 m/s, and 95% moon illumination.

Movie S11



Movie S12. Bat flying upwind toward moving turbine blades at ~0600 hours on August 17, 2012 and repeatedly returning to investigate after close encounters with blades. Blade rotation speed 14 rpm, wind out of the north-northwest (324°) at 7.6 m/s, and no moon illumination.

Movie S12

Dataset S1. MATLAB code used for finding bats and other targets in thermal surveillance camera video imagery

Dataset S1