Wind Energy Interactions with Wildlife:

Answers to Frequently Asked Questions Based on the State of the Science

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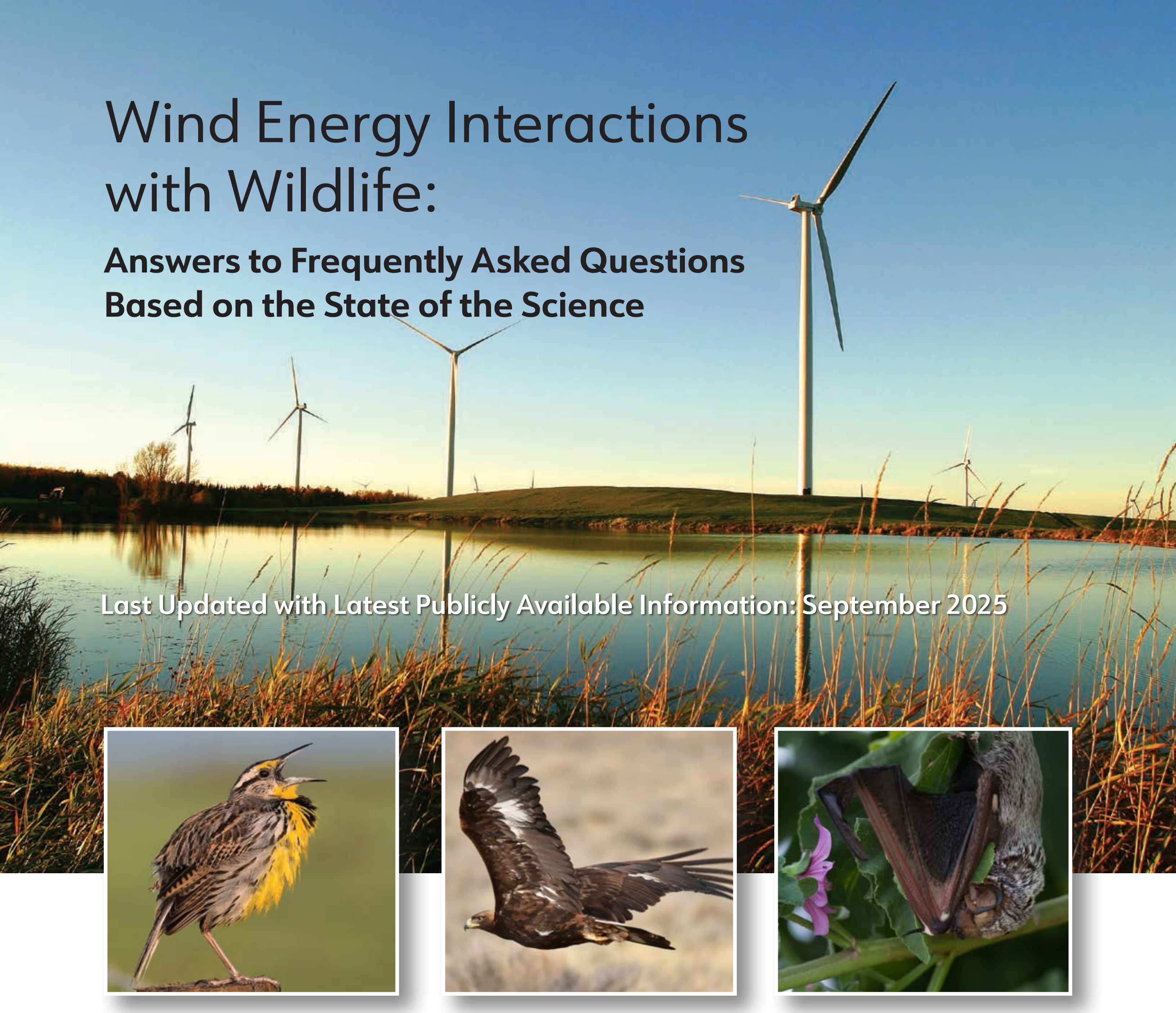

This summary reviews publicly available information about the interactions of **land-based wind power** with wildlife and the status of our knowledge regarding how to avoid or minimize adverse impacts, with a focus on North America.

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BACKGROUND: MAPLE RIDGE WIND FARM, PHOTO BY MICHAEL OKONIEWSKI, NREL • INSET, L-R: EASTERN MEADOWLARK, PHOTO BY MATTHEW PAULSON, FLICKR GOLDEN EAGLE ON SEEDSKADEE NWR, PHOTO BY USFWS MOUNTAIN-PRAIRIE, FLICKR • HOARY BAT, PHOTO BY ADAM SEARCY, FLICKR

QUESTIONS

WIND ENERGY IN THE CONTEXT OF OTHER HUMAN RELATED THREATS

- **How does wind energy benefit wildlife?**
- **How do the number of bird fatalities at wind facilities compare to other human-caused sources of direct mortality?**
- **How do the number of bat fatalities at wind energy facilities compare to other human-caused sources of mortality?**

ADVERSE IMPACTS TO WILDLIFE FROM WIND TURBINE COLLISIONS

- **What are the main adverse impacts of wind energy on wildlife in North America?**
- **Birds and Bats**
  - How do scientists measure the impacts to birds and bats from land-based wind energy?
  - Are there any recent innovations related to strike detection and activity monitoring?
  - Are bird and bat fatality rates at wind facilities consistent across regions?
  - Does turbine size (height, blade length, etc.) affect collision risk for birds and bats?
- **Birds**
  - How do types of birds differ in their risk from wind turbine collisions?
  - Do collisions between birds and wind turbines lead to population declines?
  - What behaviors are related to collision risk for birds?
- **Bats**
  - How do types of bats differ in their risk of wind turbine collisions?
  - Do collisions between bats and wind turbines lead to population declines?
  - Are there seasonal patterns of bat fatalities in the U.S.?
  - Are bats attracted to wind turbines?
  - Are bats killed by barotrauma caused by wind turbine blades?
  - How is collision risk for bats influenced by weather conditions and landscape features?
  - Are male and female bats equally at risk of collision with wind turbines?

HABITAT-BASED AND BEHAVIORAL IMPACTS TO WILDLIFE

- **Do wind facilities impact nearby bird abundance?**
- **Do wind facilities impact the survival and reproduction of nearby birds?**
- **Does wind energy impact habitat quality or movement for terrestrial vertebrates?**

STRATEGIES FOR CONSERVING WILDLIFE IMPACTED BY WIND ENERGY

- **Siting**
  - How can wind turbines be sited to reduce collision risk for raptors?
  - Can acoustic detectors be used to predict or measure collision risk for bats?
  - How do landscape variables influence bat activity and fatalities near wind facilities?
- **Collision Minimization Strategies**
  - What is currently the most reliable and effective way to reduce raptor fatalities at wind facilities?
  - What is currently the most reliable and effective way to reduce bat fatalities at wind facilities?
  - Can ultrasonic sound be used to minimize bat fatalities at wind facilities?
  - How can painting turbine blades with various colors/patterns reduce collisions?
  - Can lighting be used to minimize collision risk for birds or bats?
- **Conservation Offsets (also called Compensatory Mitigation)**
  - What conservation opportunities exist to offset impacts to birds and bats from wind energy?

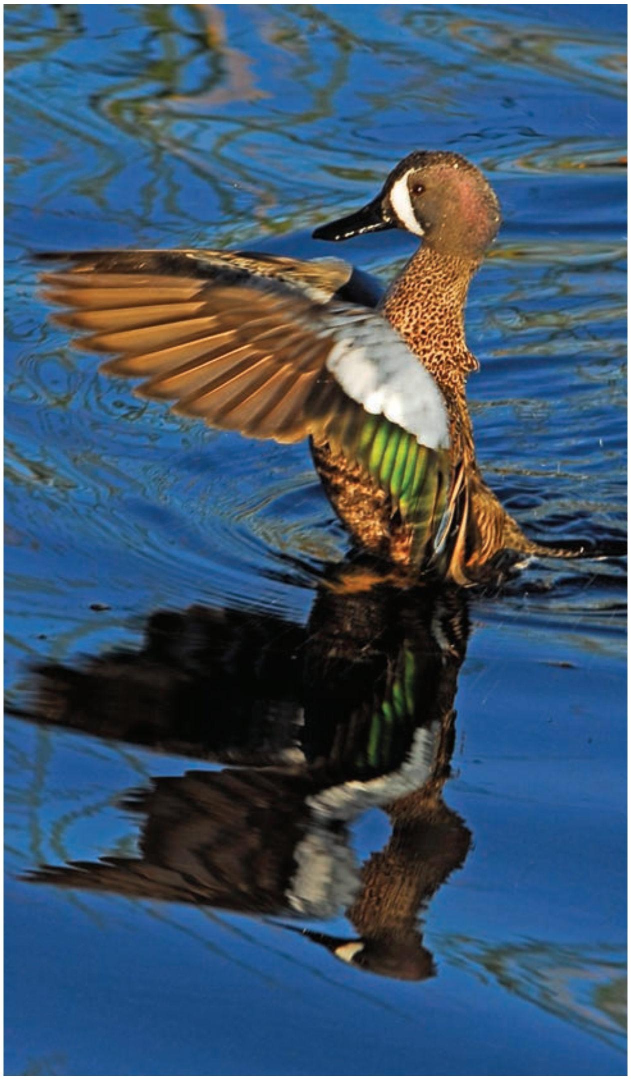
PHOTO BY IAN DICK, FLICKR

LANDSCAPE WITH TURBINES, PHOTO BY PORTLAND GENERAL, FLICKR

INTRODUCTION

Wind energy has become a substantial component of power generation and provides over 10% of the electricity generated in the United States (U.S.; U.S. Energy Information Administration 2023). Land-based wind energy in the U.S. has been projected to increase from the current capacity of 155 gigawatts (GW; as of December 2024) to between 350-646 GW by 2050 (American Clean Power 2025, U.S. Energy Information Administration 2025). While wind energy can offset fossil fuel emissions and reduce the effects of climate change on wildlife, the siting and operation of wind energy facilities also pose a risk to some species of wildlife (Arnett et al. 2008, Strickland et al. 2011, Allison et al. 2019, Katzner et al. 2025). Negative effects may include fatalities resulting from collisions with turbine blades or towers and declines in the availability, quality, or connectivity of habitat caused by construction and operation of wind energy infrastructure. For some species, concern exists that the cumulative effect of impacts from wind energy may contribute to population declines, especially as the installed capacity of wind energy increases (Gill and Hein 2022, Vander Zanden et al. 2024).

Understanding the extent and nature of wind energy's environmental impacts is essential to maximizing wind energy's benefits while addressing risks to wildlife. This summary seeks to do so by reviewing publicly available information about the interactions between land-based wind power and wildlife in North America and the status of our knowledge regarding how to avoid, minimize, and mitigate adverse impacts.



BLUE-WINGED TEAL, PHOTO BY ANDREA WESTMORELAND, FLICKR

Supporting Information

The amount of publicly available, peer-reviewed research continues to grow, reflecting the ongoing interest in understanding wind-wildlife interactions. To maintain the highest level of scientific rigor for this summary, we have based our conclusions on research that has been published in peer-reviewed journals or that appears in reports that have undergone expert, technical review.

This summary is updated and undergoes expert review periodically. Literature citations supporting the information presented are denoted in parentheses; full citations can be found online at https://rewi.org/resources/answers-to-frequently-asked-questions-based-on-the-state-of-the-science/.

Installed wind energy capacity in the U.S. continues to grow and was estimated at more than 155,000 megawatts (MW) at the end of 2024. Wind energy accounted for 10.5% of electricity generated in the U.S. in 2024, more than any other renewable energy source but substantially less than that produced by natural gas (43.3%), coal (15.2%), or nuclear power (18.2%). The power ratings of turbines installed at new projects range from 2-6.1 MW, and turbine towers range in height from 80-117 m (~262-384 ft). Turbine blades range in length from 38-79 m (~125-259ft) resulting in a maximum potential height of approximately 196 m (~643ft) and a rotor-swept area of 0.45-1.13 hectares. Blade tip speeds range from 220-290 km/hr (~134-180 mph) under normal operating conditions. The perimeter of a wind facility may encompass thousands of acres. The most current wind market information can be found at the American Clean Power Association's website.

NREL

GLOSSARY OF COMMONLY USED TERMS

Anthropogenic

Primarily or entirely caused by human activities.

Diurnal raptor

A bird of prey that is primarily active during daylight hours (e.g., eagles, hawks).

Passerines

Otherwise known as perching birds, these are birds from the order Passeriformes, the order of birds containing the most species, distinguished by feet adapted for perching (includes songbirds, ravens, and hummingbirds, among others).

Nacelle

The compartment on a wind turbine that sits atop the tower and houses the gearbox, generator, brakes and other mechanical components that control the rotation of the rotor (NYSERDA 2020).

Installed capacity

Also known as nameplate generating capacity, this is the maximum amount of electricity that a wind turbine or wind energy project can produce under ideal conditions, as designated by the turbine manufacturer (NYSERDA 2020).

Curtailment

The slowing or stopping of wind turbine rotors from spinning, often done by feathering the blades (i.e. adjusting the blade pitch so as to pick up less wind).

Cut-in wind speed

The wind speed at which the wind turbine engages with the grid (often the speed at which the wind turbine begins producing power).

RED-TAILED HAWK AND TURBINES , PUGET SOUND ENERGY WILD HORSE WIND FACILITY

Rotor swept zone

The circle of airspace covered by the wind turbine blades when the rotor is spinning.

Minimum rotor sweep

Also referred to as the air gap, this is the distance between the ground and the rotor swept zone at the closest point to the ground.

WIND ENERGY IN THE CONTEXT OF OTHER HUMAN RELATED THREATS

How does wind energy benefit wildlife?

Wind energy provides benefits to wildlife and ecosystems by reducing reliance on fossil fuels which contribute to climate change, pollution, and habitat loss.

Wind energy can offset greenhouse gas emissions from fossil fuel use and thus reduce the negative impacts of climate change (Barthelmie and Pryor 2021) that have been identified as primary threats to wildlife (Parmesan and Yohe 2003, Bateman et al. 2020, Festa et al. 2023, Adams et al. 2024). By offsetting fossil fuel extraction and burning, wind energy also provides several other wildlife benefits including little or no water use associated with electricity production, decreased air and water pollution, and reduced habitat destruction and degradation due to mining and drilling (Butt et al. 2013, Siler-Evans et al. 2013, Allison et al. 2019, Adeyeye et al. 2020). Katzner et al. (2022) highlighted the importance of evaluating the direct effects of renewable energy against the adverse effects of climate change and of non-renewable energy production, recognizing that the balance between net benefits and adverse effects will differ among species and systems.

How do the number of bird fatalities at wind facilities compare to other human-caused sources of direct mortality?

The estimated total number of collision fatalities of most bird species at wind energy facilities is much smaller (hundreds to thousands of times lower) than other leading anthropogenic sources of avian mortality.

The number of birds killed at wind energy facilities is one to four orders of magnitude lower than from other anthropogenic sources of mortality, including feral and domestic cats, power transmission lines, fossil fuels, poisoning, and collisions with buildings and windows, cars, and communication towers (Sovacool 2009, Longcore et al. 2012, Calvert et al. 2013, Loss et al. 2013, 2013b, 2014a, 2014b, 2014c, Erickson et al. 2014). Collision fatalities from wind turbines may be relatively more important to

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INDIANA BAT, PHOTO BY USFWS, MIDWEST REGION, FLICKR

populations of diurnal raptors (birds of prey active during the day), particularly golden eagles. However, collisions with wind turbines make up less than 5% of anthropogenic mortality for golden eagles (USFWS 2016, Millsap et al. 2022). Despite fossil fuels being the predominant energy source for electricity, the majority of scientific research has focused on wildlife mortality due to wind energy, with minimal research on impacts from fossil fuels, hindering comparison of their impacts (Loss et al. 2019).

How do the number of bat fatalities at wind energy facilities compare to other human-caused sources of mortality?

White nose syndrome (WNS) has rapidly caused >90% mortality in populations of several cave-dwelling species of bats in North America. In comparison, wind energy is considered by experts to be a leading conservation concern for several migratory tree-roosting bats, but fatality estimates due to other causes for these species are not available for comparison.

Experts have identified the top IUCN (International Union for the Conservation of Nature and Natural Resources)-classified threats to bats across North America to be climate change (drought), disease/invasive species (WNS), agriculture (livestock farming), and energy production (wind energy), although wind energy has been identified as the leading threat to hoary, silver-haired, and eastern red bats (COSEWIC 2023, Adams et al. 2024). Wind energy and WNS have been the leading causes of documented mortality events for bats in recent decades (O'Shea et al. 2016), but they have very different scales of impact and affect different species. WNS has caused rapid mortality exceeding 90% in populations of several species of cave dwelling bats, including northern long-eared (Endangered), Indiana (Endangered), tricolored (proposed Endangered), and little brown bats (status under review). In contrast, WNS does not significantly impact the relatively abundant species of bats recorded most frequently as fatalities at wind energy facilities: hoary bats, silver-haired bats, eastern red bats, and Mexican free-tailed bats (Alves et al. 2014, AWWI 2020b). Other human-caused sources of direct mortality for bats include vehicle and building collisions, predation by feral and domestic cats, and poisoning from pesticides (Clark and Lamont 1976, Reidinger 1976, Pybus et al. 1986, Michalak et al. 2013, Hsiao et al. 2016, Wu et al. 2020, COSEWIC 2023); the relative impact of these mortality causes compared with wind turbine collisions is not well understood.

Land-use change and climate change interact to create additional anthropogenic stressors to bats, including loss of prey availability, roost sites, and drinking water (Adams and Hayes 2008, 2021, Jones and Rebelo 2013). However, the ways in which climate change impacts North American bats require further investigation and are likely species-specific. Rising temperatures may disrupt energy balances by impacting torpor and hibernation, increasing water needs, and causing a mismatch between insect emergence and bat foraging times (Jones and Rebelo 2013). Additionally, climate change is likely to increase the frequency and intensity of wildfires, affecting both summer habitats in boreal forests and winter habitats in the USA and Mexico (Abatzoglou and Williams 2016, Goss et al. 2020). However, climate change could also benefit some North American bat species overall by allowing for range expansion (Gonçalves et al. 2021) and mitigating some harmful effects from WNS (McClure et al. 2022).

ADVERSE IMPACTS TO WILDLIFE FROM WIND TURBINE COLLISIONS

This section outlines what is known and where there is remaining uncertainty about the patterns of bird and bat collision fatalities, particularly in the continental U.S. We first examine patterns that apply to both birds and bats, then describe patterns specific to either birds or bats.

What are the main adverse impacts of wind energy on wildlife in North America?

For flying birds and bats, the primary impact of wind energy is collision mortality. For ground-dwelling wildlife, habitat quality, availability, and connectivity may be affected.

The siting and operation of wind energy facilities pose a risk to some species of wildlife (Arnett et al. 2008, Strickland et al. 2011, Allison et al. 2019). Negative effects may include fatalities resulting from collisions with turbine blades or towers and declines in the availability, quality, and/or connectivity of habitat caused by construction and operation of wind energy infrastructure (Katzner et al. 2025). For some species, concern exists that the cumulative effect of impacts from wind energy may contribute to population declines, especially as the installed capacity of wind energy increases.

Some bird and bat fatalities have been recorded at all wind energy facilities for which records are publicly available, although fatality rates vary widely and total fatalities are difficult to estimate. For birds, mean estimated fatality rates (i.e., the average estimated number of fatalities after correcting for variation in detectability and sampling intensity) from most studies range from 2.5 to 6 birds per MW (installed capacity, here and throughout) per year[1] for all species combined (Strickland et al. 2011, Loss et al. 2013, Erickson et al. 2014, REWI 2025). Fatality rates vary substantially among studies and facilities, and in the data set contained within the American Wind Wildlife Information Center (AWWIC), 75% of studies reported 3.44 or fewer fatalities per MW per year, with a median fatality estimate of 1.94 birds per MW per year (REWI 2025). Smallwood (2013) and Zimmerling et al. (2013) extrapolated data from available studies from wind energy facilities to provide rough estimates of nationwide totals: approximately 467,097 – 679,089 bird deaths per year in the U.S. and 13,330 – 21,600 bird deaths per year in Canada, though wind energy production has approximately tripled since those studies were published (American Clean Power 2025). Regardless, these totals were a small fraction of annual take when compared to bird fatalities from feral and domestic cat depredation (2.6 billion), and collisions with building windows (624 million), vehicles (213.4 million), and power lines (48.4 million; Loss et al. 2015).

Estimated bat fatality rates tend to be higher and more variable than bird fatality rates, generally ranging from a mean of 4 to 7 bats per MW per year, but with some individual projects along forested ridgelines of the central Appalachians reporting rates close to 50 bats per MW per year (Arnett et al. 2008, Strickland et al. 2011, Hein et al. 2013). Of the data included in AWWIC, 75% of post-construction mortality monitoring studies reported estimates of fewer than 7.7 bat fatalities per MW per year, with a median of 3.0 bats per MW per year (AWWI 2020*a*).

GOLDEN-CROWNED KINGLET, PHOTO BY ZANATEH, FLICKR

[1] Fatality rates are typically reported on a per turbine basis or per nameplate capacity (MW). We report fatality rates per nameplate capacity to account for differences in turbine capacity, which ranges from 100 kW to 3.0 MW or more. We acknowledge that this reporting format has difficulties, especially when it comes to assessing the effects of repowering and the potential differences in fatalities due to variations in the physical components of the turbines (Huso et al. 2021).

SILVER-HAIRED BAT, PHOTO BY LASSENNPS

Some species may avoid areas near wind facilities during construction or operation, temporarily or permanently reducing the amount of available habitat (Allison et al. 2019). See the section "*Habitat-Based Impacts to Wildlife*" for more details.

Birds and Bats

How do scientists measure bird and bat fatalities at wind energy facilities?

Many wind energy facilities hire biologists to survey land around a sample of turbines for carcasses of birds and bats, using survey data to estimate total fatalities at the facility.

At many wind energy facilities, standardized searches are conducted for the carcasses of birds and bats that collided with turbines. The number of carcasses found is adjusted based on the proportion of area searched and field trials that estimate the carcasses missed due to scavenging and imperfect searching. The number of studies reporting results of collision fatality monitoring at operating wind energy facilities has increased substantially over the years, and studies conducted at more than 100 projects are publicly available (Arnett and Baerwald 2013, Loss et al. 2013, Erickson et al. 2014, Thompson et al. 2017). Fatality reports for substantially more projects are stored within the American Wind Wildlife Information Center (AWWIC), a cooperative initiative of the Renewable Energy Wildlife Institute (REWI) and wind energy companies, which includes both publicly available and private data (AWWI 2020*a*, REWI 2025). AWWIC also includes data from projects in regions that have few publicly available fatality studies, which has improved understanding about geographic variation in collision fatalities of both birds and bats (e.g., Lloyd et al. 2023). In addition, protocols for carcass searches have become more standardized, and recent advances in estimating fatalities from carcass counts have facilitated comparisons of results from separate studies (Dalthorp et al. 2018).

Are there any recent innovations related to strike detection and activity monitoring?

An emerging field of strike detection and activity monitoring technologies seeks to improve fatality monitoring, our understanding of collision risk, and our ability to minimize the risk of collisions.

Technologies are being developed to record turbine strikes or to monitor the activity of individual animals in the rotor-swept area through the use of thermal cameras, visual cameras, impact sensors, and/or microphones (Albertani et al. 2021, Happ et al. 2021, Clocker et al. 2022, Aghababian 2023). Such technologies could be useful for improving fatality monitoring (especially in the offshore environment where carcasses cannot be recovered), or for providing information about the exact time, environmental conditions, or animal behavior preceding collisions, which could inform the development of risk minimization measures. Given the high cost of fatality monitoring, especially when using dog teams, there is also increasing interest to investigate the validity of using real-time acoustic bat activity as a proxy for collision risk at operating wind turbines in some circumstances, but so far results are inconclusive (Peterson et al. 2021, 2025).

Are bird and bat fatality rates at wind facilities consistent across regions?

Bat fatality rates appear to vary substantially among regions in the U.S. while bird fatality rates do not.

Estimated fatality rates of bats are highest at wind energy facilities in the upper Midwest and eastern forests and tend be much lower throughout the Great Plains and western U.S. (Arnett and Baerwald 2013, Hein et al. 2013). Median fatality estimates among studies contained in AWWIC ranged from 0.7 bats per MW per year in the Pacific Northwest to 8.4 bats per MW per year in the Midwest (AWWI 2020*a*). Regional variation in methodology for conducting fatality studies may be a confounding factor, and thus apparent differences in bat fatality rates among regions or habitats should be interpreted with caution (Garvin et al. 2024). Both migratory and resident bats are killed at wind energy facilities, though the proportion of migratory individuals varies by species, site, and season (Wieringa et al. 2024).

In contrast with bats, there is relatively little geographic variation in the rate of bird fatalities per MW per year (Erickson et al. 2014, REWI 2025). Median fatality estimates among studies contained in AWWIC ranged from 1.67 birds per MW per year in the Northern Rockies to 2.78 birds per MW per year in the Southwest (REWI 2025).

BLACK THROATED BLUE WARBLER, PHOTO BY KELLY COLGAN AZAR, FLICKR

Does turbine size (height, blade length, etc.) affect collision risk for birds and bats?

The effect of turbine size on bird and bat collision fatalities remains uncertain and the most influential turbine specifications likely differ for different species groups.

The tower height and blade length of turbines have been increasing in new turbine models with higher generation capacity. These changes allow the same amount of power to be generated with fewer turbines, but may affect risk. For instance, taller turbines may elevate collision fatalities due to greater overlap with flight heights of nocturnal-migrating songbirds and bats (Johnson et al. 2002, Mabee and Cooper 2004, Mabee et al. 2006, Barclay et al. 2007). A larger rotor-swept area (due to longer blades) also presumably expands the collision risk zone per turbine. Some studies show that fatalities of migratory birds and bats are more frequent at taller turbine towers (Barclay et al. 2007, Baerwald and Barclay 2009, Loss et al. 2013). In contrast, raptor fatalities were reported to have declined in two studies at Altamont Pass Wind Resource Area (California) after smaller turbines were replaced by fewer, taller turbines (Smallwood and Karas 2009, Ventus Environmental Solutions 2016). The effect of turbine height is potentially confounded by changes in the type of turbine: typically, lattice-tower turbines (which provided perching sites on the towers) have been replaced by taller monopole turbines. Other studies report mixed, species-specific effects (Anderson et al. 2022, Garvin et al. 2024) or found no effect of turbine size on fatalities (Barré et al. 2023*a*). Huso et al. (2021) suggested that fatality rates generally increase relative to the total amount of power generated across a wind facility, rather than to the size or generation capacity of the individual wind turbines used at a project.

Birds

How do types of birds differ in their risk from wind turbine collisions?

Most bird fatalities at wind energy facilities are songbirds, though fatalities of diurnal (active during the day) raptors are observed at elevated rates compared to the relatively low abundance of these species.

At least 314 of the 719 bird species that regularly occur in the U.S. have been recorded as collision fatalities (Partners in Flight 2024, REWI 2025). Small passerines (songbirds; all species in the order Passeriformes except for the larger corvids: magpies, crows, and ravens) account for approximately 57 - 59% of fatalities reported in both publicly available and private studies conducted at U.S. wind energy facilities (Erickson et al. 2014, REWI 2025). The representation of small passerines in post-construction fatality studies is less than expected given that this group of birds makes up nearly 90% of all land birds (Will et al. 2019).

However, searcher efficiency trials[2] indicate that small birds have significantly lower detection rates than large birds (Peters et al. 2014) and are removed more quickly by scavengers (Barrientos et al. 2018). Thus, unadjusted counts of carcasses likely underestimate the proportion of fatalities composed of small passerines. Passerine fatalities occur year round, with modest peaks during spring and fall at most wind energy facilities, presumably reflecting the passage of migrants during these times (Strickland et al. 2011, Erickson et al. 2014, Conkling et al. 2023, REWI 2025). Seasonal peaks in fatalities are more often observed in woodland bird species, and less often in grassland species, which are more likely to be year-round residents (Lloyd et al. 2023).

Diurnal raptors (excluding vultures) account for approximately 6.8% of reported fatalities, which is more than expected given their relatively small population sizes (AWWI 2020*b*). This may reflect an increased vulnerability to collision among this group of birds or may be an artifact of the higher detectability of carcasses of large birds (Peters et al. 2014, Nasman et al. 2021). Red-tailed hawk and American kestrel are the most commonly reported raptor fatalities; they are also the two most abundant diurnal raptors in the U.S. and raptor carcasses tend to persist longer (increasing chances of detection) than those of other species (DeVault et al. 2017, AWWI 2020*b*, Hallingstad et al. 2023).

The vulnerability of prairie grouse to collisions with turbines appears low; only greater sage-grouse and sharp-tailed grouse have been reported as fatalities in AWWIC, and the totals for both species were low (four and two carcasses, respectively; AWWI 2020*b*, Lloyd et al. 2022). Fatalities of some upland game birds, especially the non-native ring-necked pheasant and gray partridge, are relatively common, accounting for approximately 4% of all bird fatalities (REWI 2025). Fatalities of grouse and other low-flying game birds are likely to be caused by collisions with the turbine tower, rather than the blades (Stokke et al. 2020).

Fatalities of waterbirds, waterfowl, and other species characteristic of freshwater, shorelines, open water, and coastal areas (e.g., ducks, gulls and terns, shorebirds, loons and grebes) are reported infrequently at land-based wind facilities, making up 6.8% of bird fatalities (Kingsley and Whittam 2007, Gue et al. 2013, REWI 2025). There is evidence that some large birds (cranes, gulls, geese, raptors, etc.) may actively avoid collision by flying midway between turbines or adjusting flight altitude to avoid the rotor-swept area, or may avoid using habitat near turbines for stopover habitat during migration (Pearse et al. 2021, Therkildsen et al. 2021).

Do collisions between birds and wind turbines lead to population declines?

Fatality rates may be sufficient to affect population growth rates in some bird species, including several raptors, but wind energy has not been shown to cause or contribute to bird population declines.

In assessing evidence for this question, it is important to note that evidence for a reduced population growth rate (which could mean slower positive growth) is not the same as evidence for a negative growth rate (declining population). For most small passerine (songbird) species, current turbine-related fatalities constitute a very small percentage of their total population size (typically <0.02%), even for those species with the most frequently reported fatalities (Kingsley and Whittam 2007, Kuvlesky et al. 2007, Erickson et al. 2014). Conkling et al. (2022) modeled population growth for priority bird species occurring at wind energy facilities in California and concluded

HORNED LARK, PHOTO BY KENNETH COLE SCHNEIDER, FLICKR

[2] Searcher efficiency trials involve placement of bird and bat carcasses to estimate the number of carcasses missed by field technicians during fatality surveys. This estimate is combined with other sources of detection error, such as scavenger removal of carcasses, to adjust the number of carcasses found during fatality surveys and provide a more accurate estimate of collision fatalities.

that four of these species would be vulnerable to population decline in a scenario where wind turbines caused each species 1,000 additional fatalities per year. Most species have a mix of local and non-local fatalities, with approximately half of individual birds killed at wind energy facilities in California migrating through the region at the time of collision (Vander Zanden et al. 2024). Peaks in non-local bird fatalities that coincide with spring and fall migration (Vander Zanden et al. 2024) indicate that wind energy facilities have impacts beyond the resident population. Demographic modeling and long-term monitoring indicate a potential for population-level impacts at current or projected levels of collision fatalities for some raptor species including barn owl, ferruginous hawk, golden eagle, American kestrel, red-tailed hawk, and prairie falcon (Carrete et al. 2009, Bellebaum et al. 2013, Hunt et al. 2017, Diffendorfer et al. 2021, Watson et al. 2025). A higher proportion of subadult breeding golden eagles observed within the Altamont Pass Wind Resource Area compared to the surrounding area suggests that wind energy may cause demographic shifts due to adult mortality or displacement (Wiens and Kolar 2021). Although golden eagle populations are stable in the western U.S., anthropogenic take from all sources (shooting, electrocution, poisoning, collisions with vehicles, powerlines, and turbines, etc.) of golden eagles has been estimated to exceed the allowable take level that can be sustained annually by the population and, unless mitigated for, additional fatalities could contribute to population decline (Millsap et al. 2022, Gedir et al. 2025).

What behaviors are related to collision risk for birds?

The relationship between bird behavior and bird collision risk is complex and not well understood.

Flight characteristics including hovering, song flights, head position, flight tortuosity, and active flight (as opposed to soaring) may be collision risk factors for some bird species (Linder et al. 2022, Balmori-de la Puente and Balmori 2023). Some species, such as common raven and northern harrier, appear to fly around wind turbines and actively avoid collisions (Kingsley and Whittam 2007, Kuvlesky et al. 2007, Smallwood et al. 2009, Pearse et al. 2021, Therkildsen et al. 2021, Farfán et al. 2023). Foraging behavior (e.g. hovering, contouring, kiting, diving) within the height of the rotor-swept zone may contribute to the relatively high fatality rates of some raptor species, such as red-tailed hawk, golden eagle, American kestrel, and prairie falcon (Smallwood et al. 2009). Golden eagles may be less wary of wind turbines in preferred habitat and in high wind speeds (Fielding et al. 2021). Wind facilities located on ridgetops pose elevated collision risk to raptor species that soar using orographic lift (Estellés-Domingo and López-López 2024).

Bats

How do types of bats differ in their risk of wind turbine collisions?

Migratory tree-roosting bat species make up the majority of collision fatalities in North America, though Mexican free-tailed bat fatalities are common across their range in the southern U.S.

At least 25 species of bats have been recorded as collision fatalities in North America, but most (70%) of fatalities reported to date are from three migratory tree-roosting species (hoary bat, eastern red bat, and silver-haired bat; Kunz et al. 2007, Arnett et al. 2008, Arnett and Baerwald 2013, Hein et al. 2013, AWWI 2020*a*). It remains uncertain why these three species appear more vulnerable to collision fatalities than other bat species, though a "pell-mell" migration strategy, in which hoary bats and eastern red bats often initially move northward before migrating south during the fall, could elevate fatality risk for these species by increasing their migration route length and

EASTERN RED BAT, PHOTO BY MATTHEW O'DONNELL, FLICKR exposure to wind turbines (Campbell et al. 2025).

Mexican free-tailed bat, one of the most abundant bat species in the U.S. (Harvey et al. 2011), constitutes a substantial proportion of the estimated number of bats killed at wind energy facilities; percentages vary from 41 to 86% of bat fatalities reported across regions that encompass the species' range over most of the southern half of the U.S. (Arnett et al. 2008, Miller 2008, Piorkowski and O'Connell 2010). As with the migratory tree-roosting bats, it is unclear what factors aside from abundance might explain why the Mexican free-tailed bat accounts for a relatively high percentage of fatalities.

White-nose syndrome (WNS) is considered the leading cause of population declines among cave dwelling species of bats (Cheng et al. 2021), several of which are protected in the U.S. by the Endangered Species Act. Although these species make up a small fraction of carcasses found at wind turbines, their populations are so depressed by WNS that additional take by wind turbines may limit the viability of these species (Erickson et al. 2016, Cheng et al. 2021).

Do collisions between bats and wind turbines lead to population declines?

For populations of migratory tree-roosting bats, both baseline status and the impacts of wind energy are poorly understood but current science suggests that fatalities at wind facilities may contribute to declines. In cave-dwelling bat species, wind fatalities may amplify population declines due to white-nose syndrome (WNS).

Bats are long-lived, and many species have relatively low reproductive rates, making populations susceptible to localized extinction (Barclay and Harder 2003, Jones et al. 2003). Bat populations of several North American cave-dwelling species have experienced significant declines—up to 90% in some cases—following the emergence of white-nose syndrome (WNS), a fungus-caused disease that is estimated to have killed millions of bats in North America since it was first discovered in a cave in New York in 2007 (Frick et al. 2010, Turner et al. 2011, Hayes 2012, Cheng et al. 2021, Udell et al. 2022). Added mortality from wind turbine collisions may exacerbate declines among WNS-vulnerable bat species (Erickson et al. 2016).

Population sizes for migratory tree-roosting bat species, which are the most frequently observed species in wind turbine fatality surveys, are unknown and challenging to estimate; as such we don't know whether current or future collision fatality levels represent a significant threat to these species (Kunz et al. 2007, Arnett et al. 2008, Arnett and Baerwald 2013, Reichert et al. 2021). Demographic modeling indicates a potential for population-level impacts at current or projected levels of collision fatalities for hoary bats (Frick et al. 2017, Friedenberg and Frick 2021), which has sparked widespread concern and research on the impacts of wind energy on bats, and the status and trends of migratory tree bats. Recent evidence is mixed regarding population trends in migratory tree-roosting bat populations. While Green et al. (2021) found no evidence of decline at a local site and others (i.e. Cornman et al. 2021, Udell et al. 2022) reported inconclusive results, multiple studies have reported likely declines (Rodhouse et al. 2019, Davy et al. 2021, COSEWIC 2023, Adams et al. 2024). Studies have estimated effective population sizes or trends of tree bats from genetic and acoustic data, respectively, and these estimates might be useful as baselines for evaluating future impacts of collision mortality and other threats to bats (Korstian et al. 2013, Vonhof and Russell 2015, Sovic et al. 2016, Cornman et al. 2021, Reichert et al. 2021, Hale et al. 2022, Udell et al. 2022).

Are there seasonal patterns of bat fatalities in the U.S.?

Bat fatalities at wind facilities in the northern U.S. peak during the late summer and early fall.

There is a broad consensus in studies from the northern U.S. that have shown a peak in the incidence of bat fatalities in late summer and early fall, coinciding with both migration and the mating seasons of migratory tree-roosting bats (Kunz et al. 2007, Arnett et al. 2008, Baerwald and Barclay 2011, Jain et al. 2011, Arnett and Baerwald 2013). Hoary bat, eastern red bat, and big brown bat fatalities peak in August, while silver-haired bat and Mexican free-tailed bat fatalities peak in September and October (Lloyd et al. 2023). A smaller peak in fatalities during spring migration has been observed for some bat species at some facilities, most consistently for silver-haired bats (Arnett et al. 2008, Lloyd et al. 2023). In the larger sample of projects contained in AWWIC, the incidence of total bat fatalities peaks in August in northern areas and September in areas farther south (AWWI 2020*a*).

Are bats attracted to wind turbines?

Some bat species may be attracted to wind turbines, but mechanisms for attraction remain uncertain.

It has been hypothesized that the relatively high number of bat fatalities that have been observed for some species and some locations may be explained by attraction to wind turbines or wind energy facilities (Horn et al. 2008, Cryan and Barclay 2009, Solick et al. 2020, Richardson et al. 2021). There could be multiple factors attracting bats to wind turbines depending on the species (Goldenberg et al. 2021, Guest et al. 2022). Several potential attractants have been proposed, including the sounds produced by turbines, opportunities for foraging and water, potential roost sites, and opportunities for mating or other social behavior (Kunz et al. 2007, Cryan and Barclay 2009, Cryan et al. 2012, 2014, Bennett et al. 2017, Foo et al. 2017). Ultrasonic noise generated by turbines is unlikely to attract bats to turbines because ultrasound attenuates too quickly to be detected over large distances (Guest et al. 2022, Jonasson et al. 2024). Vision is likely the most important sense used by bats to perceive wind turbines from afar, and attraction to wind turbines may be stronger when bats are farther from forested habitat (Leroux et al. 2022, Jonasson et al. 2024). Further, bats have been observed engaging in investigatory behavior at turbine towers, and guano has been found on turbines, supporting the hypothesis that bats may roost on wind turbines (Bennett et al. 2017, Guest et al. 2022). Insect swarming has been documented at turbine nacelles (the shell for the gearbox and generator at the top of the tower), and there is some evidence for a positive correlation between insect abundance and bat activity at wind turbines at nacelle height (de Jong et al. 2021, Voigt 2021). There is also evidence of bats foraging at wind turbines and consuming a variety of insects including crop pests, though the extent to which foraging activity is a collision risk factor is unknown (Foo et al. 2017, Guest et al. 2022, Hale et al. 2025). A hypothesis that bats may mistake the echolocation signal of a turbine tower as a water resource remains unproven (Bennett and Hale 2018). Bats have been observed engaging in behaviors associated with scent-marking at meteorological towers (Tyler 2023). If scent marking does occur at wind turbines, it is unlikely to attract bats to a turbine from a distance greater than a few meters (Guest et al. 2022, Tyler 2023, Clerc et al. 2025*b*). Mating season coincides with the fall migration and peak bat fatality season for many species of bats, and while there are potential lines of evidence related to the hypothesis that bats are attracted to wind turbines for mating opportunities (Cryan 2008, Cryan et al. 2012), there is not yet substantial research on this topic (Guest et al. 2022).

EASTERN RED BAT, PHOTO BY YULIA KRISTOF, FLICKR

Are bats killed by barotrauma caused by wind turbine blades?

The likely cause of death for most bats at wind facilities is blunt force trauma from collisions with turbine blades. Barotrauma does not appear to be an important source of bat mortality at wind energy facilities.

Forensic examination of bat carcasses found at wind energy facilities suggests that the importance of barotrauma, i.e., injury resulting from rapidly altered air pressure caused by fast-moving wind turbine blades (Baerwald et al. 2008, Brownlee and Whidden 2011), is substantially less than originally suggested (Grodsky et al. 2011, Rollins et al. 2012). Theoretical assessments also cast doubt on the importance of barotrauma: fluid dynamics models indicate that there is a low likelihood of bats encountering sufficiently large pressure changes around blades to produce barotrauma, particularly without also experiencing blunt force trauma from collision (Lawson et al. 2020).

How is collision risk for bats influenced by weather conditions and landscape features?

Collision risk for bats increases in low wind speeds, high temperatures, and near forested habitats and open water.

Within a season, bat activity and collision risk are influenced by nightly wind speed and temperature, with increasing evidence that bat fatalities occur primarily on nights with low wind speed (Weller and Baldwin 2012, Barré et al. 2023*a*, Whitby et al. 2024). Other variables such as wind direction, changing barometric pressure, precipitation, date, or time relative to sunset and sunrise may also be important risk factors (Baerwald and Barclay 2011, Farnsworth et al. 2021, Gorman et al. 2021, Gottlieb et al. 2024). Migratory tree-roosting bats migrating along a ridgeline in the Appalachian Mountains were more active at low wind speeds, high temperatures, and following significant drops in temperature (Muthersbaugh et al. 2019). Activity also varied across the course of a night, albeit in a species-specific fashion (Muthersbaugh et al. 2019). Additional research on weather as a predictor of bat activity and fatalities could support mitigation efforts to reduce bat fatalities (Arnett et al. 2008, Baerwald and Barclay 2011, Weller and Baldwin 2012, Arnett and Baerwald 2013, Good et al. 2020). The amount of grassland surrounding wind energy facilities is inversely related to bat fatalities (Thompson et al. 2017). Conversely, landscape characteristics such as the proportion of nearby forested habitat or surface water, distance to a lake, and patch diversity may also increase bat activity and collision risk at wind facilities, though the importance of specific landscape variables and the spatial scale at which they influence bat activity varies between species (Farnsworth et al. 2021, Barré et al. 2023*b*).

Are male and female bats equally at risk of collision with wind turbines?

Collision risk for male vs. female bats is unclear, but may vary by species, location, or over time.

The ratio of male-to-female fatalities can vary by species, region, site, and over time (Arnett et al. 2008, Baerwald and Barclay 2011, LiCari et al. 2023, Weaver et al. 2025). Determining age and sex from a bat's external characteristics can be challenging, especially when carcasses have decomposed or have been partially scavenged (Korstian et al. 2013, Nelson et al. 2018). Studies using molecular methods to determine sex of bat carcasses show no evidence of a consistent sex bias in bat fatalities across species, locations, and times (Korstian et al. 2013, Nelson et al. 2018, LiCari et al. 2023). Male bias in fatalities may exist in some species such as evening bats (Korstian et al. 2013), while female bias in fatalities may exist in others such as silver-haired and southern yellow bats (Weaver et al. 2025). One genetic study of Brazilian free-tailed bats found that a 50:50 sex ratio of carcasses at wind energy facilities in California remained stable over several years, but that sex ratios varied between sites and over time at wind energy facilities in Texas (LiCari et al. 2023).

FIELDS OF WIND TURBINES, PHOTO BY SUWIT LUANGPIPATSORN, PIXABAY

HABITAT-BASED AND BEHAVIORAL IMPACTS TO WILDLIFE

Species' use of habitat can be affected by the construction and operation of wind energy facilities. Impacts can include disturbance, displacement from suitable habitat, or demographic effects due to fragmentation of habitat or changes in populations of predators, competitors, or prey. The section below outlines what is known and where there is remaining uncertainty about habitat-based impacts on birds and other terrestrial species.

Do wind energy facilities impact nearby bird abundance?

Construction and operation of wind energy facilities can reduce abundance of some bird species nearby.

Displacement from otherwise suitable habitat in response to wind energy development has been observed in some species groups including prairie grouse, songbirds, ducks, and raptors (Loesch et al. 2013, Stevens et al. 2013, Virginia L. Winder et al. 2014, V. L. Winder et al. 2014, Winder et al. 2015, Shaffer and Buhl 2016, LeBeau et al. 2017, Lebeau et al. 2017, Fernández-Bellon et al. 2019, Marques et al. 2019, Coppes et al. 2020, Kirol et al. 2020, Fielding et al. 2021, Maynard et al. 2025) though the majority (59.4%) of 71 studies in a meta-analysis found no evidence of displacement from wind energy on birds (Marques et al. 2021). Marques (2021) also found that approximately half of studies on grouse and other upland ground birds showed displacement from wind facilities, while the other half found no effect, or even attraction. Displacement may be temporary or permanent, with some species appearing to habituate to the disturbance associated with wind facilities (Pearce-Higgins et al. 2012, Shaffer and Buhl 2016, Dohm et al. 2019, Lemaître and Lamarre 2020, Watson et al. 2025). The reported extent and magnitude of displacement varies substantially among species and sites and the causes of this variation remain poorly understood. The population-level consequences of displacement due to wind energy development are unknown.

DESERT TORTOISE, RENEE GRAYSON, FLICKR

Do wind facilities impact the survival and reproduction of nearby birds?

Several studies report negative effects on survival or reproduction of some birds at wind energy facilities, though many other studies found no effect of wind energy on bird survival and reproduction.

Some demographic studies have reported negative effects of wind energy development on the survival or reproduction of some species of prairie grouse, raptors, and grassland passerines (Winder et al. 2015, Kolar and Bechard 2016, Mahoney and Chalfoun 2016, Proett et al. 2022, LeBeau et al. 2025). However, the majority of studies did not detect lower levels of survival or reproduction among prairie grouse, passerines, or ducks that lived in the vicinity of wind facilities (Gue et al. 2013, Hatchett et al. 2013, Bennett 2014, Gillespie and Dinsmore 2014, McNew et al. 2014, Harrison et al. 2017, LeBeau et al. 2017, Smith et al. 2017, 2024, Proett et al. 2019, Lloyd et al. 2022, Shaffer et al. 2023, Kelly et al. 2025).

Does wind energy impact habitat quality or movement for terrestrial vertebrates?

It is unknown whether wind energy facilities decrease habitat quality or act as barriers to land-scape-level movements by big game and other terrestrial vertebrates.

A small number of studies have evaluated the hypothesis that land-based wind energy facilities negatively affect non-flying wildlife. Proximity to a wind facility did not affect winter survival of pronghorn in Wyoming or show any consistent negative effects across multiple years (Taylor et al. 2016, Milligan et al. 2021), but it did change patterns of space use by females (Smith et al. 2020, Milligan et al. 2023). Female pronghorn were not displaced by construction of the wind energy facility but, following construction, there is some evidence they avoid going close to, or adjust their speed near wind turbines (Smith et al. 2020, Milligan et al. 2021, 2023). Development and operation of a wind facility in Oklahoma had no measurable impact on home range or diet of radio-collared Rocky Mountain elk (Walter et al. 2006). Long-term studies of desert tortoise at a California wind facility found survival of adult female tortoises was higher within the area of the facility than in an adjacent undisturbed area (Agha et al. 2015). The number of tortoises using the area encompassed by the facility declined over almost 20 years of monitoring, but it is unclear whether that trend exceeded the general population decline (Lovich et al. 2011, Ennen et al. 2012, Lovich and Ennen 2017).


JUVENILE RED-TAILED HAWK, PHOTO BY KELLY COLGAN AZAR, FLICKR

STRATEGIES FOR CONSERVING WILDLIFE IMPACTED BY WIND ENERGY

Siting

Substantial effort is made to estimate collision risk of birds and bats prior to the siting, construction, and operation of wind energy facilities under the premise that high-activity sites will pose an unacceptable risk to these species and should be avoided. Many wind energy companies choose to apply a tiered decision-making process as outlined in the Land-Based Wind Energy Guidelines published by the USFWS (2012). This approach, developed with input from multiple stakeholders, outlines a series of steps companies can take to identify potential threats to species thought to be at risk from wind energy development. Siting tools can incorporate wind and biological models, and other spatial data to identify suitable areas to site wind facilities to minimize impacts to wildlife (Hise et al. 2022, Boggie et al. 2023). Evidence suggests that siting turbines in agricultural landscapes, away from preferred habitat of the species of concern, such as forested areas, shorelines, topographic features, or known hibernacula may help to minimize impacts to birds and bats (Fielding et al. 2021, Cohen et al. 2022, Starbuck et al. 2022, 2022).

How can wind turbines be sited to reduce collision risk for raptors?

Siting individual turbines away from topographic features that attract concentrations of large raptors, nest sites, and quality habitat may reduce raptor collision fatalities at wind energy facilities.

Some analyses have indicated a relationship between raptor fatalities and raptor abundance (Strickland et al. 2011, Carrete et al. 2012, Dahl et al. 2012), although studies also suggest that raptor activity as measured by standard activity surveys may not correlate with the number of raptor fatalities resulting from collisions with turbines (de Lucas et al. 2012). Habitat quality may also be a useful predictor of collision risk in some cases (Heuck et al. 2019). Large raptors are known to take advantage of wind currents created by ridge tops, upwind sides of slopes, and canyons that are favorable for local and migratory movements (Bednarz et al. 1990, Barrios and Rodríguez 2004, Hoover and Morrison 2005, de Lucas et al. 2012, Katzner et al. 2012, Poessel et al. 2018, Marques et al. 2019, Sandhu et al. 2022), so avoiding siting wind turbines near these features could reduce collision risk. The U.S. Fish and Wildlife Service (USFWS) recommends that turbines should not be constructed within 2 miles of golden eagle nests or within 660 feet of bald eagle nests (50 C.F.R. §§ 13, 22). The USFWS's land-based wind energy guidelines (2012) outline a tiered framework for siting and designing wind facilities to avoid and minimize impacts to raptors and other wildlife.

Can acoustic detectors be used to predict or measure collision risk for bats?

The ability to predict collision risk for bats from pre-construction activity recorded by acoustic detectors, remains elusive; however, increasing evidence supports the use of acoustic monitoring at operating wind energy facilities to estimate collision risk.

The use of bat acoustic detectors is a common feature of pre-construction risk assessments for siting wind energy facilities (Strickland et al. 2011). To date, however, studies have not found a predictive relationship between pre-construction activity surveys and post-construction collision risk (Hein et al. 2013, Solick et al. 2020). Predicting bat collision risk using pre-construction activity measures would be further complicated if bats are attracted to wind turbines (see "*Are bats attracted to wind turbines?*"). Nonetheless, there is increasing evidence that bat acoustic data collected at operating wind turbines can be used to predict collision risk and estimate fatality rates (Peterson et al. 2021, 2025, Behr et al. 2023), though this method has limitations (Voigt et al. 2021, 2022).

How do landscape variables influence bat activity and fatalities near wind energy facilities?

Variation in bat fatality rates may be influenced by landscape features affecting activity and migration routes, such as nearby forest or water bodies.

Activity of migratory bats may be influenced by landscape features such as land cover, topography, and presence of water bodies. Variation in bat activity due to these features may be related to the observed variation in fatality rates among projects (Baerwald and Barclay 2009, Santos et al. 2013, Thompson et al.

DRY LAKE WIND POWER PROJECT, PHOTO BY IBERDROLA RENEWABLES, INC

2017, Peters et al. 2020, Farnsworth et al. 2021, Barré et al. 2023*a*), although other studies have found no relationship between bat fatality rates and landscape or habitat features (Horn et al. 2008, Arnett and Baerwald 2013, Bennett and Hale 2018). Relating fatality rates to landscape features around a wind energy facility could be useful in siting wind farms to avoid higher-risk areas (Kunz et al. 2007, Kuvlesky et al.

2007, National Academy of Sciences 2007, Arnett et al. 2008, Santos et al. 2013, Davy et al. 2021) though in some areas, there is substantial overlap between bat habitat and wind resources, so curtailment or other minimization strategies may be more successful (Huang et al. 2024). Increasingly, wind energy siting recommendations for bats include building in open, flat, agricultural landscapes, and away from forests and topographic features (Starbuck et al. 2022, 2022).

Collision Minimization Strategies

Wind energy companies also employ a variety of technologies and operational techniques to minimize fatalities of vulnerable species at operating wind energy facilities.

What is currently the most reliable and effective way to reduce raptor fatalities at wind energy facilities?

Selective shutdown (curtailment) of turbines can be an effective strategy for reducing fatalities of some raptor species.

Some of the highest raptor fatality rates have been observed in southern Spain where raptors congregate to cross the Strait of Gibraltar to Africa during migration (Ferrer et al. 2012). Over 13 years of implementation ofselective shutdown of turbines with the greatest number of fatalities across 20 wind farms in Spain resulted in a substantial reduction in fatalities of griffon vultures (92.8%) and other soaring birds (e.g., raptors, storks; 61.7%; Ferrer et al. 2022). Some wind facilities in the U.S. employ people to monitor and curtail turbines for eagles, but there is increasing interest in using automated systems to reduce collision risk for eagles (McClure et al. 2022, Smith et al. 2025).

Camera-based systems coupled with machine vision algorithms can detect and classify eagles in real time (McClure et al. 2018, Gradolewski et al. 2021, Duerr et al. 2023, Gémard et al. 2025, Smith et al. 2025) in the vicinity of a wind project and have demonstrated the ability to substantially reduce eagle fatalities (estimates from different analyses range from 50 to 85%) via automated curtailment at a wind energy facility in Wyoming (McClure et al. 2022, Huso and Dalthorp 2023). Other systems seek to reduce collisions through the use of audio or visual deterrents (Albertani et al. 2021, Boycott et al. 2021, Felton et al. 2024). Additional research is needed to reduce curtailment orders triggered by non-target species, such as vultures (Duerr et al. 2023), and to determine whether these systems are effective in different locales and for different species. Radar-based systems have yet to demonstrate efficacy at detection and identification of target species (Washburn et al. 2022). Painting turbine blades with contrasting colors and patterns as a risk minimization strategy is also an active area of research (see below "*How can painting turbine blades with various colors/patterns reduce collisions*?").

JUVENILE BALD EAGLE, PHOTO BY ELSIE.HUI, FLICKR

What is currently the most reliable and effective way to reduce bat fatalities at wind energy facilities?

Curtailing turbine blade rotation when bats are at highest risk substantially reduces bat fatalities.

Meta-analyses have clearly demonstrated the effectiveness of curtailment (greatly reducing or stopping turbine blade rotation) at low wind speeds at reducing bat fatalities at wind energy facilities, and that the efficacy of curtailment increases with higher cut-in wind speeds (i.e. the minimum wind speed/threshold at a which turbine is programed to begin spinning and generating power; Adams et al. 2021, Whitby et al. 2024). Compared to normally operating turbines (typical cut-in speeds 3-4 m/s), Whitby et al. (2024) estimated a 33% reduction in bat fatalities for every 1.0 m/s increase in cut-in speed, with an average of a 62% reduction in bat fatalities at wind facilities operating with a 5.0 m/s cut-in speed. In an effort to improve the efficacy of curtailment and limit losses in electricity production, there is a developing field of "smart" curtailment strategies, which incorporate additional inputs such as real-time bat activity (Rabie et al. 2022, Vallejo et al. 2023, Newman et al. 2024) or environmental variables such as wind direction, temperature, precipitation, or time of night and season (Martin et al. 2017, Farnsworth et al. 2021, Squires et al. 2021, Barré et al. 2023*b*, Gottlieb et al. 2024) into the curtailment prescription. One smart curtailment approach that combined real-time wind speed and bat activity data reduced estimated bat fatalities at a facility by nearly 75% relative to control turbines, but also increased electricity generation losses from curtailment in comparison to traditional curtailment with a cut-in speed of 4.5 m/s (Rabie et al. 2022). Losses in electricity generation are highly dependent on the curtailment parameters and site-specific variables, and can range from 1-10% reduction in Annual Energy Production (Maclaurin et al. 2022). Further study to better predict periods of high collision risk for bats could optimize timing of curtailment and minimize power loss.

Additionally, raising the minimum rotor sweep (ground clearance of the rotor sweep) may help reduce risks, though not in place of curtailment (Garvin et al. 2024). Ultrasonic deterrents are not yet considered a reliable source of reducing collision risk for bats (see below: "*Can ultrasonic sound be used to minimize bat fatalities at wind facilities?").*

Can ultrasonic sound be used to minimize bat fatalities at wind facilities?

Ultrasonic emitters may deter bats away from rotor-swept areas and reduce bat fatalities for some species, but they may increase fatalities for others.

Experimental trials have shown that ultrasonic devices can modify flight behavior (speed, tortuosity), and reduce bat activity and foraging success, and evaluation of similar devices installed on wind turbines has shown that they can reduce overall bat fatalities (Arnett et al. 2013, Romano et al. 2019, Gilmour et al. 2020, 2021, Weaver et al. 2020, Good et al. 2022). However, there is evidence that fatality rates of eastern red bats may increase when ultrasonic acoustic deterrents are active (Romano et al. 2019, Clerc et al. 2025*a*). Results are mixed as to whether (Good et al. 2022) or not (Clerc et al. 2025*a*) deployment of an ultrasonic acoustic deterrent along with curtailment can result in greater fatality reductions than curtailment alone. Ultrasound attenuates quickly, so getting effective coverage of the rotor-swept zone is a major challenge, particularly as larger turbines are built (Gilmour et al. 2021, Good et al. 2022).

How can painting turbine blades with various colors/patterns reduce collisions?

Preliminary studies aiming to increase turbine visibility and reduce collision fatalities through various blade painting strategies have shown mixed results.

Since the 1990's bird vision has been of leading interest to scientists interested in mitigating wind-wildlife challenges. A small behavioral study documented that trained red-tailed hawks and American kestrels have lower visual acuity than expected, which could impact their ability to perceive the blades of operating wind turbines (PNAWPPM-IV 2001). A laboratory study investigating the retinal activity of anesthetized American kestrels further supported this theory and found that painting turbine blades with various contrasting colors and patterns could reduce the "motion smear" that raptors may experience when approaching spinning turbines blades, allowing flying raptors to better see and thus avoid operating wind turbines (Hodos 2003). Building on this, a pilot field experiment in Norway testing the efficacy of painting a single blade black, found a 70% reduction in overall bird fatality rates for turbines with black-painted blades (when ptarmigans were excluded; May et al. 2020). However promising, the results were preliminary, as the study size was small (with only four painted turbines paired with all white control turbines) and showed high variation in fatality rates among years. Furthermore, results for eagles were inconclusive, as no eagles were found at either control or painted turbines after painting. Regardless the study in Norway has inspired additional investigations into the method across the globe (e.g., Blary et al. 2023, Hancock et al. 2025), with mixed results. A U.S. study currently underway should have results available within a few years. Additionally, ultraviolet (UV) paint, hypothesized to be more visible to birds, did not reduce collisions in one study (Young et al. 2003) and controlled behavioral trials have indicated that some raptor species show little response to UV light (Hunt et al. 2015).

Blade painting strategies have also been proposed to reduce collision risk for bats. In a field experiment,

MEXICAN FREE-TAILED BATS EXITING BRACKEN BAT CAVE, PHOTO BY USFWS HEADQUARTERS, FLICKR

Jonasson et al. (2025) found that bats appeared to be less likely to approach black painted surfaces than white surfaces when both were dimly lit by artificial moonlight, suggesting that blade painting strategies to reduce the reflectivity of turbine blades to moonlight could help reduce bat fatalities at wind energy facilities.

Can lighting be used to minimize collision risk for birds or bats?

There is little evidence that lighting on wind turbines decreases or increases collision risk to birds or bats.

The FAA regulates the lighting required on structures (including wind turbines) taller than 199 feet to ensure air traffic safety. For wind turbines, the FAA currently recommends strobe or strobe-like lights that produce momentary flashes interspersed with dark periods up to three seconds in duration, and they allow wind energy facilities to light a proportion of the turbines in a facility (e.g., one in five), triggering all lights synchronously (FAA 2007). Light pollution is known to contribute to fatal bird collisions with buildings and other infrastructure, and to alter migratory movements (Burt et al. 2023). However, the number of bat and songbird fatalities at turbines using FAA-approved lighting is not greater than that recorded at unlit turbines (Kerlinger et al. 2010, Bennett and Hale 2014). One study (Bennett and Hale 2014) recorded higher eastern red bat fatalities at unlit turbines compared to those using red aviation lights; no differences were observed for other bat species between lit and unlit turbines. Similarly, there is no evidence to support the use of UV light as a deterrent for eagles, nocturnally migrating birds, or bats (Hunt et al. 2015, Cryan et al. 2022). While lights have not been shown to increase fatalities at the individual turbine scale, a hypothesis that lighting may attract bats to wind energy facilities from a distance has not been tested (Jonasson et al. 2024).

Conservation Offsets (also called Compensatory Mitigation)

What conservation opportunities exist to offset impacts to birds and bats from wind energy?

Wind energy companies can fund efforts to reduce other sources of eagle and bat mortality through "compensatory mitigation" programs administered by the U.S. Fish and Wildlife Service (USFWS) as well as voluntary initiatives.

Wind companies are required to offset incidental eagle take (fatalities) incurred at their facilities in accordance with the Bald and Golden Eagle Protection Act (BGEPA; 16 U.S.C. §§ 668–668d, as amended), by preventing other sources of eagle fatalities. Under the new General Permit option, wind companies offset projected incidental eagle take before any take actually occurs. Historically, the primary means by which wind companies could offset eagle take was through retrofitting power poles to prevent electrocution (USFWS 2013). With the publication of the revised "Eagle Rule" (50 C.F.R. §§ 13, 22), the USFWS is working to adopt additional methods of compensatory mitigation including lead abatement via incentivizing the use of copper bullets over lead for hunting (Cochrane et al. 2015, Slabe et al. 2024) and vehicle collision prevention via the relocation of roadkill away from roadsides (Lonsdorf et al. 2018, 2023, Slater et al. 2022). Another compensatory mitigation strategy based on treating golden eagle nestlings for parasites and disease is in development (Heath et al. 2024, 2025).

Wind companies are also required to offset incidental take of bats and other species listed under the Endangered Species Act (16 U.S.C. §§ 1531-1544) such as the Indiana bat and northern long-eared bat, by preventing other sources of bat fatalities. If a wind facility is predicted to incur take of a threatened or endangered species, they can submit an Incidental Take Permit (ITP) and Habitat Conservation Plan (HCP) to the U.S. Fish and Wildlife Service, which outline measures to minimize and then compensate for unavoidable take. Common measures to offset take of endangered bats include erecting gates preventing human entry into known bat hibernacula, and land acquisition (Newman and Surrey 2025). The U.S. Fish and Wildlife Service has also indicated that funding research on white nose syndrome (WNS) and wind energy collision minimization is an acceptable mitigation option (U.S. Department of Interior 2023). Additional compensatory mitigation measures have been proposed such as improving forested habitat, improving or providing roost sites, or creating foraging habitat, but these measures have not yet been validated (Voigt et al. 2024).

While companies are required to offset impacts beyond what can be avoided and minimized, some companies also take voluntary actions to offset potential risks. One example of this is the Wind Energy Condor Action Team (WECAT) agreement with USFWS, which developed a conservation plan that, among other actions, funds a full time employee for the California condor captive breeding program (USFWS 2023). No there are no records to date of California condors colliding with wind turbines, so this incidental take permit provides an example of a proactive measure by wind energy companies and USFWS to conserve the California condor population.

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This summary focuses on wildlife interactions with land-based wind energy. The following resources can provide a starting point for information on wildlife interactions with offshore wind energy (REWI does not endorse and is not responsible for the content within these links):
https://www.audubon.org/our-work/climate/clean-energy/birds-and-offshore-wind-report
https://www.fisheries.noaa.gov/new-england-mid-atlantic/marine-life-distress/frequent-questions-offshore-wind-and-whales
https://rwsc.org/

Suggested Citation: Renewable Energy Wildlife Institute (REWI). 2025. Wind Energy Interactions with Wildlife: Answers to Frequently Asked Questions Based on the State of the Science. Washington, DC. Available at www.rewi.org.

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About REWI

The Renewable Energy Wildlife Institute (REWI) is an independent 501(c)3 organization that develops and leverages scientific research around renewable energy interactions with wildlife, habitats, and ecosystems. Built on a partnership of renewable energy companies, conservation and science organizations, and public agencies, REWI develops innovative approaches and independent results that advance renewable energy expansion while meeting conservation goals.

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